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An integrated greenhouse gas assessment of an alternative to slash-and-burn agriculture in eastern Amazonia

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Abstract

Fires set for slash-and-burn agriculture contribute to the current unsustainable accumulation of atmospheric greenhouse gases, and they also deplete the soil of essential nutrients, which compromises agricultural sustainability at local scales. Integrated assessments of greenhouse gas emissions have compared intensive cropping systems in industrialized countries, but such assessments have not been applied to common cropping systems of smallholder farmers in developing countries. We report an integrated assessment of greenhouse gas emissions in slash-and-burn agriculture and an alternative chop-and-mulch system in the Amazon Basin. The soil consumed atmospheric methane (CH_4) under slash-and-burn treatment and became a net emitter of CH_4 to the atmosphere under the mulch treatment. Mulching also caused about a 50% increase in soil emissions of nitric oxide and nitrous oxide and required greater use of fertilizer and fuel for farm machinery. Despite these significantly higher emissions of greenhouse gases during the cropping phase under the alternative chop-and-mulch system, calculated pyrogenic emissions in the slash-and-burn system were much larger, especially for CH_4. The global warming potential CO_2-equivalent emissions calculated for the entire crop cycles were at least five times lower in chop-and-mulch compared with slash-and-burn. The crop yields were similar for the two systems. While economic and logistical considerations remain to be worked out for alternatives to slash-and-burn, these results demonstrate a potential 'win-win' strategy for maintaining soil fertility and reducing net greenhouse gas emissions, thus simultaneously contributing to sustainability at both spatial scales.

Keywords: biomass burning, CH_4, global warming potentials, methane, mulching, nitric oxide, nitrous oxide, shifting agriculture, soil

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Introduction

The sustainability of agricultural systems must be considered at both local scales, where soil fertility and crop yield are paramount, and at global scales, where unsustainable increases in greenhouse gas concentrations are occurring in the atmosphere due, in part, to agricultural activities. Full accounting of all greenhouse gas emissions have been calculated for only a few intensive agricultural systems (Robertson *et al*., 2000; West & Marland, 2002; Robertson & Grace, 2004; Mosier *et al*., 2005) and for the initial conversion of mature tropical forest to agriculture (Palm *et al*., 2005). Here, we provide the first such integrated assessment of greenhouse gas emissions for slash-and-burn agriculture compared with an alternative chop-and-mulch system designed for smallholder farmers in the eastern Amazon Basin.

Estimates of the number of people engaged in slash-and-burn agriculture, also known as shifting agriculture, ranges from 37 to 300 million people (Sanchez *et al*., 2005). Up to 1 billion hectares of land have been affected, although the area currently under production is smaller (Sanchez *et al*., 2005). This agricultural system is characterized by cycles of cutting and burning fallow

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vegetation for site preparation, a cropping phase of 2–4 years, and a fallow phase when native vegetation reclaims the site. Increasing pressures on limited agricultural land by growing human populations has resulted in shortening of fallow periods in traditional slash-and-burn agriculture practices throughout much of the world (Sanchez *et al*., 2005). Biomass burning releases greenhouse gases (Andreae & Merlet, 2001) and other air pollutants (Andreae *et al*., 2002, 2004; Lohman *et al*., 2007) and may impoverish the soil of carbon (C) and nutrients (Davidson *et al*., 2004) if the fire-return interval becomes too short, as is now often the case (Sanchez *et al*., 2005). The contribution of all forms of biomass burning to total global emissions is estimated at 7% for methane (CH_4), 3% for nitrous oxide (N_2O), 14% for nitric oxide (NO), 45% for carbon monoxide (CO), and 6% for volatile organic compounds (VOCs) (Prather *et al*., 2001).

A system of mechanically chopping the fallow vegetation and converting it to mulch during site preparation has been demonstrated as a means of avoiding the use of fire and effectively conserving nutrients on the site (Kato *et al*., 1999; Sommer *et al*., 2004; Denich *et al*., 2005). However, agricultural practices that might reduce pyrogenic emissions could also enhance soil emissions of some of these same gases by increasing nutrient inputs to the soil and by altering soil water dynamics and soil aeration. A mulch layer that retains water, impedes oxygen diffusion, and provides substrate for heterotrophic activity could significantly increase denitrification and methanogenesis, thus possibly increasing soil emissions of CH_4 and N_2O (Davidson & Schimel, 1995).

The objective of this study was to measure soil emissions of the greenhouse gases, CH_4, and N_2O, and the tropospheric ozone precursor, NO, throughout an entire cropping cycle in slash-and-burn and chop-and-mulch fields and in an adjacent 15-year-old fallow field with secondary forest vegetation. We then compare these flux measurements with estimates of emissions from the fire used to prepare the slash-and-burn field, using measurements of the fallow biomass and published emission factors for each of these gases. Finally, we develop budgets of greenhouse warming potentials (GWPs) for both cropping systems, which include fire emissions, soil emissions, fertilizer consumption and diesel fuel consumption.

Materials and methods

Site description

This research was conducted at the Federal Rural University of Amazonia experimental farm, which is located in the municipality of Igarape Açu (1°07′S; 47°36′W), in the Brazilian state of Pará, about 120 km east of the state capital city of Belém. The dominant vegetation of the region was once moist lowland tropical forest, but is now a mosaic mostly of secondary forests, pastures and small agricultural fields of corn, rice, beans and manioc, which were established first during the rubber extraction era of the late 19th century and then expanded by government rural development programs in the mid-20th century (Vieira *et al*., 2003). Secondary fallow vegetation now covers roughly half of the area, with each smallholder's field of crops or fallow vegetation rarely exceeding 2 ha (Sommer *et al*., 2004). The population density is about 21 people km^{-2}, so demand for agricultural land is high, and nearly all fallow is recleared for cropping within a few years (Vieira *et al*., 2003).

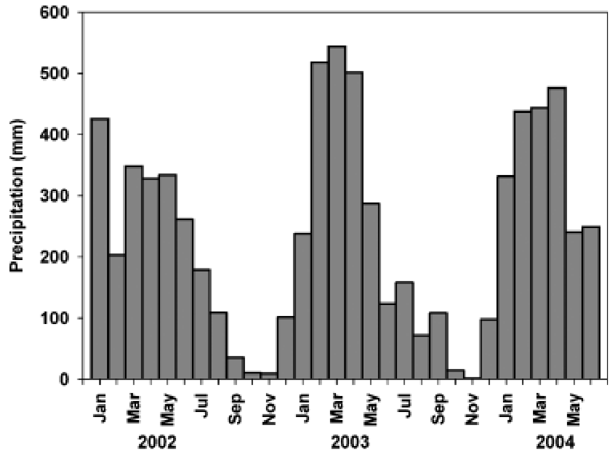

Fig. 1 Monthly precipitation measured at the Federal Rural University of Amazonia experimental farm, Igarape Açu, Brazil.

The soils in the study area are classified as Typic Hapludults and are acidic, sandy (65–80% sand), and characterized by low plant-available P, low cation exchange capacity, and high subsoil aluminum saturation (Sommer *et al*., 2004). Mean annual temperature is 26 °C with little seasonal variation. Mean annual precipitation is 2200 mm, with a distinct dry season from June to November (Fig. 1).

Site preparation

A 15-year-old fallow area was prepared for planting during the dry season of 2001. This secondary forest contained 99.6 ± 19.5 (1 SD; $N = 10$ plots; 10 m × 10 m) Mg ha^{-1} at the time of site preparation. Two fields (1 ha each) were cut and burned in November 2001 and two fields (also 1 ha each) were cut and mulched in December 2001, using a tractor-driven modified maize chopper. A few of the tree boles were too large for the chopping machinery

(>40 cm diameter at breast height) and had to be transported off the site. All fields were planted in maize in January 2002. The mulched fields were fertilized with 60 kg N, 60 kg P, and 30 kg K ha^{-1} (as urea, triple superphosphate and potassium chloride) at time of planting of corn. In addition, 30 kg N ha^{-1} as urea was added in the mulched fields 45 days after germination of the corn. Previous research has shown that nutrients are immobilized in the mulch, and that fertilization during the first year is necessary to obtain good crop yield with mulching (Kato *et al*., 1999). Fertilizers are not used in the chop-and-mulch system after the first year and are very seldom used by slash-and-burn farmers. In both systems, cassava was planted under the maize in February 2002, and the maize was harvested in May 2002. The fields were weeded, and leguminous trees (*Acacia mangium*, Willd, and *Sclerolobium paniculatum*, Vogel) were planted in 2 m × 2 m spacing in June 2002. The cassava was harvested in June 2003, and the fields were allowed to return to enriched fallow.

Soil emissions of trace gases

At the beginning of the experiment, a 10 m × 10 m study plot was established within each of the two fields for each of the two agricultural treatments. A fifth plot was located in an adjacent fallow field with 15-year-old secondary forest vegetation. Eight polyvinyl chloride (PVC) rings (20 cm diameter) were inserted about 2 cm into the soil in each of these five plots. Flux measurements were begun before treatment in November 2001. The rings had to be removed before the burning and mulching treatments and then reinstalled afterwards and left in place for the duration of the study. Flux measurements were repeated once every 1–3 months until June 2004.

A dynamic chamber method was used for measuring fluxes of NO (Verchot *et al*., 1999). A vented PVC cover made from an end-cap of a 20 cm diameter PVC pipe was placed over a PVC ring to make a flux measurement. Air drawn from the chamber was circulated through a nafion gas sample dryer, a Scintrex LMA-3 NO_2 analyzer (Scintrex Ltd, Concord Ontario, Canada) and then back to the chamber, using teflon tubing and a battery-operated pump, at a flow rate of 0.5 L min^{-1}. Varying the flow rate from 0.4 to 1.2 L min^{-1} had no detectable effect on measured flux rates. NO is converted to NO_2 by a CrO_3 converter, and the NO_2 is detected by chemiluminescent reaction with Luminol. Fluxes were calculated from the rate of increase of NO concentrations, recorded by a datalogger at 12 s intervals between 1 and 3 min after placing the cover over the ring. The instrument was calibrated twice daily in the field. An instrument failure prevented NO measurements after May 2003.

Fluxes of N_2O and CH_4 were measured using a static chamber technique (Verchot *et al*., 1999, 2000) and using the same chamber bases as those described above. A 20 mL sample of headspace gas was collected by syringe from a vented chamber top at 30 s, 10, 20, and 30 min after placing the chamber top over the ring. These gas samples were analyzed in a laboratory in Belém by gas chromatography within 48 h, using an electron capture detector for N_2O analysis and a flame ionization detector for CH_4 analysis (Verchot *et al*., 1999, 2000). Fluxes were calculated from the rate of concentration change, determined by linear regression. A few data gaps resulted from occasional failure of the gas chromatographs. Both dynamic and static chamber flux measurements were made on the same day and, in most cases, within 90 min of each other.

Statistical analyses were performed on SYSTAT10 software. A repeated measures ANOVA was used to test treatment and treatment-by-date effects. Main effects were burning, mulching, and continuous fallow. Owing to non-normal distributions of the flux data, all values were log-transformed before statistical analyses.

Soil analyses

Soil water content was measured gravimetrically twice per month. Two replicate samples per study plot and date were removed, using a soil coring devise, and divided into 0–5, 5–10, 10–20, 20–40, and 40–60 cm depth increments. Soil bulk density and nutrient concentrations were measured in February 2002, within about 1 month of completion of all site preparation activities, using a bulk density soil coring devise designed to avoid compaction while sampling depth increments of 0–5, 5–10, 10–20, 20–30, and 30–50 cm. Duplicate profiles were measured in each study plot. The litter layer (including the mulch) was measured by destructive sampling of six 0.25 m^2 quadrants. Soil C and nutrient concentrations were measured in samples from each study plot, removed with a soil coring devise for depth increments of 0–5, 5–10, 10–20, and 20–30. Nutrient measurements were repeated in triplicate in each plot in October 2003, after the last crop harvest, and C measurements were similarly repeated in December 2004, at the end of the experiment.

Soil samples were dried and passed through a 2 mm sieve to remove roots. C and nitrogen (N) concentrations were measured using a LECO CNS-2000 analyzer (LECO Corporation, St Joseph, MI, USA). All other soil chemical analyses follow standard Embrapa procedures (Embrapa, 1997). Soil pH was measured in water and in 1 N KCl. A Mehlich-I dilute double acid extraction procedure (Amacher, 1996) was used to estimate available P, and the P was quantified spectrophotometrically (Murphy & Riley, 1962). Ammonium and nitrate were extracted in 2 M KCl and measured colorimetrically following cadmium reduction of nitrate to nitrite.

Calculation of GWP

Pyrogenic emissions of trace gases and their CO_2-equivalents (Table 1) were calculated from the product of measured fallow biomass, a combustion efficiency of 93% measured in a nearby fallow burning experiment (Sommer *et al.*, 2004), and literature values of emission factors for tropical forests (Andreae & Merlet, 2001). The CO_2-equivalent consequences of fertilizer and diesel fuel use were calculated using literature values as follows:

Nitrogen fertilizer

$$[(90\,\mathrm{kg\,N\,ha^{-1}} \times 0.86\,\mathrm{kg\,C\,kg^{-1}\,N}) + 24\,\mathrm{kg\,C\,ha^{-1}}] \times 44\,\mathrm{kg\,CO_2}/12\,\mathrm{kg\,C} = 370\,\mathrm{kg\,CO_2\,ha^{-1}}, \quad (1)$$

where $90\,\mathrm{kg\,N\,ha^{-1}}$ is the summed N application rates of two applications, $0.86\,\mathrm{kg\,C\,kg^{-1}\,N}$ is the conversion factor for N fertilizer production (from Table 3 of West & Marland, 2002), and $24\,\mathrm{kg\,C\,ha^{-1}}$ is the additional C cost of two fertilizer applications in the field (from Table 7 of West & Marland, 2002).

Phosphorus fertilizer

$$(60\,\mathrm{kg\,P_2O_5\,ha^{-1}} \times 0.17\,\mathrm{kg\,C\,kg^{-1}\,P_2O_5}) \times 44\,\mathrm{kg\,CO_2}/12\,\mathrm{kg\,C} = 37\,\mathrm{kg\,CO_2\,ha^{-1}}, \quad (2)$$

where $60\,\mathrm{kg\,P_2O_5\,ha^{-1}}$ is the total P application rate, $0.17\,\mathrm{kg\,C\,kg^{-1}\,P_2O_5}$ is the conversion factor for P fertilizer production (from Table 3 of West & Marland, 2002), and no additional application cost is added because it is already included in the accounting of the first N application, which was done simultaneously with P and K.

Potassium fertilizer

$$(30\,\mathrm{kg\,K_2O\,ha^{-1}} \times 0.12\,\mathrm{kg\,C\,kg^{-1}\,K_2O}) \times 44\,\mathrm{kgCO_2}/12\,\mathrm{kg\,C} = 13\,\mathrm{kg\,CO_2\,ha^{-1}}, \quad (3)$$

where $30\,\mathrm{kg\,K_2O\,ha^{-1}}$ is the total K application rate and $0.17\,\mathrm{kg\,C\,kg^{-1}\,K_2O}$ is the conversion factor for K fertilizer production (from Table 3 of West & Marland, 2002).

Diesel fuel combustion by chop-and-mulch machinery

$$300\,\mathrm{L\,ha^{-1}} \times 0.71\,\mathrm{kgC\,L^{-1}} \times 44\,\mathrm{kgCO_2}/12\,\mathrm{kg\,C} = 780\,\mathrm{kg\,CO_2\,ha^{-1}}, \quad (4)$$

where $300\,\mathrm{L\,ha^{-1}}$ is the estimated diesel fuel use for the chop-and-mulch operation and $0.71\,\mathrm{kgC\,L^{-1}}$ is conversion factor for diesel fuel combustion (from Table S7 of Robertson *et al.*, 2000).

We use the 100-year integrated GWPs of 23 and 296 for CH_4 and N_2O (Ramaswamy *et al.*, 2001), respectively, to calculate the CO_2-equivalents on a mass basis of all net releases of these gases to the atmosphere from the soil, fire, and use of fertilizers and diesel fuel that we were able to measure or calculate.

Table 1 Calculation of pyrogenic emissions from the slash-and-burn treatment using published emission factors (grams of gaseous compound emitted per kilogram of dry fuel consumed) for tropical forest biomass Andreae & Merlet (2001), assuming that 99.6 Mg dry matter $\mathrm{ha^{-1}}$ in the fallow vegetation was cut and burned with a combustion efficiency of 93% Sommer *et al.* (2004)

	Emission factor	Fire emission	CO_2 equivalents
Methane	6.8 ± 2.0	$630\,\mathrm{kg\,CH_4\,ha^{-1}}$	$14\,000\,\mathrm{kg\,CO_2\,ha^{-1}}$
Nitrous oxide	0.20 (best guess)	$19\,\mathrm{kg\,N_2O\,ha^{-1}}$	$5600\,\mathrm{kg\,CO_2\,ha^{-1}}$
Nitric oxide	1.6 ± 0.7	$130\,\mathrm{kg\,NO\,ha^{-1}}$	Not applicable

All values are rounded to two significant figures.

Results

Soil emissions

The most striking effect of the mulching treatment was an increase in net emissions of CH_4 from the soil (Fig. 2a). The soils were a net sink for CH_4 before site preparation (negative values in Fig. 2a), and they remained net sinks in the burned and continuous fallow areas. In contrast, the soil in the mulched treatment area became a net source of CH_4 during the first postplanting wet season and remained so for the duration of the study. Interpolating these data to estimate emissions for the entire 26-month trace gas measurement period, the soils of the burned and fallow treatments had a net uptake of 2–5 $\mathrm{kg\,CH_4\,ha^{-1}}$, whereas the soils in the mulching treatment area were a net source of $16\,\mathrm{kg\,CH_4\,ha^{-1}}$ (Table 2). These net CH_4 uptake rates are within the range reported in mature and young forests of the eastern Amazon region (Verchot *et al.*, 1999, 2000). In contrast, the mean net emissions in the mulched area (Fig. 2a) are about four times higher than the peak mean net emissions of $1.1\,\mathrm{mg\,CH_4\,m^{-2}\,day^{-1}}$ measured during the wet season in an active cattle pasture (Verchot *et al.*, 2000).

Low soil emissions of NO and N_2O were measured in the continuous fallow area, consistent with published annual flux estimates of other aggrading secondary

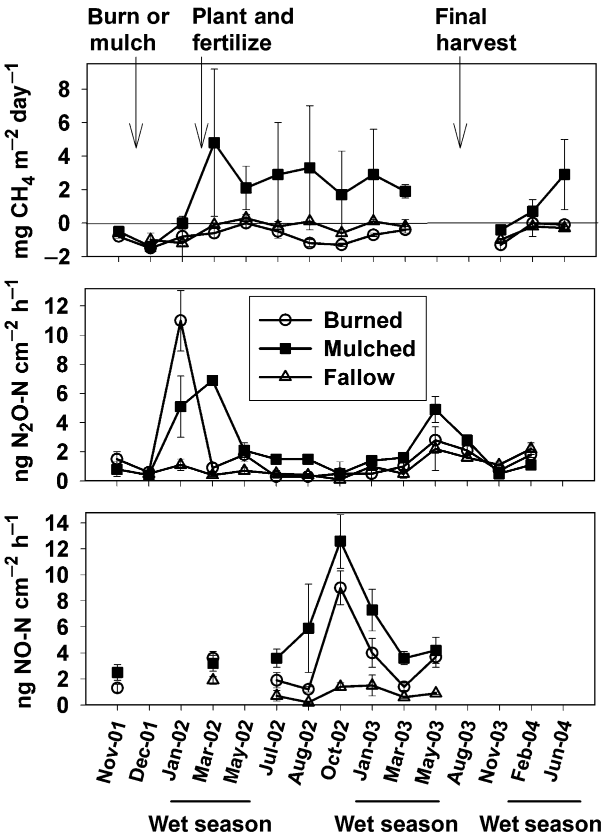

Fig. 2 Soil emissions of trace gases (means and standard errors) for slash-and-burn, chop-and-mulch, and continuous fallow vegetation treatments. A repeated measured ANOVA on log-transformed data indicated that treatment effects and time were significant ($P<0.01$) for all three gases. Treatment-by-time interactions were also significant ($P<0.01$) for NO and N_2O ($P<0.05$). N_2O, nitrous oxide; NO, nitric oxide.

forests in the eastern Amazon region, where conservative N cycling properties have been observed (Verchot *et al*., 1999; Vasconcelos *et al*., 2004; Davidson *et al*., 2007). There was a brief pulse of N_2O emission early in the wet season after the burning treatment, but thereafter, N_2O emissions were consistently and significantly higher in the mulching treatment area (Fig. 2b). Emissions of NO were highest in the mulching treatment area from July 2002 through March 2003 (Fig. 2c). Although statistically significant, the differences between mulched and burn treatments for NO and N_2O were only 1–3 kg N ha^{-1} over the 26-month measurement period (Table 2). The additions of N to the soil as ash in the slash-and-burn treatment and as fertilizer in the mulching treatment probably contributed to increased NO and N_2O emissions. The slash-and-burn treatment eliminated the litter layer and transferred ash to the mineral soil, increasing the pH, available-P, and extractable ammonium and nitrate of the top 5 cm of

Table 2 Estimates of soil emissions by management phase

	Preplanting (60 days)	Crops (480 days)	Postharvest fallow (240 days)	Sum
Methane (CH_4; kg CH_4 ha^{-1})				
Slash-and-burn	−0.7	−3.2	−1.1	−5.0
Chop-and-mulch	−0.4	13.4	2.6	+15.6
Continuous fallow	−0.7	−0.4	−1.2	−2.3
Nitrous oxide (N_2O; kg N ha^{-1})				
Slash-and-burn	0.8	1.2	0.9	2.9
Chop-and-mulch	0.4	2.9	0.8	4.2
Continuous fallow	0.1	0.8	0.9	1.9
Nitric oxide (NO; kg N ha^{-1})				
Slash-and-burn	0.1	4.1	nd	4.2
Chop-and-mulch	0.0	6.6	nd	6.6
Continuous fallow	0.0	1.2	nd	1.2

The study period was divided into preplanting, crop, and postharvest fallow periods and the mean flux estimate for each period was used to estimate the total soil emissions during that period for each treatment. Calculations for the postharvest fallow period were truncated in February 2004, because that was the last date for which both N_2O and CH_4 fluxes were successfully measured. Negative values for CH_4 indicate net uptake of atmospheric CH_4 by the soil; positive values indicate net efflux from the soil to the atmosphere.

soil (Table 3). Nearly 2 years later, these elevated post-burn values were no longer apparent. Some temporal variation in extractable nutrients was also observed in the chop-and-mulch and continuous fallow treatments, which may be confounded with seasonal effects, but the differences between sampling dates were smaller in magnitude and of the opposite sign as those observed for the slash-and-burn treatment (Table 3).

An increase in production of CH_4 and N_2O under the mulch layer is not surprising given the increased inputs of C and N substrates and changes in moisture regimes. The top 5 cm of mineral soil remained wetter in 2003 and 2004 under the chop-and-mulch treatment relative to the slash-and-burn and continuous fallow treatments (Fig. 3). The same trends occur in the 5–10 cm depth interval, and no differences among treatments in soil water content were observed below 10 cm (not shown). These moist conditions, along with inputs of labile substrates, apparently increased the incidence of anaerobic microsites where methanogenesis and denitrification would be favored (Davidson & Schimel, 1995).

Comparing soil and pyrogenic emissions

Using a biomass estimate of 99.6 Mg dry matter ha^{-1} in the fallow vegetation when the site was cut and burned, a combustion efficiency of 93% measured in a nearby burning experiment (Sommer *et al*., 2004), and emission

Table 3 Soil pH, available-P, and extractable NH_4^+ and NO_3^- in the top 5 cm mineral soil measured after site preparation in February 2002 and after the final crop harvest in October 2003

	pH in water		pH in 1 M KCl		Mehlich P (mg kg^{-1})		NH_4^+ (mg kg^{-1})		NO_3^- (mg kg^{-1})	
Treatment	Feb02	Oct03	Feb02	Oct03	Feb02	Oct03	Feb02	Oct03	Feb02	Oct03
Slash-and-burn	7.19 (0.29)	5.43 (0.18)	6.82 (0.42)	4.63 (0.21)	73.1 (18.8)	4.11 (0.44)	20.0 (0.9)	8.9 (3.8)	22.1 (3.2)	3.9 (0.3)
Chop-and-mulch	6.07 (0.24)	5.27 (0.39)	4.83 (0.22)	4.79 (0.08)	4.83 (0.87)	9.41 (1.48)	15.2 (3.6)	24.6 (4.2)	6.2 (1.7)	6.6 (0.5)
Continuous fallow	5.59 (0.07)	5.23 (0.25)	4.41 (0.09)	4.28 (0.22)	2.69 (0.30)	3.89 (0.40)	13.5 (4.3)	25.1 (3.5)	3.9 (1.4)	4.2 (0.4)

Means are followed by standard errors (in parentheses; $n = 2$ in 2002; $n = 6$ in 2003).

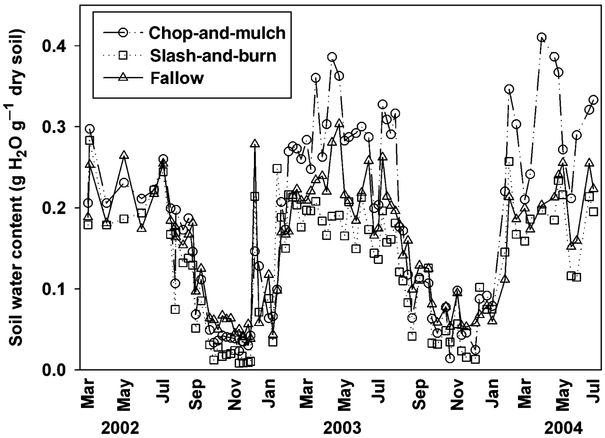

Fig. 3 Gravimetric soil moisture of the 0–5 cm depth of the mineral soil.

factors for tropical forest biomass burning from the literature (Andreae & Merlet, 2001), we calculate that per hectare fire emissions were 630 kg CH_4, 19 kg N_2O, and 130 kg NO (Table 1). These pyrogenic emissions are 42, 3, and 10 times higher than the highest summed soil emissions of CH_4, N_2O, and NO, respectively, for the 26-month trace gas measurement period for any of the study sites. Therefore, the remarkably high soil emissions of CH_4 in the mulching treatment are dwarfed by the much higher pyrogenic emissions of CH_4 in the slash-and-burn system (Table 4). The avoided fire emissions of N_2O are more modest, but the avoided NO emissions from fire are also an order of magnitude larger than the increased soil NO attributed to mulching (Tables 2 and 3).

Discussion

GWP

Including the fire emissions demonstrates that a net decrease in total CH_4 emissions occurs when slash-and-burn is replaced by chop-and-mulch, whereas the opposite conclusion would have been reached if only soil emissions were considered. The uncertainty of average tropical forest biomass CH_4 emission factors is about 20–30% (Andreae & Merlet, 2001), although the uncertainty for any single fire could be larger due to variation of fire intensity and completeness of biomass combustion. Ward *et al*. (1992) reported CH_4 emission factors for a secondary forest near Marabá, Brazil, which had similar biomass as the forest in our study, that were 30% lower than the global mean of all tropical forests of Andreae & Merlet (2001). On the other hand, Ferek *et al*. (1998) reported CH_4 emission factors from six Amazonian forest fires that were, on average, 16% (flaming phase) and 84% (smoldering phase) higher than the global mean of Andreae & Merlet (2001), although the types of forests and their biomass were

Table 4 Comparison of greenhouse warming potentials (GWP) for a 100-year time frame of emissions from slash-and-burn and chop-and-mulch cropping systems over approximately a 2-year cycle

	Slash-and-burn		Chop-and-mulch	
	Flux	CO_2 equivalents	Flux	CO_2 equivalents
Soil CH_4 efflux	−5.0	−120	16	370
Fire CH_4 emissions	630	14 000	0	0
Soil N_2O-N efflux	2.9	1300	4.2	2000
Fire N_2O-N emissions	12	5600	0	0
N fertilizer	0	0	90	370
P fertilizer	0	0	60	37
K fertilizer	0	0	30	13
Diesel fuel for mulching	0	0	300	780
Total CO_2 equivalents		21 000		3600

All values are in kg ha^{-1}, except for diesel fuel, which is in L ha^{-1}. All values are rounded to two significant figures.
CH_4, methane; N_2O, nitrous oxide; N, nitrogen; P, phosphorous; K, potassium.

not specified. Variation also occurs in the combustion efficiency among fires. We used a combustion efficiency of 93%, which was reported for a previous slash-and-burn fire at this site, and which is near the midpoint of the ranges of 91–95% and 85–98% reported by Mackensen *et al*. (1995) and by Ferek *et al*. (1998), respectively. Despite uncertainties in the application of combustion efficiencies, emission factors, and the interpolation of soil emission measurements, the order-of-magnitude difference in soil and pyrogenic emissions calculated in this study indicates that net reduction in total CH_4 emissions when mulching technology is adopted in lieu of slash-and-burn techniques is a robust finding.

Unlike long-lived greenhouse gases, NO is relatively short-lived in the atmosphere due to rapid photochemical reactions that produce tropospheric ozone (O_3), which is a greenhouse gas that is also photochemically dynamic (Prather *et al*., 2001). A large pulse of NO emissions during a fire used for site preparation could have different air quality impacts than would a gradual release of NO from the soil throughout the cropping and fallow phases. On the other hand, fires are set throughout the dry season in this landscape, as the shifting cultivation schemes of farmers dictate, and so replacing slash-and-burn practices with a fire-free cropping system would reduce fire emissions of NO throughout much of every dry season at the landscape scale.

The GWP CO_2 equivalents from soil emissions, fertilizer use, and diesel fuel use in the chop-and-mulch treatment were not trivial, but they were nearly six times smaller than the total GWP CO_2 equivalents of slash-and-burn system (Table 4). Most of this difference is due to pyrogenic emissions of CH_4.

Unfortunately, even this analysis is not complete. For example, we cannot convert differences in NO emissions to O_3 concentrations and then to the CO_2-equivalent GWP of O_3, so we do not include differences in NO emissions in our analyses of GWP. Eliminating fire in the agricultural cycle would also reduce emissions of CO and VOCs. These radiatively important gases interact with CH_4, NO, and O_3 in the troposphere, thus possibly influencing the net balance of these gases and their reactive products, but the net effect is difficult to include in GWP calculations (Prather *et al*., 2001).

Tropical agricultural soils can also be sources and sinks of atmospheric CO_2 (Palm *et al*., 2005). However, changes in soil C stocks are difficult to quantify because of a combination of large soil C stocks and large spatial heterogeneity. The mulching treatment started out with higher soil C stocks, due to the mulch layer, but that layer had decomposed by the end of the experiment, so that there were no significant differences in either litter layer or mineral soil C (Table 5). A much more spatially intensive sampling effort would have been required to detect statistically significant differences of soil C stocks among treatments, if they existed. We do not include changes in soil C stocks in our GWP analysis, but note that this omission could cause an underestimate in the

Table 5 Soil carbon measured after site preparation in February 2002 and at the end of the experiment in December 2004

		Carbon concentration ($g\,kg^{-1}$)		Carbon stock ($Mg\,ha^{-1}$)	
Treatment and depth (cm)	Bulk density ($g\,cm^{-3}$)	Feb02	Dec04	Feb02	Dec04
Slash-and-burn					
Litter layer		0 ± 0	455 ± 9	0.0	1.5 ± 0.6
0–10	1.41 ± 0.05	16.8 ± 0.1	13.4 ± 1.7	24.2 ± 0.2	19.0 ± 1.2
10–20	1.61 ± 0.02	12.1 ± 0.8	13.9 ± 1.5	19.5 ± 1.2	22.3 ± 2.5
20–30	1.61 ± 0.04	8.7 ± 1.3	8.3 ± 0.6	14.1 ± 2.1	13.3 ± 0.9
Profile sum	–	–	–	57.8 ± 3.5	56.1 ± 4.9
Cho-and-mulch					
Litter layer	–	323 ± 65	476 ± 10	17.7 ± 0.4	1.9 ± 0.3
0–10	1.34 ± 0.04	15.7 ± 0.7	14.8 ± 1.2	21.1 ± 0.9	19.7 ± 0.7
10–20	1.54 ± 0.02	10.8 ± 0.8	11.3 ± 0.7	16.6 ± 1.2	17.5 ± 1.0
20–30	1.54 ± 0.02	8.6 ± 0.7	8.9 ± 0.5	13.2 ± 1.0	13.8 ± 0.7
Profile sum	–	–	–	68.6 ± 3.7	52.9 ± 2.2
Continuous fallow					
Litter layer	–	415 ± 83	453 ± 10	4.3 ± 0.1	2.7 ± 0.3
0–10	1.25 ± 0.04	13.4 ± 1.3	18.7 ± 4.8	16.8 ± 1.7	22.8 ± 2.7
10–20	1.59 ± 0.07	10.2 ± 0.3	10.5 ± 0.9	16.3 ± 0.5	16.6 ± 1.4
20–30	1.57 ± 0.02	8.8 ± 0.1	8.4 ± 1.0	13.8 ± 0.1	13.9 ± 1.3
Profile sum	–	–	–	50.4 ± 2.7	56.0 ± 4.0

Bulk density was measured only in 2002 and was assumed not to change in order to calculate C stocks in 2004. Means are followed by standard errors ($n = 6$ for litter layers; $n = 2$ for soil C in 2002; $n = 6$ for soil C in 2004; $n = 4$ for bulk density in 2002).

GWP advantage of the chop-and-mulch system, because some of the mulch might become sequestered in the underlying mineral soil. We also do not include biomass C sequestered in the secondary forest vegetation during the fallow period, because both cropping systems periodically remove this biomass, so that neither accumulates significant aboveground plant biomass C over the long term.

Implications for sustainability

The harvest yields have been shown to be similar in several experiments comparing these two cropping systems over the last decade, provided that fertilizers are used in the chop-and-mulch system to overcome nutrient immobilization by soil microbial biomass (Kato *et al.*, 1999; Sommer *et al.*, 2004; Denich *et al.*, 2005). In this experiment, the harvest of corn grain was higher in the chop-and-mulch treatment ($1.55 \pm 0.09\,\mathrm{Mg\,ha^{-1}}$; mean and 1 SD; $N = 10$; $3\,\mathrm{m} \times 5\,\mathrm{m}$ plots) than in the slash-and-burn treatment ($0.97 \pm 0.16\,\mathrm{Mg\,ha^{-1}}$). The yield of manioc root was also slightly higher in the chop-and-mulch treatment ($16.2 \pm 1.2\,\mathrm{Mg\,ha^{-1}}$; $N = 10$; $3\,\mathrm{m} \times 5\,\mathrm{m}$ plots) than in the slash-and-burn treatment ($14.2 \pm 1.1\,\mathrm{Mg\,ha^{-1}}$). These values are similar to those commonly achieved by local farmers using their traditional slash-and-burn cropping systems throughout this region.

The economic considerations of these agricultural systems are complex and beyond the scope of this study, but we can mention some recent relevant developments in Brazil. Additional research and development of the mulching technology has begun in the Brazilian states of Amazonas, Acre, Rondônia, Roraima, Amapá, and Maranhão. Proposals are pending in both state and federal agencies to fund programs to provide wider access of the mulching technology to smallholder farmers at affordable costs. Governments at all levels have public interest incentives to reduce the use of fire in order to lower human health risks associated with poor regional air quality (Mendonça *et al.*, 2004) and to lower risks of accidental fire-associated loss of infrastructure investments on neighboring properties (Nepstad *et al.*, 2001; Mendonça *et al.*, 2004). Intensification of agriculture is often hampered by risk of loss of investments due to pervasiveness of fire in the landscape (Nepstad *et al.*, 2001), but it is politically difficult to prohibit fire if smallholder farmers do not have a viable alternative (Lohman *et al.*, 2007). Clearly, the various private and public sector options for local communities of farmers to support the cost of the chop-and-mulch machinery and fertilizer applications must be explored further.

The mulching system offers farmers new economic opportunities, because it is less susceptible to drought stress and is not limited to site preparation only when burning is feasible during the dry season. This new flexibility affords innovation in the number of crops and types of crops grown each year, which may have important advantages for the economic viability of this agricultural system (Denich *et al.*, 2005). Both slash-and-burn and chop-and-mulch systems in this relatively densely populated area of eastern Amazonia represent a form of continuous agricultural land use, although both also depend on a fallow land cover phase, which provides a rotating source of ecosystem services in the landscape, such as wildlife habitat and water quality protection (Vieira *et al.*, 2003). In both systems, the fallow is eventually recleared and very little, if any, land is permanently abandoned. Hence, sustainable agricultural productivity is crucial for the people of these communities. The chop-and-mulch system affords the possibility to intensify the agricultural productivity of this land use while also minimizing environmental impacts and reducing pressure for complete deforestation to continuous, high-input, row-crop agriculture.

Additional financial support and economic incentives for the elimination of fire in smallholder agriculture could be included in international aid programs and in international greenhouse gas emissions trading programs of the Kyoto Protocol (Denich *et al.*, 2005; Lohman *et al.*, 2007). However, additional research would be needed to address uncertainties in estimates of GWP of greenhouse gas emissions that would be avoided by more widespread adoption of a fire-free alternative to slash-and-burn. These uncertainties include the effects of variable young forest biomass on emission factors during burning, the effects of mulch layer depth and soil texture on soil emissions under mulch, and calculations of appropriate amortization of fire avoidance benefits as a function of fallow phase length and fire return interval, which often vary among regions. The results of this study demonstrate that the avoidance of fire yields sufficiently large GWP benefits that further investigation of these sources of uncertainty, which would be needed to establish a basis for establishing greenhouse gas avoidance credits, and further investigation of socioeconomic considerations are warranted. From a biogeochemical perspective, which is the primary focus of this study, we conclude that the chop-and-mulch alternative to slash-and-burn offers a win-win strategy of increased sustainability of nutrient retention at the local scale while also reducing net greenhouse emissions, which is important for sustainability of human agricultural activities at the global scale.

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