Integration of remotely sensed and ancillary data to assess the impacts of shifting cultivation

Integração de dados de detecção remota com dados complementares para a avaliação dos impactos da agricultura de corte e queima

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Abstract

Annual emissions of CO_2 from biomass burning in shifting cultivation systems in Brazil were estimated as the product of area burned, aboveground biomass, combustion completeness and emission factor. The total area of shifting cultivation was derived from the Global Land Cover 2000 map for South America, while the area cleared and burnt annually was obtained by multiplying the total area by the rotation cycle of shifting cultivation, calculated using cropping and fallow lengths reported in the literature. Aboveground biomass accumulation was estimated as a function of the duration and mean temperature of the growing season, soil texture type and length of the fallow period. Published combustion completeness and emission factor values were used. Two scenarios were set using minimum and maximum fallow lengths and emissions calculated. Results revealed that a reduction of emissions in shifting cultivation systems is not easily achieved by extending the length of the fallow period. Results also showed a good agreement between the spatial distribution of shifting cultivation in Brazil, obtained with remote sensing, and the location of studies describing fallow and cropping periods practiced in shifting cultivation systems.

Key words: Shifting cultivation; biomass burning; atmospheric emissions; tropical forests; remote sensing.

Resumo

As emissões anuais de CO_2 provenientes da queima de biomassa em sistemas de agricultura de corte e queima no Brasil foram estimadas como o produto da área queimada, da biomassa acima do solo, do fator de combustão e do fator de emissão. A área total afetada por este tipo de agricultura foi obtida a partir do mapa Global Land Cover 2000 da América do Sul, enquanto a área cortada e queimada anualmente foi obtida multiplicando a área total pelo ciclo de rotação, calculado

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a partir de dados sobre a duração dos períodos de cultivo e de pousio reportados na literatura. A acumulação de biomassa acima do solo foi estimada em função da duração e da temperatura média do período de crescimento, do tipo de textura do solo e da duração do período de pousio. Foram utilizados valores publicados dos fatores de combustão e de emissão. Foram estabelecidos dois cenários usando valores mínimos e máximos da duração do período de pousio e calculadas as emissões. Os resultados revelaram que uma redução das emissões atmosféricas em sistemas de agricultura de corte e queima não é facilmente alcançada através do aumento do período de pousio. Os resultados também mostraram uma boa concordância entre a distribuição espacial da agricultura de corte e queima no Brasil, obtida através de sensoriamento remoto, e a localização dos estudos que descrevem este tipo de agricultura.

Palavras-chave: Agricultura de corte e queima; queima de biomassa; emissões atmosféricas; florestas tropicais; sensoriamento remoto.

Introduction

Shifting cultivation has been practiced for thShifting cultivation has been practiced for thousands of years in forests around the world, especially in the tropics, where it provides livelihood for rural populations (PEDROSO JÚNIOR et al., 2008). The main rationale for shifting cultivation is the effective use of the existing soil fertility. In the most common system, vegetation is cut, allowed to dry for some time and then is burnt, raising the level of nutrients just before the preparation of soil for planting. After some years of cultivation the land is abandoned and there is a regrowth of the natural vegetation, the fallow vegetation, that, especially when consisting of forest (secondary forest), stores nutrients that will be made available for crops by fire in the next cropping cycle. Shifting cultivation is also known as slash-and-burn agriculture (*agricultura de corte e queima in Brazil*) or swidden agriculture. In this study information about the spatial distribution of shifting cultivation, derived from remotely sensed data, is integrated with ancillary data to derive estimates of CO_2 emissions from biomass burning in shifting cultivation systems in Brazil following the method proposed by Silva et al. (2011) to estimate greenhouse gas emissions from shifting cultivation in the tropics.

Shifting cultivation systems are highly dynamic, changing on an annual basis. During each dry season, new areas of primary or secondary forest are selected and cleared by the households that usually have several plots in different stages of cultivation (COOMES et al., 2000). Spatially, it is an agricultural system that leads to a complex mosaic of primary or mature forest, cultivation fields and fallow vegetation (e.g., BROWN, 2006), which may consist of bush or secondary forest. This temporal and spatial variation is challenging when using remote sensing to estimate the spatial distribution and extent of shifting cultivation. The Global Land Cover 2000 product (GLC2000, BARTHOLOMÉ; BELWARD, 2005) is the only available global land cover with regionally optimized maps whose legends include classes explicitly concerning shifting cultivation. It was derived with 14 months of global daily images acquired by the 1-km spatial resolution VEGETATION instrument on board SPOT-4 satellite between 1 November

1999 and 31 December 2000. The low spatial resolution of the imagery used in global land cover maps is an additional difficulty for satellite based land cover mapping in areas where shifting cultivation is the dominant agricultural system due to the small size of cultivation fields (e.g., 0.7 ha in Santa Catarina, Brazil; SIMINSKI; FANTINI, 2007). In consequence, what is mapped by this type of land cover products is not the area under cultivation but a mosaic of agriculture and secondary forests. The GLC2000 map for South America, for example, has a class named "Mosaic of agriculture and degraded forest formations", with the following description: "This is a common class across South America and corresponds to shifting cultivations, agroforestry, fragmented forests and secondary forest and rural complex...". For this reason, only combining this spatial information with data about the length of the cultivation and fallow periods it is possible to estimate the area of forest cleared and burnt annually in shifting cultivation systems.

An alternative approach to estimate the area of forest that each year is cleared to be used in shifting cultivation would be the use of tropical deforestation maps. There are several products available (e.g., TREES project, ACHARD et al., 2004) but the problem is that they not give information on the future trend of the deforested areas, i.e., they not differentiate between permanent and temporary deforestation. In shifting cultivation systems the areas cleared are used for cultivation only for some years and then are abandoned. Ramankutty et al. (2007), in their review about estimating carbon emissions from tropical deforestation, point that to accurately estimate carbon fluxes from land cover change it is critical to understand the land cover dynamics following deforestation. According to these authors, tracking the fate of cleared forest at the global scale is exceptionally challenging and would require observations at high spatial and temporal resolutions, detailed classifications schemes and careful change detection, in order to separate gross deforestation from net deforestation.

All previous studies concerning estimates of biomass burning emissions from shifting cultivation (SEILER; CRUTZEN, 1980; FEARNSIDE, 2000; HOUGHTON, 2003; LAUK; ERB, 2009) used the Food and Agriculture Organization (FAO) statistics to derive the area of shifting cultivation. In the pioneer study of Seiler and Crutzen (1980) this area was obtained by multiplying the population engaged in shifting cultivation by the average land requirement per capita for this type of agriculture. Population engaged in shifting cultivation was roughly estimated as a fraction of rural population or obtained also from data published by FAO. The other studies used directly the FAO data on the extent of shifting cultivation. In all studies the emissions estimates were derived at global or continental level since the FAO Forest Resources Assessment data on shifting cultivation are not disaggregated by country. Moreover, the most recent data provided by FAO on the global area under shifting cultivation are from 1980. The objective of the present study is to estimate CO_2 emissions from biomass burning in shifting cultivation systems in Brazil, using remotely sensed and ancillary data, and to assess the sensitivity of these estimates to changes in the length of the fallow period.

Case Study: Co_2 Emissions From Shifting Cultivation In Brazil

Estimates of trace gas and aerosol emissions from biomass burning require data on burned area, amount of biomass per unit area, combustion completeness (the proportion of biomass consumed during the fire) and emission factors (the amount of atmospheric species released per unit mass of biomass burned). The classical equation of Seiler and Crutzen (1980) for pyrogenic emissions estimation is:

$$Ei = A \times AGB \times CC \times EFi, \qquad (1)$$

where Ei is the emission of species i (g), A is the burned area (ha), AGB is the aboveground biomass (Mg ha^{-1}), CC is the combustion completeness (fraction) and EFi is the specific emission factor (g kg^{-1}). Eq. (1) was adapted to the special case of pyrogenic gas emission from shifting cultivation, given that there are no direct estimates of the area of forest cleared and burned annually in this type of agricultural system, and that the biomass present at the time of clearing depends on how many years natural vegetation is allowed to recover, i.e., the length of the fallow period.

The area of shifting cultivation was derived from the Global Land Cover 2000 map, which was produced from satellite imagery. We assumed that this area is the total area affected by shifting cultivation in each country, i.e., includes the area of fields under cultivation and the area of fallow vegetation. We also assumed that, sooner or later, depending on the cultivation cycle, all areas of fallow vegetation or secondary forest will be cleared for cultivation. These assumptions may lead to some overestimation of the area of shifting cultivation in some countries, since not all secondary forests result from shifting cultivation. In Brazil, for example, much secondary vegetation is not part of a shifting cultivation system, but rather results from abandonment of cattle pastures (FEARNSIDE, 2000). The area of fallow vegetation cleared and burned annually per country (A in Eq. 1) was calculated as:

$$A = TA \times 1/(CP+FP), \qquad (2)$$

where A is the area cleared and burned annually (ha), TA is the total area of shifting cultivation (ha), CP is the cropping period (years) and FP is the fallow period (years). $CP+FP$ is the length of the rotation cycle and $1/(CP+FP)$ represents the fraction of the total area of shifting cultivation in a given country that is cleared and burned for cultivation each year. TA was computed from the GLC2000 land cover map.

The relation between cropping period and fallow period is a measure of the intensity of shifting cultivation. The shorter the fallow period, the more stationary does farming become (RUTHENBERG, 1976). Within the continuum from long fallow rotation to permanent cultivation, length of fallow is highly variable. It can differ from village to village and among households of a particular village, but can also vary among the different plots of the same household (GLEAVE, 1996). It is problematic to find reliable and consistent data for large regions, for an agricultural system that is considered the most complex and multifaceted form of agriculture in the world (THRUPP et al., 1997). Table 1 shows the cropping and fallow periods reported in the literature for Brazil. Figure 1 shows the spatial distribution of shifting cultivation in Brazil according to the GLC2000 regional map. The location of the studies included in table 1 is overlaid.

Table 1. Cropping and fallow periods (years) in Brazil, reported in the literature

State	Cropping	Fallow	Reference
Rio de Janeiro	3	5	Aboim et al., 2008
Acre and Rondônia	2	2 – 5	Lewis et al., 2002
Maranhão	1	Until mil-1960s: 15 – 20 Present: 3 – 4	Porro, 2005
Pará (Bragantina)	1 – 2	Long fallow: 8.8 – 14.6 Short fallow: 3.8 – 4	Metzger, 2002
Pará (Altamira)	1 – 2	3 – 30 (mean: 8.6)	Silva-Forsberg and Fearnside, 1997
Santa Catarina	6 – 8	15 – 20 (by law: < 5 – 7)	Siminski and Fantini, 2007

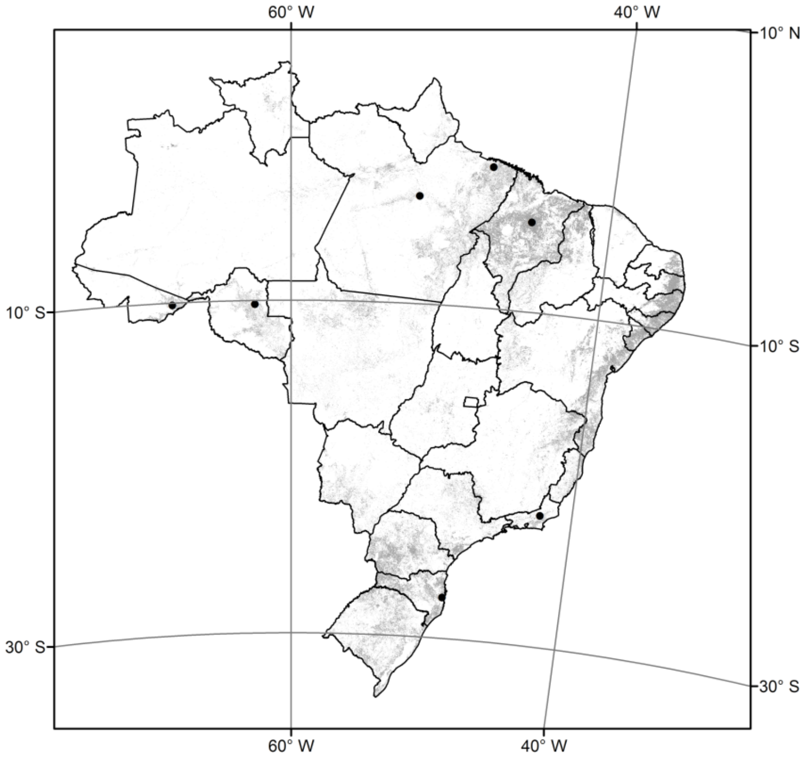

Figure 1. Spatial distribution of shifting cultivation in Brazil (gray shading) according to the Global Land Cover 2000. The location of case studies (black circles, Table 1) describing shifting cultivation systems is overlaid.

Biomass accumulation following disturbance caused by shifting agriculture practices (*AGB* in Eq. 1) was estimated based on the equations developed by Zarin et al. (2001). These authors used the data from Johnson et al. (2000), which compiled global data on the aboveground biomass accumulation in secondary forests. Zarin et al. (2001) developed global equations (for different soil texture: sandy and non-sandy) and tested their regional applicability with validation data from the Amazon, not included in the global data set from which equations were derived:

$$AGB_s = -65.8011+23.8542\times \ln(FP\times T\times L/365), \quad (3)$$

$$AGB_{ns} = 0.4299\times(FP\times T\times L/365), \quad (4)$$

AGB_s and AGB_{ns} are the aboveground biomass accumulation in sandy and non-sandy soils (Mg ha^{-1}), respectively, FP is the fallow period (years), T is the growing season temperature (ºC), and L the duration of the growing season (days) ($L/365$ is the duration of the growing season as a fraction of the year). The product $FP\times T\times L/365$ is an index that represents the increase in metabolic processes commonly associated with increased temperature in the presence of adequate moisture (JOHNSON et al., 2000).

Combustion completeness (CC in Eq. 1) is the fraction of biomass exposed to fire that is actually consumed (ARAÚJO et al., 1999). Combustion completeness depends on vegetation type, moisture content and meteorological conditions during the fire. In the case of shifting cultivation, vegetation is cut at the end of the wet season or at the beginning of the dry season, allowed to dry for some time and then burnt, raising the level of nutrients just before the preparation of soil for planting. The proper time to burn is very important. If the land is burned too soon after clearing, vegetation will be too moist and burning will be rather incomplete, soil fertility may not be enough to guarantee agricultural productivity and weeds may start establishing in the burnt field before planting (WARNER, 1991). Ideally, a field will be burned at the end of the dry season (e.g., GUPTA, 2000).

Biomass loadings and fractions of biomass burned (combustion completeness) are difficult and expensive to measure in tropical forests. The few studies available indicate high variability among years and among sites, on a micro scale, at any given site (FEARNSIDE et al., 1999). Most studies describing tropical forest clearing experiments were conducted in Brazil. Table 2 presents estimates of combustion completeness from seven experiments performed in Brazil concerning 17 burns in forests with different land use histories: primary forests and second- and third-growth forests. The estimates refer to overall combustion completeness, i.e., they include several biomass compartments (different trunk and branch sizes, leaves, litter, etc.). We assumed a combustion completeness value of 44.9%, which is the mean of the values in table 2.

We also assumed that all aboveground biomass present at the time of clearing is cut and exposed to fire. This may lead to some overestimation, because in some shifting cultivation systems very large trees are not cut (e.g., GUPTA, 2000) and part of the biomass may be removed for house construction, charcoal making or as firewood (e.g., LIANG et al., 2009). Emissions from biomass removed for firewood and charcoal are implicitly included, by using estimates of the biomass exposed to fire that have not been reduced to reflect removal of these products, although the combustion completeness and emission factors of these types of biomass burning would be different from the ones of the slash burned in cleared forests.

Table 2. Combustion completeness values reported in studies describing clearing experiments in Brazil

Forest type	Location	Combustion Completeness (%)	Reference
Primary rain forest	Pará	20.1	Araújo et al. (1999)
Rain forest[a]	Mato Grosso	19.5; 22.7; 41.8; 47.5; 61.5	Carvalho et al. (2001)
Primary rain forest	Amazonas	20.5	Carvalho et al. (1998)
Rain forest	Amazonas	30.0	Fearnside et al. (2001)
Rain forest	Pará	43	Fearnside et al. (1999)
Secondary rain forest (second- and third growth)	Pará and Rondônia	42.5; 47.3; 52.7; 62.5; 63.2; 87.5	Hughes et al. (2000)
Primary rain forest	Rondônia	47.0; 54.0	Guild et al. (1998)

Note: [a] The type of forest is not stated.

After estimating biomass loading, on a dry weight basis, and biomass consumption (biomass loading times combustion completeness), the emission factor (*EFi* in Eq. 1) allows the estimation of the total emission of each compound. An emission factor is defined as the amount of a compound released per amount of dry biomass consumed, expressed in units of g kg^{-1}. Andreae and Merlet (2001) evaluated information on emissions from various types of biomass burning (savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, charcoal burning, agricultural residues) reported in a large number of publications and presented the emission factors for a large variety of species. We used an updated version of these data provided by M. O. Andreae (pers. comm., 2009). The emission factor (mean and standard deviation) for CO_2 is 1626 ± 39 g kg^{-1}.

Table 3 presents annual estimates of CO_2 emissions from biomass burning in shifting cultivation in Brazil for two scenarios: short and long fallow period. The minimum and maximum fallow lengths reported in the literature for Brazil (Table 1) were used to set the two scenarios. As most studies report cropping periods of one, two or three years, we used two years as an average length for the cropping period.

Table 3. CO_2 emissions from shifting cultivation in Brazil: short and long fallow scenarios

Scenario	Total area of shifting cultivation (ha)	Fallow period (year)	Area cleared per year (ha yr^{-1})[a]	Aboveground biomass at the time of clearing (Mg ha^{-1})	Biomass cleared and exposed to fire per year (Mg yr^{-1})	Biomass burned per year[b] (Mg yr^{-1})	Emission of CO_2 (Mg yr^{-1})
Short fallow	70713991	2	17678498	16.5	292078170	131143098	213238678
Long fallow	70713991	20	3214272	71.5	229696217	103133601	167695236

Notes: [a] Calculated with Eq. (2), assuming a cropping period of 2 years.

[b] Assuming a combustion completeness of 44.9%.

Concluding Remarks

This study shows the advantage of combining spatial data obtained with remote sensing with other spatial data sets (soil texture, climate variables) and with information obtained by literature review. Data on the area cleared annually in shifting cultivation systems are not available and previous studies used statistics from FAO instead of spatial data. There is a good agreement between the spatial data and the literature review (Figure 1), but we could not find any reference reporting cropping or fallow periods for several Brazilian states. The amount of biomass exposed to burning and the proportion of that biomass consumed during the fire represents a major domain of uncertainty in every exercise of pyrogenic emissions estimation. Most studies used published aboveground biomass values. In the approach followed in this study, biomass accumulation is dependent on climatic conditions and on the age of the secondary vegetation, i.e. the length of the fallow period. The combustion completeness value used in our study is within the range of values used in global biomass burning calculations. Although the large difference in the fallow periods used to set the short and long fallow scenarios, the difference between the CO_2 emissions is only 21%. The relationship between the length of the fallow period and the magnitude of pyrogenic emissions depends on the balance between the area cleared annually (which in turn depends on the fallow period) and the biomass accumulation rate, which is a function of the length and temperature of the growing season and soil texture. The area cleared in the short fallow scenario is unrealistically high but the small difference in the emissions estimates of the two scenarios reveal that a reduction of emissions in shifting cultivation systems it is not easily achieved by extending the length of the fallow period.

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