Forest Ecology and Management 262 (2011) 555–560

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Estimating state-wide biomass carbon stocks for a REDD plan in Acre, Brazil

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ARTICLE INFO

Article history:
Received 17 November 2010
Received in revised form 13 April 2011
Accepted 14 April 2011
Available online 17 May 2011

Keywords:
Above-ground biomass
Carbon map
Climate change
Land-cover
Palm and bamboo forests
REDD

ABSTRACT

As in many other developing countries, the state government of Acre, Brazil, is developing a program for compensating forest holders (such as communities of rubber tappers and indigenous peoples as well as small, medium and large private land holders) reducing their emission of atmospheric heat-trapping gases by not deforesting. We describe and then apply to Acre a method for estimating carbon stocks by land cover type. We then compare the results of our simple method, which is based on vegetation mapping and ground-based samples, with other more technically demanding methods based on remote sensing. We estimated total biomass carbon stocks by multiplying the measured above-ground biomass of trees >10 cm DBH in each of 18 forest types and published estimates for non-forest areas, as determined by measurement of 44 plots throughout the state (ranging from 1 to 10 ha each), by land-cover area estimated using a geographical information system. State-wide, we estimated average above-ground biomass in forested areas to be 246 ± 90 Mg ha^{-1}; dense forest showed highest (322 ± 20 Mg ha^{-1}) and oligotrophic dwarf forest (*campinarana*) the lowest biomass (20 ± 30 Mg ha^{-1}). The two most widespread forest types in Acre, open canopy forests dominated by either palms and bamboo (for which ground-based data are scant), support an estimated 246 ± 44 and 224 ± 50 Mg ha^{-1} of above-ground biomass, respectively. We calculate the total above-ground biomass of the 163,000 km^2 State of Acre to be 3.6 ± 0.8 Pg (non-forest biomass included). This estimate is very similar to two others generated using much more technologically demanding methods, but all three methods, regardless of sophistication, suffer from lack of field data.

1. Introduction

Biomass estimation methods range from ground-based and site-specific to remotely sensed and global (e.g., Saatchi et al., 2007; Chave et al., 2005; Clark, 2004, 2007; GOFC-GOLD, 2009). For government agencies and other organizations intent on participating in growing voluntary and incipient carbon conservation programs, reliable and cost-effective methods for measuring and monitoring carbon stocks and fluxes are much needed (Gibbs et al., 2007; Angelsen, 2009). To assist in this quest, we compare estimates of standing stocks of above-ground live forest biomass (AGB) in the State of Acre, Brazil calculated from forest type maps and field plot data with the more technologically sophisticated remote-sensing methods used by Saatchi et al. (2007) and Nogueira et al. (2008).

Amazonian forests have the potential to provide a partial solution to the global climate change problem if protected and properly managed, or to contribute to the problem if allowed to be destroyed. They store approximately 86 ± 17 Pg C in biomass (Saatchi et al., 2007), with an additional 41–47 Pg in soil organic matter down to 1 m depth (Cerri et al., 2000; de Moraes et al., 1995). While still the largest tropical forest in the world, the 2000–2009 deforestation rate in the Brazilian Amazon was 17,500 ± 3000 km^2 a^{-1} (INPE, 2010). Such conversions of high biomass content forest into low biomass pastures and agriculture fields cause the emission of great quantities of greenhouse gases including CO_2 and CH_4 (Fearnside, 1985; Houghton et al., 2001; IPCC, 2007). These massive land cover changes also have regional and local impacts, reducing the quantity and quality of environmental services provided by natural ecosystems such as hydrological cycles and soil conservation (Fearnside, 1999, 2008; Sweeney et al., 2004).

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doi:10.1016/j.foreco.2011.04.025

For more than 10 years, the government of Acre, the western most state in the Brazilian Amazon, has promoted forest conservation and sustainable forest management. Despite these efforts, uncontrolled logging and forest clearing principally for cattle pastures have continued at a rapid rate. Based on government-approved forest management plans for 2000–2009, which represents only a fraction of the area affected, 1.6×10^5 ha (160 $km^{-2}\ a^{-1}$) of forests in Acre were selectively logged (Pereira, 2009). What is more certain is that about 14% of Acre's forests were cleared at a rate of 530 ± 94 $km^{-2}\ a^{-1}$ (INPE, 2010). The situation is particularly grave in eastern Acre where some counties have already lost 20–75% of their forests (Brown et al., 2007). From 1977 to 2003, deforestation in Acre alone resulted in estimated net emissions from above-ground losses of 180–240 Tg C (Salimon and Brown, 2009).

Given that large scale land-cover changes such as those in Acre have substantial impacts on climates and human well-being, mitigation actions are necessary. In response to this need, the Acre State Government has started to work on a reduced emissions from deforestation and forest degradation (REDD) plan to compensate rubber tappers, indigenous groups, and private land holders for reducing carbon emissions by not clearing forest. Such a mechanism should be eligible for support from several public funds, such as the Amazônia Fund (BNDES, 2010) as well as voluntary and possibly regulated carbon markets to secure payment for avoided deforestation.

One of the first steps towards implementation of a REDD plan is to estimate forest carbon stocks. Such estimates are crucial for REDD monitoring and subsequent fundraising from public funds or carbon markets. Our goal in this paper is to quantitate and map total carbon stocks in Acre on the basis of forest and other land cover types. We compare the results we obtain using this technologically simple method that we believe is appropriate for many local governments in developing countries with the much more sophisticated modeled and remote-sensing based results of Saatchi et al. (2007) and Nogueira et al. (2008).

2. Methods

2.1. Basic approach

Acre's total forest carbon stock was estimated by multiplying above-ground biomass carbon in trees >10 cm DBH (stem diameter at 1.3 m) for each of 18 forest types by the area of each forest type using land cover data provided by the State Environmental Office (Acre, 2000, 2006; see below for details). These forest types are based on the Brazilian Forest Classification System (Veloso et al., 1991). Sample plots used to quantitate biomass carbon were assigned to one of the map's forest types based on plot coordinates (Table 1). We interpolated biomass for the forest classes for which there are no plot data by averaging biomass of the most similar forest classes for which data are available. Most of the forest types with no ground data resemble "bamboo open forest", "palm open forest", or "dense forest" but vary in bamboo or palm density. For example, we estimated the biomass for the forest type mapped as "bamboo open + - palm open + dense forest", for which we lack field data, as the mean of "bamboo open forest", "palm open forest", and "dense forest." Field data were particularly scarce for the central region of Acre, mainly due to difficult access, as well as for the bamboo and palm forests that cover this and other remote regions of the state (Fig. 1). For oligotrophic dwarf forest, a biomass value was extracted from the literature (Barbosa and Ferreira, 2004).

2.2. Biomass estimation

Standing above-ground live biomass (AGB) was estimated for trees >10 cm DBH from 44 plots distributed from lowland alluvial to sub-montane forests over an elevation range of 160–450 m (Table 2). Data were obtained from the Universidade Federal do Acre and Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA/AC).

With the aim of using as straightforward, simple, and practical method as possible to produce a carbon map that could be used in REDD plans or any other carbon inventory assessment, we estimated above-ground tree biomass using the allometric equation of Brown (1997) that is based solely on DBH. Although there are many other more data-demanding allometric equations that include wood density and tree height as independent variables (e.g., Chave et al., 2005; Nogueira et al., 2008; Chambers et al., 2001) or that are for palms or grasses (i.e., Saldarriaga et al., 1988; Alamgir and Al-Amim, 2008), as in our case, the required data are often lacking of dubious quality. Furthermore, none of these equations were calculated using data from our study region or for bamboo-dominated forests. We were also comfortable with our simple approach because we recognize that our datasets include substantial taxonomic uncertainties (recent evaluations of inventories for government- and Forest Stewardship Council-approved management plans in Acre showed that some management plots can have more than 50% identification errors; Daly et al., personal communication). The equation we used to predict above-ground live tree biomass (AGB; in kg) from DBH was:

$$AGB = 42.69 - 12.800(DBH) + 1.242(DBH^2) \quad (1)$$

Above-ground biomass estimates for anthropogenic land cover types were extracted from published values for Acre (young secondary forests and pastures: Salimon and Brown, 2000; Salimon et al., 2004; agricultural areas: IBGE, 2010). Water bodies and urban areas were assumed to contain no biomass. Since secondary forests can have a wide range of biomass, we used average values from sites of 4–11 years since abandonment.

2.3. Above-ground live biomass map

A carbon stock map was generated in the ARCGIS environment based on vegetation and land cover maps supplied by the State Environmental Office. These maps were generated based on visual classification and digitalization from the RADAMBRASIL maps and overlaid by satellite images (2004 Landsat TM imagery) for correction of polygons (Pereira and Bersch, 2006).

We selected from the vegetation map all forested polygons and deleted those with anthropogenic land cover types. From the land-cover map, we selected all polygons associated with anthropogenic cover (urban areas, agricultural fields, pastures, and reservoirs) and rivers, and deleted the forested polygons. This procedure was necessary because on the vegetation map there was a single polygon type for anthropogenic cover, and likewise, on the land-cover map there was a single polygon type for natural vegetation. We then created a shapefile with the combined forest vegetation and anthropogenic land cover polygons. In the database file associated with the new shapefile, we created new columns that contained AGB values calculated from the sample plot data, and then mapped above-ground biomass stocks (in Mg ha^{-1}). Results are presented in Mg, Tg, and Pg of biomass (10^6, 10^{12} and 10^{15} g, respectively) and uncertainty is presented as one standard deviation of the mean.

We compare our results with the Acre portion of the Amazon Basin-wide biomass map of Saatchi et al. (2007) that was generated based on 19 remote sensing metrics and more than 500 plot measurements of biomass. For the extraction of Acre's biomass estimate from Saatchi et al. (2007), we masked Acre on their biomass map and then summed all pixels' biomasses (mid-point values) for the masked region. We also compare our results with those of Nogueira et al. (2008), who present maps of biomass for the