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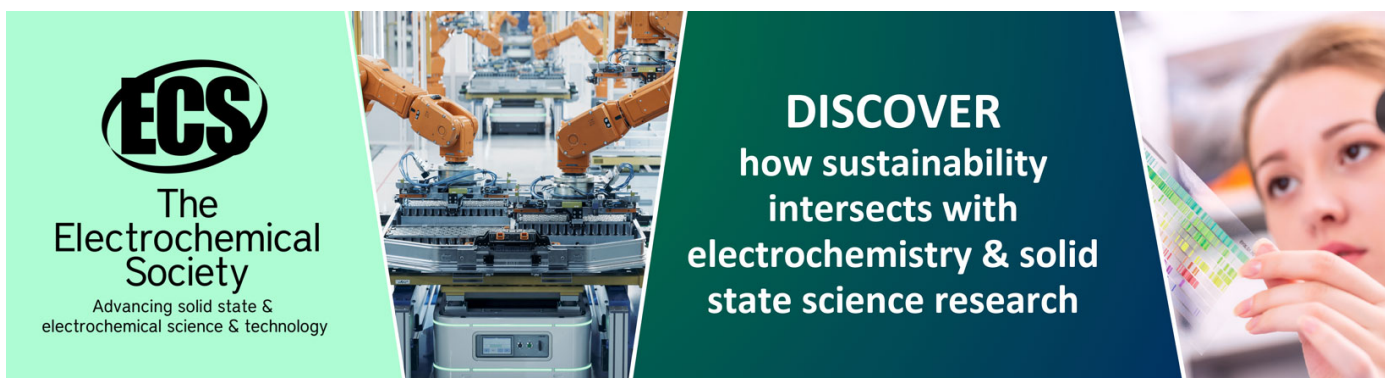
An integrated framework for evaluating the effects of deforestation on ecosystem services

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An integrated framework for evaluating the effects of deforestation on ecosystem services

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Abstract. Deforestation often results in massive carbon emissions and loss of ecosystem services. The objective of this paper is to develop an integrated approach to quantitatively derive changes in forest carbon stock and changes in the economic value of forest carbon due to deforestation. Combining the best available remote sensing and socioeconomic datasets, this approach establishes a comprehensive baseline of deforestation in terms of area, carbon and monetary value change. We applied this end-to-end evaluation method in the Brazilian state of Rondonia to assess the ecological and economic effects of its recent deforestation from 2000 to 2005. Our results suggest that deforestation occurred at an average rate of 2834 km²/yr during the study period, leading to 31 TgC/yr “committed carbon emissions” from deforestation. Coupling with the social cost of carbon at \$23/tC and a market discount rate at 7%, this translates to \$622 million U.S. dollars/yr loss in the economic value of forest carbon.

1. Introduction

Forest ecosystems provide a wide range of essential services to people, such as producing fiber and fuel; regulating climate; purifying water; offering cultural, spiritual and recreational benefits; as well as supporting terrestrial biodiversity [1]. The world's forest cover has been decreasing rapidly due to an increasing intensity of anthropogenic activities. Developing countries, where most tropical forests are located, often lack the economic and policy incentives to avoid deforestation, or on the contrary, promote converting forest to other land uses (e.g. pastureland). The value of forest ecosystems is often ignored or underestimated in current decision-making processes [1,2], because many critical ecosystem services (such as regulating climate) provided by forest are positive externalities that are not priced in the market.

Ecosystem services can be regarded as capital assets, and assessments of ecosystem services value (ESV) is starting to play an important role in the formulation of public policies, e.g. reduce emissions from deforestation and forest degradation (REDD). Of primary concern to REDD is the carbon regulation service provided by forest ecosystems. Estimating the financial cost of REDD requires reliable method of characterizing forest value and quantifying value change due to deforestation. Valuation of forest carbon requires information on how much carbon is stored in the forest, how much carbon can forest sequester and how to attach a price to the stored or sequestered carbon. However, substantial uncertainties exist in both forest carbon stock estimation [3] and the derivation of per unit carbon price [4,5], resulting in multiplied uncertainties in carbon valuation. Methods are even rarer for

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monitoring changes in ESV due to deforestation, which requires greater consistency between measurements taken over time.

The objective of this paper is to propose an integrated evaluation framework to quantitatively derive changes in forest carbon stock and changes in the value of forest carbon due to deforestation. The method consists of three successive steps as a hierarchy of increasing complexity: (1) forest area loss is quantified using multi-temporal multi-resolution optical remote sensing data; (2) the derived forest area loss is then combined with spatially explicit biomass density data to estimate losses in forest carbon stock; (3) the market value of lost carbon stock is assessed using an integrated ecological and economic model.

2. Study area

The study area is the Brazilian state of Rondonia in the southern Amazon. We chose this study area because it has undergone massive deforestation over the last four decades as a result of road construction, colonization, and the associated settlement of farmers who slash and burn forests for crop plantation and cattle ranching [6]. The construction of the main highway, BR-364, completed in 1984, opened up the connection between the northwestern frontier with the more industrialized center-south region of Brazil and facilitated extensive immigration into the state [6]. Deforested land patches are typically distributed along major roads and form the Rondonia ‘fish-bone’ pattern. The study area contributes approximately 15% of all area deforested in the Brazilian Amazon from 2000 to 2005 (INPE, available at http://www.obt.inpe.br/prodes/prodes_1988_2012.htm).

3. Data and methods

3.1. Mapping forest cover and forest cover loss

We use Landsat images to quantify the spatial extent of forest change at 30-m resolution from 2000 to 2005. A total of 34 world reference system-2 (WRS-2) image tiles (table 1) were selected from the Global Land Survey (GLS) Landsat dataset, an assembly of Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images circa-2000 and -2005 optimized for land cover mapping and change detection [7]. The selected satellite images were first converted to surface reflectance, filtered by removing cloud, shadow and water pixels [8], and then integrated with the Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) Tree Cover dataset [9] to produce Landsat VCF tree cover for both 2000 and 2005 for each 30-m pixel [10]. Landsat VCF layers for the two epochs were then used to derive forest change using a probabilistic continuous field change detection method. It should be noted that the acquisition dates of the GLS images used in this study range from 1999 to 2001 for the 2000 epoch and from 2004 to 2007 for the 2005 epoch respectively, which vary from tile to tile. Therefore, we divided the change estimates by the actual year difference per WRS-2 tile to calculate annual change rate.

Table 1. Landsat images used in this study

WRS-2 path/row	GLS2000s image date	GLS2005s image date	WRS-2 path/row	GLS2000s image date	GLS2005s image date
P001/r066	1999-07-10	2005-07-10	P231/r069	2001-08-11	2005-07-21
P001/r067	2000-07-28	2005-07-10	P232/r066	2001-08-02	2005-07-04
P229/r068	2001-08-13	2006-06-08	P232/r067	2001-09-19	2006-06-29
P229/r069	2001-08-13	2006-06-24	P232/r068	2001-09-19	2006-05-12
P230/r068	1999-08-15	2006-07-01	P232/r069	2001-09-19	2006-05-12
P230/r069	2000-08-01	2006-07-01	P233/r066	2001-06-22	2007-07-01
P231/r066	2001-08-11	2005-07-21	P233/r067	2000-08-22	2005-06-17
P231/r067	2001-08-11	2005-07-21	P233/r068	2001-06-22	2004-06-30
P231/r068	2001-08-11	2005-07-21			

3.2. *Mapping forest carbon stocks and forest carbon loss*

We use the spatially explicit carbon density data provided by [11] to estimate forest carbon stocks in 2000 and annual forest carbon loss from 2000 to 2005 due to deforestation. The carbon density map was produced by integrating 493 in situ forest inventory plots data with Light detection and ranging (Lidar), MODIS surface reflectance, shuttle radar topography mission as well as quick scatterometer data to generate above-ground biomass, below-ground biomass and carbon density (50% of total biomass) at 1-km spatial resolution. To resolve the resolution difference between our forest change map (i.e. 30-m) and the carbon density map, we aggregated our forest change data from 30-m to 1-km to calculate the percentage of 30-m forest pixels and the percentage of forest loss pixels within each 1-km grid. Forest carbon stocks in 2000 and annual forest carbon loss were then calculated per 1-km grid by multiplying carbon density with the aggregated percent forest cover and percent forest loss, respectively. All the 1-km grids over the study area were then summarized to derive the municipality-level estimate of forest carbon stock as well as carbon loss. It should be noted that the estimated forest carbon loss only represents the “committed carbon emissions” rather than the total carbon emissions from deforestation. A full accounting of carbon emissions associated with deforestation must include estimates of other fundamental carbon pools, such as soil carbon, dead organic matter, as well as carbon emissions from the succeeding land uses after deforestation (e.g. ranching), etc. [12,13].

3.3. *Estimating the economic value of lost carbon*

We use InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) – a spatially explicit modeling suite based on local ecological production functions and economic valuation methods [2,14] – to quantify the economic value of lost carbon in the study area. The carbon valuation module of InVEST quantifies the economic value of carbon sequestration based on a number of inputs such as the physical quantity of carbon sequestration, marginal carbon value or market price, discount rates, etc. We applied InVEST in the study area using the derived carbon loss map, the social cost of carbon (SCC), as well as a market discount rate of 7% per year, which is one of the recommended discount rates by the U.S. government for cost-benefit analysis of environmental projects, to calculate per 1-km grid value loss. All the 1-km grids of value loss were then added up to derive the municipality-level estimate of economic loss.

The social cost of carbon represents the economic damage of climate change from an extra tone of CO₂ emission today, accumulated over time and discounted back to present day [15]. Thus, the SCC, in theory, defines what the society should be willing to pay to avoid future damage resulted from incremental carbon emissions. It is conceptually different from marginal abatement cost, which represents the cost of reducing emissions rather than the benefit of avoiding future damage. According to the economic theory, if the SCC calculations were complete and markets perfect, carbon tax or the price of tradable permits should be set equal to the SCC. The SCC is estimated with integrated assessment models of climate change, but different models generate considerably different estimates of SCC. A meta-analysis of 94 estimates revealed a median value of \$14/tC and a mean value of \$93/tC [5], but later an extended meta-analysis of 211 studies suggested a mean value of \$23/tC [4]. We chose this mean value of \$23/tC in our forest carbon valuation in this study.

4. Results and discussions

Spatially explicit presentation of forest cover in year 2000, annual forest cover loss, forest carbon stocks in year 2000, and annual forest carbon loss is illustrated in figure 1. By removing cloud, shadow and ETM+ Scan Line Corrector (SLC)–off pixels in either date of the Landsat image pair, 97.54% Landsat pixels were analyzed. Within this clearly observed area, forests occupied 171882 km² land in year 2000, accounting for approximately 72.34% of the total land area in Rondonia. From 2000 to 2005, gross forest clearing occurred at an average rate of 2834 km²/yr. Dividing the deforested area by the total land area of the state, annual deforestation rate was 1.19% during the study period, which represents 1.65% of forest cover in year 2000. Recent deforestation patches were spatially distributed

in the neighborhood of previously cleared land, indicating the continuing expansion of agricultural land use in Rondonia.

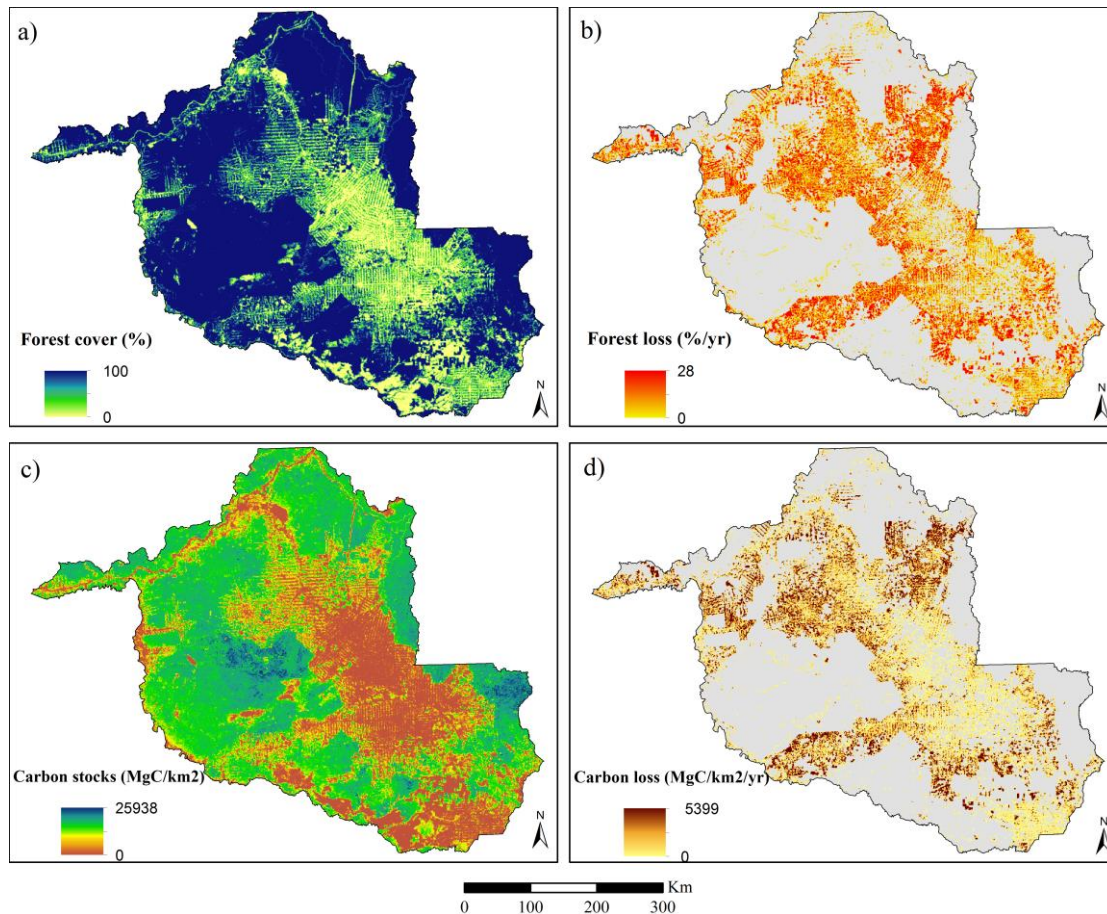


Figure 1. a) Percent forest cover in year 2000; b) annual percent forest cover loss from 2000 to 2005; c) forest carbon stocks in year 2000, including above- and below-ground biomass; d) annual forest carbon loss from 2000 to 2005. (All maps are at 1-km spatial resolution)

The total carbon stock in Rondonia's forests was 1.9 PgC in year 2000, with a mean carbon density of 128 MgC/ha. Municipality-level carbon emissions from deforestation were estimated to be 31 TgC/yr from 2000 to 2005, which contributes roughly 9% of Brazil's gross deforestation emissions or nearly 4% of pan-tropical deforestation emissions during this period [16]. The average carbon density of cleared forests was 109 MgC/ha – less than the mean carbon density of all living forests in year 2000, which is probably because forest clearing activities were carried out in both primary as well as secondary forests.

Applying the social cost of carbon at \$23/tC and a market discount rate at 7%, the physical loss of forest carbon translates to \$622 million U.S. dollars/yr loss in the economic value of forest carbon. The measured value loss is essentially a function of carbon price and market discount rate, and therefore uncertainties in the estimates of SCC and discount rates inevitably propagate to the estimate of value loss. A lower carbon price and or a higher discount rate imply a lower estimate of value loss, and vice versa.

5. Conclusions

The main advantage of this end-to-end evaluation approach is to build a comprehensive baseline of deforestation in terms of area, carbon and monetary value change. Spatially explicit deforestation baseline at regional and national scale is fundamental information to devising policies that aim at mitigating greenhouse gas emissions. Integrating the best available remote sensing and socioeconomic datasets, the application of this approach in the Brazilian state of Rondonia indicates that forests have been continually clearing from 2000 to 2005 at an average rate of 2834 km²/yr, releasing 31 TgC/yr carbon dioxide to the atmosphere and inducing potential economic losses at an rate of \$622 million U.S. dollars/yr. Similar studies are needed to encompass other types of ecosystem services to develop a systematic assessment of the multi-dimensional consequences of land cover and land use change.

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