REDD+: a carbon stock-flow analysis of the Brazilian Amazon municipalities

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The size of forest carbon stocks and the extent of reductions in flow of net carbon emissions from forestry are key criteria for REDD+ benefit sharing and policy targeting. We perform a carbon stock-flow analysis of the 552 municipalities that make up the Brazilian Amazon forest using official data, technical procedures for estimating REDD+ emissions and removals, and fuzzy classification. We find that the municipalities held 70.2 Pg C in their forests in 2013 and were responsible for reducing the net emissions flow by 6.3 Pg CO\textsubscript{2} from 2006 to 2013. We classify the municipalities in terms of their carbon stock-flow and identify 63 priority municipalities for REDD+ benefit sharing (those with large carbon stocks and/or high flow reductions). We assess the main national mitigation plan of REDD+ for the region and observe that it has successfully focused on the net source priority municipalities. However, the plan has not consistently focused on the net sink and large stock priority municipalities, which can lead to leakage in important carbon pools. We suggest the use of the stock-flow criteria to perform REDD+ benefit sharing among the municipalities and the inclusion of the stock-flow criteria for defining target municipalities in further revisions of the mitigation plan.

Keywords: REDD+ policy - benefit sharing - forest carbon stock-flow - Brazilian Amazon - fuzzy classification

Introduction

The Amazon is one of the largest and most important forests in Brazil. It contains the largest carbon stock, supplies essential environmental services and provides livelihood to thousands of traditional peoples and communities.\textsuperscript{[70,76,106]} REDD+ initiatives in the region have contributed to sharp reductions in deforestation rates and enabled the protection of important forest areas.\textsuperscript{[7,56]} However, the Brazilian Amazon still faces many challenges: its new deforestation pattern is based on a large number of small and widely spread polygons, which implies a more complex and expensive strategy of monitoring and control;\textsuperscript{[56,77]} many forest activities are still based on non-sustainable practices;\textsuperscript{[61,72,77]} land tenure problems have generated areas of conflict;\textsuperscript{[31,77,90]} pressures from several sectors have threatened indigenous rights;\textsuperscript{[34,54,67]} and recent official data show that deforestation rates are increasing again, especially in areas with higher carbon content.\textsuperscript{[3,53,105]}

The potential REDD+ financial incentives (benefits) that will be received by the Brazilian federal government should be shared among the Amazon districts to leverage positive results, such as reductions in deforestation and the creation of protected areas, and contribute to overcoming local challenges.\textsuperscript{[24,25,67]} Although the National Policy on REDD+ is still being debated in the Brazilian congress, there is a consensus that the most important criteria for REDD+ benefit sharing among the Amazon districts should be (i) the size of their forest carbon stocks (stock criterion) and (ii) the extent of their reductions in net carbon emissions by reducing deforestation and forest degradation, as well as promoting carbon removals by forests (flow criterion).\textsuperscript{[24,25,33,40,75,84,85]} Moreover, stock-flow criteria are essential for

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targeting important forest areas for REDD+ initiatives. Therefore, stock-flow analyses are needed to establish effective and equitable REDD+ benefit sharing and to guide REDD+ policies in the Amazon forest. [46]

The main objective of this paper is to perform a stock-flow analysis of the 552 municipalities that make up the Brazilian Amazon. Specifically, we (i) estimate the forest carbon stocks of each municipality in 2013 and their reduction in net carbon emissions from 2006 to 2013, (ii) identify the priority municipalities for REDD+ benefit sharing according to the stock-flow criteria, and (iii) compare the priority municipalities with the 89 target municipalities of the main national mitigation plan of REDD+ for the region, the Action Plan for the Prevention and Control of Deforestation in the Brazilian Legal Amazon (PPCDAm). [77] To achieve these objectives, we perform statistical analyses of official spatial data. [37,38,51,53,78,79] use technical procedures to estimate REDD+ emissions and removals [5] and use a fuzzy classification method. [63,96,115]

The second section provides a literature review of REDD+. The third section provides a background on the Brazilian Amazon. The fourth section describes the data and methods. The fifth section presents and discusses our findings. The sixth section concludes the study. We also provide supplementary material that contains detailed information about the methods and results derived from this study. Our supplementary data on stock-flow may be useful for further research, public discussion and policies aimed at mitigating climate change through the land-use change and forestry (LUCF) sector. [4]

REDD+

Carbon emissions from deforestation and forest degradation in the tropics have received significant attention from the United Nations Framework Convention on Climate Change (UNFCCC). Emissions from these sources represent a considerable portion of the global carbon budget [1,47,62,95,113] and amounted to 2.82 Pg C year−1, or 27% of the major anthropogenic global emissions, in the early 2000s. [91] Moreover, their mitigation costs are considerably less than those of other relevant greenhouse gas (GHG) emitting sectors. [12,14,27,35,66,86,102,104]

Brazilian researchers were the first to propose a mechanism to compensate developing countries for reducing emissions through cutbacks in deforestation rates. [83,97] However, the REDD+ mechanism was only discussed by the UNFCCC at its 11th Conference of the Parties (COP-11), later in 2005, in Montreal, Canada. [110] At this session, the governments of Papua New Guinea and Costa Rica noted the importance of financially supporting developing countries to reduce emissions from deforestation. They argued that although deforestation was the main source of emissions in these countries, only reforestation and afforestation activities were eligible for carbon credits through the Clean Development Mechanism (CDM), as stated in the Marrakesh Accords. [109]

The discussion of this mechanism has gained strength in the recent COPs, and its scope has been extended to other activities other than deforestation. The objective of REDD+ includes reducing emissions not only from deforestation in developing countries, but also from forest degradation, as well as promoting the conservation of forest carbon stocks, sustainable management of forests and the enhancement of forest carbon stocks in these countries. [111] Therefore, REDD+ also focuses on increasing carbon removal by forests, which plays a relevant role in the global carbon budget. [99]

Recent studies have discussed methods for REDD+ benefit sharing among and within developing countries that will contribute to achieving the mechanism’s overall objectives. [28,33,40,43,75,82,84,85,104] Although they consider different approaches and geographic coverages, all of these studies regard the stock-flow criteria as important to REDD+ benefit sharing. One of the main advantages of this approach is to stimulate emission reductions in high deforestation countries and to compensate low deforestation countries that conserve and protect their forest carbon stocks. Nationally, the stock-flow approach not only aims to promote effective emission reductions of large landholders with high opportunity costs but also aims to provide fair rewards to those communities that have historically conserved and protected forest ecosystems. Therefore, this approach appears to adequately address international and national distributive justice, which is one of the main issues of REDD+ benefit sharing. [100] Moreover, Cattaneo et al. [29] and Griscom et al. [42] simulated REDD+ benefit sharing among developing countries using several methods and found that the stock-flow approach can provide the most equitable, cost-efficient and effective outcomes. However, benefit sharing mechanisms should also consider other important issues, such as land tenure regularization, clarification of carbon credit rights, and the allocation of funds to governments to enable the implementation of REDD+ policies. [107]

Many national REDD+ policies have been developed worldwide. [26] These policies comprise a wide set of instruments, such as disincentives (e.g. regulations, fines, taxes and protected areas), incentives (e.g. subsidies, payments for environmental services and certification) and enabling instruments (e.g. environmental education, land-use planning, land tenure regularization and enforcement of property rights). [13] The equity, cost-efficiency and effectiveness of these instruments depend on many factors, including institutional
context, policy designs and management decisions. However, there is evidence that REDD+ policies should comprise a mix of these instruments, and no one instrument can be considered a ‘silver bullet’. [10,13,60,99] In the next section, we briefly discuss the REDD+ policy background in the Brazilian Amazon.

Brazilian Amazon

In this section, we provide information on the Brazilian Amazon’s geographic coverage, socioeconomic aspects and REDD+ policies.

- **Geographic coverage**
  The Amazon forest comprises nine of the 26 Brazilian states including all of the states of Acre, Amapá, Amazonas, Pará and Roraima, and parts of the states of Maranhão, Mato Grosso, Rondônia and Tocantins (Figure 1). The region covers 552 municipalities in these states (supplementary material) and a total area of 420 million hectares or 84% of the Legal Amazon. [38,48]

  Many policies for the Amazon forest consider a wider region called the Legal Amazon. [15,17] This region includes all of the states of Mato Grosso and Rondônia, larger areas of the states of Maranhão and Tocantins, and a small area of the state of Goiás (Figure 1). The Legal Amazon covers 775 municipalities and a total area of 502 million hectares, [49] which includes 100% of the Amazon, 37% of the Cerrado and 40% of the Pantanal. [57]

  Protected areas in Brazil include Conservation Unities (UCs) [20] and Indigenous Lands (TIs). [16,18,19] These protected areas in the Brazilian Amazon presently cover 206 million hectares, [37,78] not including overlaps and oceanic areas, which is equivalent to 49% of the Amazon (Figure 2). They have contributed to forest conservation and reductions in deforestation rates, [101,114] as well as to the defense of indigenous rights. [94]

- **Socioeconomic aspects**
  Most of the Amazon municipalities have very low socioeconomic indicators compared to the other Brazilian municipalities (Figure 3) and are dependent on government expenditures. [52] The Amazon municipalities with the best socioeconomic indicators are located in the southern and eastern regions, which are known as the arc of deforestation. The economy in these municipalities is strongly based on the agricultural sector (Figure 4), which includes farming, livestock, forestry, timber and fisheries. This sector generates notable pressure for deforestation and forest degradation in the region and in many situations is based on non-sustainable activities, such as selective logging, monoculture farming and extensive livestock. [61,72,77]

- **REDD+ policies**
  The main Brazilian policy for mitigating climate change is the National Policy on Climate Change (PNMC). [22,23] The PNMC establishes goals for relevant sectors in Brazil and indicates sectoral mitigation plans to reach these goals. The goal for the LUCF sector in the Amazon consists of reducing the deforestation rate by 80% compared to a business-as-usual scenario for 2020.
that assumes the continuation of the average deforestation rate from 1996 to 2005. The mitigation plan for the Amazon is the Action Plan for the Prevention and Control of Deforestation in the Brazilian Legal Amazon (PPCDAm).

The PPCDAm was created in 2004 and is currently in its third phase, which comprises the period from 2012 to 2015. [77] The first phase included the period from 2004 to 2007, [71] and the second was from 2009 to 2011. [73] The plan has obtained positive results, and there is evidence that it has strongly contributed to the cutbacks in the Amazon deforestation rates in recent years. [7,56] The third phase of the PPCDAm has a budget of R$ 1.43 billion (US$ 641 million using a conversion of 2.23 R$ = 1 US$) and contains 195 mitigation activities that are organized into three thematic axes: (i) land tenure regularization and land use planning, (ii) monitoring and control, and (iii) promotion of sustainable productive activities. The PPCDAm’s activities are executed by institutions of all jurisdictions and across the entire Legal Amazon region. However, for each axis, the plan indicates target municipalities that have been prioritized for the implementation of the activities (Figure 5). The plan targets 89 municipalities and considers the following criteria for selecting them according to each of the three thematic axes: (i) strategic location, including municipalities along the border of the most dense and preserved forests, close to large infrastructure projects that are under construction, and in the Marajó archipelago, (ii) inclusion on the monitoring and control list of the Brazilian Ministry of the Environment (MMA), [21] and (iii) selected target municipalities of the two first axes in addition to two other municipalities that are involved with the Program for the Acceleration of Growth (PAC), which is the major infrastructure program in Brazil.

The National Policy on REDD+ is still being debated in the Brazilian congress, and it will establish principles, instruments, funds and benefit sharing parameters. [24,25] Since 2009, the MMA has coordinated an effort to construct a National Strategy on REDD+ through an inter-ministerial working group, [88] which will define the country’s strategy to achieve the objectives of REDD+.

Data and methods
This section presents the data and methods that we used to perform the stock-flow estimation, identify the priority municipalities and compare them to the PPCDAm’s target municipalities.

Stock-flow estimation
To estimate the carbon stocks and flow reductions for each municipality, we mainly used spatial data [38] from
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The database comprises 4,309,535 polygons with 30 information fields, such as area, municipality, state, carbon content of pools, land use in 1995, land use in 2002, gross CO$_2$ emissions, CO$_2$ removals, and net CO$_2$ emissions (gross emissions minus removals).

Our flow reduction estimation for each municipality (the reduction of net carbon emissions) is given by the difference between the baseline net emissions (reference level) and the net emissions that occurred in the last 8 years, i.e. from 2006 to 2013 (Eq. (1)). We assumed that the baseline net emissions in this period were constant and equal to the average net emissions from 1996 to 2005 (Eq. (2)). We established this reference level based on the business-as-usual parameters of the PNMC and the first draft of the Brazilian National Strategy on REDD+.

\[
FR_m = \sum_{y=2006}^{2013} (RL_{m,y} - NE_{m,y})
\]

(1)

\[
RL_{m,y} = \frac{\sum_{y=1996}^{2005} (NE_{m,y})}{10}
\]

(2)

\[
NE_{m,y} = FO_{m,y} + FF_{m,y} + OF_{m,y}
\]

(3)

where $FR_m$ is the flow reduction in municipality $m$; $RL_{m,y}$ is the reference level for municipality $m$ in year $y$; $NE_{m,y}$ is the net emissions in municipality $m$ in year $y$; $FO_{m,y}$ is the FO emissions in municipality $m$ in year $y$; $FF_{m,y}$ is the FF emissions/removals in municipality $m$ in year $y$; and $OF_{m,y}$ is the OF removals in municipality $m$ in year $y$.

Our stock estimation in each municipality is relative to the year 2013 and considered the three carbon pools that are suggested by the Intergovernmental Panel on Climate Change (IPCC).

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Climate Change (IPCC) [55] i.e. living biomass (above- and belowground), dead organic matter, and soil (30 cm depth). Because the carbon stock data from the last inventory refer to the year 2002, we updated the data to 2013 by reducing the estimated net CO₂ emissions from 2003 to 2013 from the carbon stocks in 2002 using Eq. (12). We converted the CO₂ emissions to carbon using the molecular weight ratio of 12/44 C/CO₂.

\[ CS_{m,y}^{2013} = CS_{m,y}^{2002} - 12/44 \times \sum_{y=2003}^{2013} NE_{m,y} \]  

(12)

where \( CS_{m,y}^{2013} \) is the forest carbon stock in municipality \( m \) in 2013; and \( CS_{m,y}^{2002} \) is the carbon stock in municipality \( m \) in 2002.

### Priority municipalities

To identify the priority municipalities for REDD+ benefit sharing we first classified all 552 municipalities in terms of their carbon stocks (small, medium and large) and then in terms of their flow reductions (low, medium and high) using a fuzzy classification method. [63,96,115] We assumed that the priority municipalities were those with large carbon stocks and/or high flow reductions.

In fuzzy classification, a membership function is established to represent the similarity relation between pairs of data. This function assigns a similarity grade to each ordered pair. Clusters of data can then be formed when the data in each cluster achieve a minimum similarity grade. Therefore, the method allows groups of data to be created when the classes do not have sharply

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### Table 1. Rules and equations used to estimate the annual FO, FF and OF emissions/removals in each municipality from 1995 to 2002.

| LUCF | Rules | Equation |
|------|-------|----------|
| FO   | We distributed the total FO emissions in each municipality [39] throughout the 8 years proportionally to its annual deforested area, which is available from [53] (Eq. (4)). | \[ FO_{m,y} = FO_{m} \times DA_{m,y} / \sum_{y=1995}^{2002} DA_{m,y} \]  

(4) |
| FF   | We distributed the total FF emissions/removals in each municipality [38] equally throughout the 8 years (Eq. (5)). | \[ FF_{m,y} = FF_{m,y} / 8 \]  

(5) |
| OF   | We distributed the total OF removals in each municipality [38] equally throughout the 8 years (Eq. (6)). | \[ OF_{m,y} = OF_{m,y} / 8 \]  

(6) |

where \( FO_{m} \) is the total FO emissions in municipality \( m \) from 1995 to 2002; \( DA_{m,y} \) is the deforested area in municipality \( m \) in year \( y \); \( FF_{m} \) is the total FF emissions/removals in municipality \( m \) from 1995 to 2002; and \( OF_{m} \) is the total OF removals in municipality \( m \) from 1995 to 2002. See the supplementary material for details.

### Table 2. Rules and equations used to estimate the annual FO, FF and OF emissions/removals in each municipality from 2003 to 2013.

| LUCF | Rules | Equation |
|------|-------|----------|
| FO   | We calculated the annual FO emissions in each municipality by multiplying its deforested area in each year [39] by its average emissions per deforested area [58] (Eq. (7)). The last official estimation of the Brazilian GHG emissions used a similar method. [60] | \[ FO_{m,y} = DA_{m,y} \times AED_{m} \]  

(7) |
| FF   | We divided the FF emissions/removals into two types (Eq. (8)): (i) emissions from forest degradation – e.g. selective logging and native forests converted to secondary forest – and removals from regeneration of secondary forest; and (ii) removals from native forests in protected areas (UCs and TIs while ignoring overlaps). We assumed that the type i emissions/removals were constant and equal to the average annual type i emissions/removals from 1995 to 2002 [39] (Eq. (9)). | \[ FF_{i,y} = DR_{i,y} / 8 \]  

(9) |
| OF   | We defined the annual OF removals in each municipality as being constant and equal to its average annual OF removals from 1995 to 2002 [39] (Eq. (6)). | \[ OF_{m,y} = OF_{m,y} \times PA_{m,y} \]  

(6) |

where \( AED_{m} \) is the average emissions per deforested area in municipality \( m \) from 1995 to 2002; \( FF_{i,y} \) is the type i emissions/removals in municipality \( m \) in year \( y \); \( DR_{i,y} \) is the total emissions/removals from forest degradation and forest regeneration in municipality \( m \) from 1995 to 2002; \( PA_{m,y} \) is the native forest area under protection in municipality \( m \) in 2013; \( AR \) is the average rate of removals of native forests in protected areas; \( AP_{m} \) is the average native forest area in the UCs and TIs in municipality \( m \) in 2002; and \( PA_{m,y} \) is the area of the UCs and TIs in municipality \( m \) in 2013. See supplementary material for details.
defined boundaries. [115] The main advantage of using this method in our study is to identify groups of municipalities with similar carbon stock and flow reduction profiles using a relative data analysis instead of discretionary parameters. Therefore, our method provides new insights for forest classification, such as those performed by Fonseca et al., [36] Griscom et al., [42] and Mollicone et al. [82] Methods based on fuzzy logic, such as this classification, have been widely used in climate change and environmental assessments in which uncertainties and imprecisions are relevant. [2,11,30,32,58,88]

We performed the following steps. (i) We normalized the estimated data of carbon stock and flow reduction to the range from 0 to 1. (ii) We identified mild inferior outliers as those values that were lower than the first quartile minus 1.5 times the interquartile range and mild superior outliers as those values that were higher than the third quartile plus 1.5 times the interquartile range. We identified extreme outliers (inferior and superior) using a fence of 5 times the interquartile range. We disregarded mild and extreme outliers in the fuzzy classification and included them in the large stock or high flow reduction groups if they were superior outliers or in the small stock or low flow reduction groups if they were inferior outliers. In the case of an excessive number of outliers (more than 10% of the data set), we only disregarded the extreme outliers and considered the mild outliers. (iii) We established a membership function to represent the similarity relation between the municipalities in terms of their carbon stocks (Eq. (13)) and another membership function to represent the similarity relation between the municipalities in terms of their flow reductions (Eq. (14)). (iv) We applied the membership functions to each normalized data set. (v) We verified whether the similarity relations complied with basic properties, such as reflexivity, symmetry and transitivity, and, if they did not, we applied the necessary procedures. [63,86,115] (vi) We tested different minimum similarity grades until three well-defined clusters of municipalities were formed according to the three classification categories of carbon stock and flow reduction. (vii) And we identified the priority municipalities as those with large carbon stocks and/or high flow reductions; and $FR_{ij}$ is the difference between the normalized flow reductions in municipalities $i$ and $j$.

### Comparison to PPCDAm

We compared the identified priority municipalities with the target municipalities of the PPCDAm [77] using maps developed in QGIS [93] based on the official shapefile of the Brazilian municipalities. [51]

#### Results and discussion

This section presents and discusses the results of this study (see supplementary material for more details).

### Stock-flow estimation

We estimated that the total carbon stock of the 552 municipalities in 2013 was 70,241 Tg C. This estimation is consistent with that found by Nogueira et al. [98] which only considered the stocks in the above- and belowground biomass while also considering carbon stocks of non-forest vegetation. Most of the municipalities had stocks of up to 254 Tg C, and there were 63 outliers (mild and extreme) that had stocks ranging from 262 to 2,980 Tg C (Figure 6). The municipalities with the larger stocks are located in the central and northwestern regions of the Amazon forest (Figure 7), which include the majority of the protected areas (Figure 2). The municipalities with the smaller stocks are located in the southern and eastern regions (Figure 7) near the Cerrado (Figure 1) – which contains vegetation with lower carbon content – and where the cumulative deforestation is higher (arc of deforestation). The supplementary material describes the details of our stock estimation.

![Figure 6. Distribution of the carbon stocks in the 552 Brazilian Amazon municipalities in 2013.](image-url)

Figure 6. Distribution of the carbon stocks in the 552 Brazilian Amazon municipalities in 2013. The line within the box represents the median, the box represents the interquartile range, the whiskers are equal to 1.5 times the interquartile range, the circles represent mild outliers, and the crosses represent extreme outliers.
We estimated that the total flow reduction of the 552 municipalities from 2006 to 2013 was 6,288 Tg CO$_2$, of which the reference level emissions were 6,556 Tg CO$_2$ and the net emissions were 268 Tg CO$_2$. This flow reduction was mainly caused by reductions in the gross emissions from deforestation and by increases in the removals from new protected areas. Due to this large reduction in flow, the Amazon has been changing from a net carbon source to a net carbon sink (Figure 8). The last official estimation of the national GHG emissions [69] did not capture this information mainly because it did not consider the removals from protected areas that were created after 2002, which were substantial. [114] Moreover, this flow reduction is consistent with that found by Nepstad et al. [87] which only considered the gross emissions from deforestation and the above-ground biomass as carbon pool. From 2006 to 2013, 358 municipalities were net sources, and 194 were net sinks. A relatively small number of municipalities, 29, emitted more than their reference level, which was likely due to a very low reference level and/or to leakages, i.e. local increases in deforestation due to mitigation activities in neighboring regions. Therefore, these municipalities showed negative flow reductions (Eq. (1)). Most of the municipalities presented flow reductions between -13 and 38 Tg CO$_2$, and there were 39 outliers (mild and extreme) with flow reductions between 39 and 230 Tg CO$_2$ (Figure 9c). The flow reductions of the source municipalities were higher than those of the sink municipalities (Figures 9a and 9b). The municipalities with the highest flow reductions are concentrated in the arc of deforestation and in the northwestern region (Figure 10). The flow reductions in the former area were mainly due to cutbacks in the gross emissions from deforestation, where some municipalities even became sinks. The flow reductions in the latter area were mainly due to carbon removals from new protected areas. The supplementary material describes the details of our flow estimation.

- **Priority municipalities**

We classified the 552 municipalities in terms of their carbon stocks in 2013 and their flow reductions from 2006 to 2013 using the fuzzy classification method and our estimated data. The similarity relations between the municipalities’ stocks and flows (Eqs. (13) and (14)) complied with the reflexivity and symmetry properties. However, we had to perform a max-min composition to make them transitive. We determined the desired clusters of municipalities using minimum similarity grades of 0.96 for the stock classification and 0.97 for the flow classification. We considered the mild outliers in the stock classification due to the excessive number of mild and extreme outliers (Figure 6).

The ranges of carbon stocks for each profile are: (i) small – from 0 to 472 Tg C; (ii) medium – from 522 to 564 Tg C; and (iii) large – from 591 to 2,980 Tg C. The ranges of flow reductions for each profile are: (i) low – from -13 to 33 Tg CO$_2$; (ii) medium – from 34 to 36 Tg CO$_2$; and (iii) high – from 37 to 230 Tg CO$_2$. The results show that no municipality has a stock that is within the gaps between the upper and lower bound.
values of the profile ranges. Moreover, the large stock and high flow profiles had wider ranges due to the large number of outliers with high values (Figures 6 and 9). We observed that most of the municipalities have small stocks and low flow reductions (Figure 11c). On the other hand, we identified 63 municipalities with large carbon stocks and/or high flow reductions, which we identify as priority municipalities for REDD+ benefit sharing. Thirty-eight of these municipalities are net sources (Figure 11b), and 25 are net sinks (Figure 11a). Together, they hold 50% of the Amazon’s carbon stock and are responsible for 26% of the Amazon’s flow reduction. The priority municipalities are located in the central and northwestern regions as well as in the arc of deforestation (Figure 12). Finally, we performed simple linear regressions between the carbon stock or flow reduction data (y-axis) and the Amazon area of the municipalities (x-axis) and observed that the carbon stocks are highly influenced by the explanatory variable \((R^2 = 0.98)\), but the flow reductions are not \((R^2 = 0.21)\). The first finding can be explained by the fact that larger Amazon municipalities are generally more preserved and protected than the smaller ones (Figures 1 and 2). The second finding is related to the fact that flow reductions have both source and sink components that vary through time and are not necessarily related to area.

Figure 9. Distribution of the flow reductions of the 552 Brazilian Amazon municipalities from 2006 to 2013. (a) The 194 sink municipalities. (b) The 358 source municipalities. (c) All municipalities. The lines within the boxes represent the medians, the boxes represent the interquartile ranges, the whiskers are equal to 1.5 times the interquartile range, the circles represent mild outliers, and the crosses represent extreme outliers.

Figure 10. Map of the flow reductions of the 552 Brazilian Amazon municipalities from 2006 to 2013.

Figure 11. Stock-flow classification of the 552 Brazilian Amazon municipalities. (a) The 194 sink municipalities. (b) The 358 source municipalities. (c) All municipalities. The percentages are the share of each profile in the total carbon stock or flow reduction in the Brazilian Amazon.
Comparison to PPCDAm

We compared the 63 priority municipalities that were identified in this study with the 89 target municipalities of the PPCDAm. Thirty-three municipalities are both priority and target municipalities (Figure 13a). Twenty of these municipalities are net sources with high flow reductions that have been targeted by PPCDAm based on the criteria of the monitoring and control thematic axis. The remaining 13 municipalities, regardless of their stocks or flows, are included in the PPCDAm’s target list due to their strategic locations for the activities of the land tenure regularization and land use planning thematic axis.

Thirty municipalities are priority municipalities but not target municipalities (Figure 13b). Seventeen of these municipalities are net sinks with large stocks. Coincidently, they are located in regions with poorer socioeconomic indicators (Figure 3) and could therefore be the focus of the activities of PPCDAm’s thematic axis for the promotion of sustainable productive activities. They are also located in regions of protected areas with relevant extents and could therefore be the focus of activities of the land tenure regularization and land use planning thematic axis, such as management improvements and control of land invasions by third parties. The remaining 13 municipalities are located in the arc of deforestation and showed high flow reductions.

Although these remaining municipalities were not targeted by PPCDAm based on the monitoring and control thematic axis criteria, they might have been influenced by the enforcement actions in their neighboring municipalities.

Fifty-six target municipalities are not priority municipalities (Figure 13c). All of them are either in the arc of deforestation (but have not significantly reduced their flows) or in strategic regions from the perspective of the PPCDAm’s thematic axes for the promotion of sustainable productive activities and for land tenure regularization and land use planning. Although these municipalities were not included in our priority list based on the carbon criteria, they are important for preventing the advancement of the deforestation in the Amazon forest and for contributing to biodiversity conservation.

The 89 target municipalities hold 34% of the Amazon’s carbon stock and accounted for 34% of the Amazon’s flow reductions (Figure 14c). Sixty-five of them are net sources (Figure 14b), and 24 are net sinks (Figure 14a). The analysis of the results shows that the PPCDAm has successfully focused on the net source priority municipalities, which indicates that the plan has contributed to the sharp reduction in the gross emissions in the Amazon region. However, the plan has not consistently focused on the net sink and large stock priority municipalities, which can lead to leakage in important carbon pools. Finally, we observed that 62% of the 29 municipalities with increased flow have small stocks, are located in the arc of deforestation and have not been targeted by PPCDAm. This indicates...
Figure 13. Comparison between the 63 priority municipalities for REDD+ benefit sharing and the PPCDAm’s 89 target municipalities. (a) The 33 municipalities that are in both groups. (b) The 30 priority municipalities that are not target municipalities. (c) The 56 target municipalities that are not priority municipalities.
that minor leakages in the arc of deforestation region may already be occurring.

**Limitations and directions for further research**

The stock-flow data for the Brazilian Amazon forest are subject to a significant degree of uncertainty \[3,45,81\]. Although we used official data in our study, statistical improvements could be performed for future research. Moreover, to update the stock-flow data from the last national GHG inventory, we used information from several official sources \[37,38,55,78\] that have several differences and limitations. Although our method has minimized these differences and limitations to some extent (‘Data and methods’ section and supplementary material), the analysis should be updated with the database from the new inventory, which will probably be released in 2015.

We followed the methods of the national GHG inventory to estimate carbon removals from the Amazon forests; therefore, we assumed that they have a constant yearly sink capacity (Eq. (10)). However, our analysis period includes severe droughts in the region that affected the Amazon’s sink capacity. \[6,92\] Future studies could address this limitation and estimate specific carbon removal rates by considering climatic effects.

To estimate the flow reductions in each municipality, we established reference levels based on the average net emissions from 1996 to 2005, according to the parameters of the PNMC. Although the use of reference levels based on historical emissions has been a trend, \[33\] these years notably include the highest deforestation period in the Brazilian Amazon region. Therefore, the use of this reference level could overestimate the flow reductions and discourage the efforts that are necessary to reach zero deforestation. Moreover, flow reductions are highly influenced by the adopted reference level. \[29,33,41,42\] Therefore, further studies could test stricter and municipality-specific reference levels and perform sensitivity analyses.

In this study, we propose REDD+ benefit sharing based on the stock-flow criteria (see supplementary material). To stimulate non-carbon benefits, \[98,103,112\] REDD+ benefit sharing mechanisms and policy targeting may also be based on other criteria in addition to the carbon stock and flow. \[8,59,65\] such as poverty reduction, land tenure clarification, biodiversity conservation, water resource protection, increased incomes of traditional peoples and communities, and mitigation costs. In the Brazilian Amazon, these aspects are relevant considering the recent challenges and socioeconomic fragilities that are discussed in this study. We suggest that the development of a REDD+ benefit sharing mechanism and policy targeting for the Brazilian Amazon also incorporate these dimensions of REDD+.

**Conclusion**

In this article, we performed a carbon stock-flow analysis of the 552 municipalities that make up the Brazilian Amazon. Our estimation showed that these municipalities held 70.241 Tg C in their forests in 2013 and were responsible for reducing the flow of net emissions by 6,288 Tg CO\(_2\) from 2006 to 2013. This flow reduction was mainly caused by reductions in the gross emissions from deforestation and by increases in the removals from new protected areas. Due to this large flow reduction, the Amazon forest has been changing from a net carbon source to a net carbon sink. However, initiatives such as REDD+ are important to maintain this trend in the future.

We observed that most of the municipalities had small stocks and low flow reductions. However, we identified 63 municipalities with large carbon stocks and/or high flow reductions, which we suggested to be the priority municipalities for REDD+ benefit sharing. Thirty-eight of these municipalities are net sources,
and 25 are net sinks. Together, they hold 50% of the Amazon's carbon stock and were responsible for 26% of the Amazon's flow reduction.

We compared these priority municipalities with the 89 target municipalities of the main national mitigation plan of REDD+ for the biome, the PPCDAm. We observed that the PPCDAm has contributed to the large reductions in gross emissions in the Amazon forest by successfully targeting net source priority municipalities. However, net sink and large stock priority municipalities are not being consistently targeted by the plan, which can lead to leakage in important carbon pools.

We conclude our study by suggesting (i) the use of the stock-flow criteria to perform REDD+ benefit sharing among the municipalities and (ii) the inclusion of the stock-flow criteria for defining target municipalities in further revisions of the PPCDAm. This analysis can also be performed in other Brazilian forests and in other developing countries with large forest covers.

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Supplementary Material

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References

1 Achard F, Eva HD, Mayaux P et al. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*. 18, 1–11 (2004). doi:10.1029/2003GB002142.
2 Acosta L, Klein RJT, Reidma P et al. A spatially explicit scenario-driven model of adaptive capacity to global change in Europe. *Global Environmental Change*. 23, 1211–1224 (2013). doi:10.1016/j.gloenvcha.2013.05.008.
3 Aguiar APD, Ometto JP, Nobre C et al. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: The INPE-EM framework applied to the Brazilian Amazon. *Global Change Biology*. 18, 3346–3366 (2012). doi:10.1111/j.1365-2486.2012.02782.x.
4 Ajani JI, Keith H, Blakers M et al. Comprehensive carbon stock and flow accounting: A national framework to support climate change mitigation policy. *Ecological Economics*. 89, 61–72 (2013). doi:10.1016/j.ecolecon.2013.01.010.
5 Angelsten A, Boucher D, Brown S et al. Modalities for REDD+ reference levels: technical and procedural issues. Washington, DC: Meridian Institute (2011).
6 Aragão LE, Poulter B, Barlow JB et al. Environmental change and the carbon balance of Amazonian forests. *Biological Reviews*. 89, 913–931 (2014). doi:10.1111/brv.12088.
7 Assunção J, Gaudour CC, Rocha R. Deforestation slowdown in the Legal Amazon: Prices or police? San Francisco: CPI (2012).
8 Atela JO, Quinn CH, Minang PA. Are REDD projects pro-poor in their spatial targeting? Evidence from Kenya. *Applied Geography*. 52, 14–24 (2014). doi:10.1016/j.apgeog.2014.04.009.
9 Barros AE, Macdonald EA, Matsumoto MH et al. Identification of areas in Brazil that optimize conservation of forest carbon, jaguars, and biodiversity. *Conservation Biology*. 28, 580–593 (2013). doi:10.1111/cobi.12202.
10 Barua SK, Uusivuori J, Kuuluvainen J. Impacts of carbon-based policy instruments and taxes on tropical deforestation. *Ecological Economics*. 73, 211–219 (2012). doi:10.1016/j.ecolecon.2011.10.029.
11 Basurto X. Linking multi-level governance to local common-pool resource theory using fuzzy-set qualitative comparative analysis: Insights from twenty years of biodiversity conservation in Costa Rica. *Global Environmental Change*. 23, 575–587 (2013). doi:10.1016/j.gloenvcha.2013.02.011.
12 Börner J, Wunder S, Wertz-Kanounikoff S et al. Direct conservation payments in the Brazilian Amazon: Scope and equity implications. *Ecological Economics*. 69, 1272–1282 (2010). doi:10.1016/j.ecolecon.2009.11.003.
13 Börner J, Vosti SA. Managing tropical forest ecosystem services: An overview of options. In: Muradian R, Rival L, editors. *Governing the provision of ecosystem services*. Dordrecht, Heidelberg, New York, London: Springer (2013).
14 Börner J, Wunder S, Wertz-Kanounikoff S et al. Forest law enforcement in the Brazilian Amazon: Costs and income effects. *Global Environmental Change*. 29, 294–305 (2014). doi:10.1016/j.gloenvcha.2014.04.021.
15 Brazil. Law nº 5173, October 27, 1966. *Plano de valorização econômica da Amazônia*. Brasília: Republic Presidency (1966).
16 Brazil. Law nº 6001, December 19, 1973. *Estatuto do índio*. Brasília: Republic Presidency (1973).
17 Brazil. Complementary law nº 31, October 11, 1977. *Criação do estado de Mato Grosso do Sul*. Brasilia: Republic Presidency (1977).
18 Brazil. Constituição da república federativa do Brasil. Brasilia: Republic Presidency (1988).
19 Brazil. Decree nº 1775, January 8, 1996. *Procedimento administrativo de demarcação das terras indígenas*. Brasilia: Republic Presidency (1996).
20 Brazil. Law nº 9985, July 18, 2000. *Sistema Nacional de Unidades de Conservação da Natureza - SNUC*. Brasilia: Republic Presidency (2000).
21 Brazil. Decree nº 6321, December 21, 2007. *Ações relativas à prevenção, monitoramento e controle de desmatamento no Bioma Amazônica*. Brasília: Republic Presidency (2007).
22 Brazil. Law nº 12187, December 29, 2009. *Política Nacional sobre Mudança do Clima - PNMC*. Brasilia: Republic Presidency (2009).
23 Brazil. Decree nº 7390, December 9, 2010. *Política Nacional sobre Mudança do Clima - PNMC*. Brasilia: Republic Presidency (2010).
24 Brazil. Law project nº 195/2011, February 8, 2011. *Sistema Nacional de REDD*. Brasilia: Chamber of Deputies (2011).
25 Brazil. Law project nº 212/2011, May 3, 2011. *Sistema Nacional de REDD*. Brasilia: Federal Senate (2011).
26 Brockhaus M, Di Gregorio M. National REDD+ policy networks: from cooperation to conflict. *Ecology and Society*. 19, (2014). doi:10.5751/ES-06643-190414.
27 Busch J, Strasburg B, Cartaner A, Lubowski R et al. Comparing climate and cost impacts of reference levels for reducing emissions from
of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal protocol. São José dos Campos: FUNCAE (2010).

38 FUNCATE (Foundation of Science, Applications and Spatial Technologies). Spatial data of the land use, land-use change and forests report of the 2nd Brazilian inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal protocol. São José dos Campos: FUNCAE (2010).

39 FUNCAE (Foundation of Science, Applications and Spatial Technologies). Land use, land-use change and forests report of the 2nd Brazilian inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal protocol. São José dos Campos: FUNCAE (2010).

40 GCF (Governors’ Climate and Forests Task Force). Proposta de alocação das reduções de emissões ‘U-REDD’ nos estados brasileiros membros do GCF. Manaus: IDESAM (2014).

41 Griscom B, Shoch D, Stanley B et al. Sensitivity of amounts and distribution of tropical forest carbon credits depending on baseline rules. Environmental Science & Policy, 12, 897–911 (2009). doi:10.1016/j.envsci.2009.07.008.

42 Griscom B, Cortez R. Establishing efficient, equitable, and environmentally sound reference emissions levels for REDD+: A stock-flow approach. Arlington, VA: The Nature Conservancy (2011).

43 Harris NL, Petrova S, Stolle F et al. Identifying optimal areas for REDD+ intervention: East Kalimantan, Indonesia as a case study. Environmental Research Letters, 3, 1–11 (2008). doi:10.1088/1748-9326/3/3/035006.

44 Houghton RA, Lawrence KT, Hackler JL et al. The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates. Global Change Biology, 7, 731–746 (2001). doi:10.1111/j.1365-2486.2001.00426.x.

45 Houghton RA, Greenglass N, Baccini A et al. The role of science in Reducing Emissions from Deforestation and Forest Degradation (REDD). Carbon Management, 1, 253–259 (2010). doi:10.1016/j.cmct.2010.29.

46 Houghton RA. The emissions of carbon from deforestation and degradation in the tropics: Past trends and future potential. Carbon Management, 4, 539–546 (2013). doi:10.1016/j.cmct.2013.41.

47 IBGE (Brazilian Institute of Geography and Statistics). Mapa de biomas do Brasil. Rio de Janeiro: IBGE (2004).

48 IBGE (Brazilian Institute of Geography and Statistics). Geoestatísticas de recursos naturais da Amazônia Legal 2003. Rio de Janeiro: IBGE (2011).

49 IBGE (Brazilian Institute of Geography and Statistics) Shapefile of the Legal Amazon. (2014). Available from: ftp://gofrp.ibge.gov.br/mapas_interativos.

50 IBGE (Brazilian Institute of Geography and Statistics) Shapefile of the Brazilian municipalities in 2005. (2014). Available from: ftp://gofrp.ibge.gov.br/malhas_digitais/municipio_2005.

51 IBGE (Brazilian Institute of Geography and Statistics) Gross domestic product of the Brazilian municipalities. (2014). Available from: http://downloads.ibge.gov.br/downloads_estatisticas.htm.

52 INPE (Brazilian National Institute for Space Research) Program of monitoring the Brazilian Amazon forest by satellites (2014). Available from: http://www.obt.inpe.br/prodes/index.php.

53 IPAM (Amazon Environmental Research Institute), ISA (Socio-Environmental Institute), & Imazon (Amazon Institute of People and the Environment). O aumento no desmatamento na Amazônia em 2013: Um ponto fora da curva ou fora de controle? Brasília: IPAM (2014).

54 IPCC (Intergovernmental Panel on Climate Change). Good practice guidance for land use, land-use change and forestry. Kanagawa: IPCC; 2003.

55 IPEA (Institute for Applied Economic Research), CEPAL (United Nations Economic Commission for Latin America and the Caribbean), & GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). Avaliação do Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal: PPCDAm 2007–2010. Rio de Janeiro: IPEA (2011).

56 ISA (Socio-Environmental Institute). Amazônia brasileira 2009. São Paulo: ISA (2009).

57 Kok K. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Global Environmental Change, 19, 122–133 (2009). doi:10.1016/j.gloenvcha.2008.08.003.

58 Koning F, Auñigaña M, Bravo M et al. Bridging the gap between forest conservation and poverty alleviation: The Ecuadorian Socio Bosque program. Environmental Science & Policy, 14, 531–542 (2011). doi:10.1016/j.envsci.2011.04.007.

59 Lambin EF, Meyfroidt P, Rueda X et al. Effectiveness and synergies of policy instruments for land use governance in tropical regions. Global Environmental Change, 28, 129–140 (2014). doi:10.1016/j.gloenvcha.2014.06.007.
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61 Lapola DM,MartelliniLA,PeresCAet al. Pervasive transition of the Brazilian land-use system. Nature Climate Change. 4, 27–35 (2014). doi:10.1038/nclimate2056.

62 Le Quére C, Raupach MR,CanadellJG et al. Trends in the sources and sinks of carbon dioxide. Nature Geoscience. 2, 831–836 (2009). doi:10.1038/ngeo689.

63 Lee KH. First course on fuzzy theory and applications. Berlin:Springer-Verlag (2005).

64 Lin L,Sills E,CheshireH. Targeting areas for Reducing Emissions from Deforestation and forest Degradation (REDD+) projects in Tanzania. Global Environmental Change, 24, 277–286 (2014). doi:10.1016/j.gloenvcha.2013.12.003.

65 Luttrell C,Loft L,GebaraMF et al. Who should benefit from REDD+? Rationales and realities. Ecology and Society. 18, 52 (2013). doi:10.5751/ES-08583-140452.

66 MattssonE,PerssonUM,Ostwald M,Nissanka SP. REDD+ readiness implications for Sri Lanka in terms of reducing deforestation. Journal of Environmental Management. 100, 29–40 (2012). doi:10.1016/j.jenvman.2012.01.018.

67 May PH,Milikkan B,Gebara MF. The context of REDD+ in Brazil: Drivers, agents, and institutions. Bogor: CIFOR (2011).

68 MCTI (Brazilian Ministry of the Science, Technology and Innovation). 2nd Brazilian inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal protocol. Brasil: MCTI (2010).

69 MCTI (Brazilian Ministry of the Science, Technology and Innovation). Estimativas anuais de emissões gaseosas de efeito estufa no Brasil. Brasilia: MCTI (2013).

70 MMA (Brazilian Ministry of the Environment). Avaliação e identificação de ações prioritárias para a conservação, utilização sustentável e repartição dos benefícios da biodiversidade na Amazônia brasileira. Brazilia: MMA/SFB (2001).

71 MMA (Brazilian Ministry of the Environment). Plano de ação para a prevenção e controle do desmatamento na Amazônia Legal (PPCDAm). 1ª fase. Brasil: MMA (2004).

72 MMA (Brazilian Ministry of the Environment). Plano Amazônia Sustentável: Diretrizes para o desenvolvimento sustentável da Amazônia Brasileira. Brasilia: MMA (2008).

73 MMA (Brazilian Ministry of the Environment). Plano de ação para a prevenção e controle do desmatamento na Amazônia Legal (PPCDAm). 2ª fase. Brasilia: MMA (2009).

74 MMA (Brazilian Ministry of the Environment). The Brazilian REDD Strategy. Copenhagen: MMA (2009).

75 MMA (Brazilian Ministry of the Environment). REDD+ relatório de painel técnico do MMA sobre financiamento, benefícios e cobenefícios. Brasilia: MMA (2012).

76 MMA (Brazilian Ministry of the Environment). Florestas do Brasil em ranho. Brasilia: MMA/SFB (2013).

77 MMA (Brazilian Ministry of the Environment). Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm). 3ª fase. Brasilia: MMA (2013).

78 MMA (Brazilian Ministry of the Environment). Shapefile of the Conservation Units. (2014). Available from: http://www.mma.gov.br/areas-protégidas/cadastro-nacional-de-ucs/dados-georreferenciados.

79 MMA (Brazilian Ministry of the Environment). Shapefile do Brasil do Sistema Amazonico Biomosaic (2014). Available from: http://mapas.mma.gov.br/i3geo/dadosdownload.htm.

80 MMA (Brazilian Ministry of the Environment). REDD+. (2014). Available from: http://www.mma.gov.br/redd/.

81 MMA (Brazilian Ministry of the Environment). Brazil’s submission of a forest reference emission level for deforestation in the Amazonia biome for result-based payments for REDD+ under the UNFCCC. Brasilia: MMA (2014).

82 Mollicone D,Achard F,Federici S et al. An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. Climatic Change. 83, 477–493 (2007). doi:10.1007/s10584-006-9231-2.

83 Mourinho P, Schwartzman S. Tropical deforestation and climate change. Paris: Instituto de Pesquisa Ambiental da Amazônia (IPAM); (2005).

84 Mourinho P, Stella O,Lima A et al. REDD no Brasil: Um enfoque amazônico: Fundamentos, críticas e estruturas institucionais para um regime nacional de Redução de Emissões por Desmatamento e Degradação Florestal – REDD. Ed. rev. e atual. Brasilia: CGEE (2011).

85 Mourinho P,M Martins OS, Christovam M et al. The emerging REDD+ regime of Brazil. Carbon Management 2, 587–602 (2011). doi:10.4155/cmt.11.46.

86 Nepstad D,Soares-Filho BS, Mert F et al. The end of deforestation in the Brazilian Amazon. Science. 326, 1350–1351 (2009). doi:10.1126/science.1182108.

87 Nepstad D, McGrath D, Stickler C et al. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science. 344, 1118–1123 (2014). doi:10.1126/science.1248525.

88 Nobre RCM,Roturino Filho OC, Mansur WJ et al. Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool. Journal of Contaminant Hydrology. 94, 277–292 (2007). doi:10.1016/j.jconhyd.2007.07.008.

89 Nogueira EM,Yanai AM, Fonseca FO et al. Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. Global Change Biology. 21, 1271–1292 (2015). doi:10.1111/gcb.12798.

90 Nolte C,Agrawal A, Barreto P. Setting priorities to avoid deforestation in Amazon protected areas: Are we choosing the right indicators? Environmental Research Letters. 8, 1–7 (2013). doi:10.1088/1748-9326/8/1/015039.

91 Pan Y,Birdsey RA,Fang J et al. A large and persistent carbon sink in the world’s forests. Science. 333, 988–993 (2011). doi:10.1126/science.1201609.

92 Phillips OL,Aragão LE, Lewis SL et al. Drought sensitivity of the Amazon rainforest. Science. 323, 1344–1347 (2009). doi:10.1126/science.1164033.

93 QGIS. QGIS Geographic Information System. Open Source Geospatial Foundation Project. (2014).

94 Ricardo F. Terras Indígenas & Unidades de Conservação da natureza: O desafio das sobreposições. São Paulo: ISA (2004).

95 Richter Jr D deB,Houghton RA. Gross CO₂ fluxes from land-use change: implications for reducing global emissions and increasing sinks. Carbon Management 2, 41–47 (2011). doi:10.4155/CMT.10.43.

96 Ross TJ. Fuzzy logic with engineering applications. West Sussex, UK: John Wiley & Sons Ltd (2010).

97 Sammilli M,Mourinho P, Schwartzman S et al. Tropical deforestation and the Kyoto Protocol: An editorial essay. Climatic Change. 71, 267–276 (2005). doi:10.1007/s10584-005-8074-6.

98 Schafszm M, Morse-Jones S, Posen P et al. The importance of local forest benefits: Economic valuation of Non-Timber Forest Products in the Eastern Arc Mountains in Tanzania. Global Environmental Change. 24, 295–305 (2014). doi:10.1016/j.gloenvcha.2013.08.018.

99 Seymour F,Angelsen A. Summary and conclusions: REDD wine in old wineskins?
In: Angelsen A, Brockhaus M, Kanninen M, Sills E, Sunderlin WD, Wertz-Kanounnikoff S, editors. Realising REDD+: National strategy and policy options. Bogor, Indonesia: CIFOR (2009).

Skutsch M. Slicing the REDD+ pie: Controversies around the distribution of benefits. CAB Reviews. 8, 1–10 (2013). doi:10.1079/pvsnrr20138020.

Soares-Filho B, Moutinho P, Nepstad D et al. Role of Brazilian Amazon protected areas in climate change mitigation. Proceedings of the National Academy of Sciences. 107, 10821–10826 (2010). doi:10.1073/pnas.0913048107.

Stern N. The economics of climate change: The Stern review. Cambridge: Cambridge University Press (2006).

Stickler CM, Nepstad DC, Coe MT et al. The potential ecological costs and cobenefits of REDD: A critical review and case study from the Amazon region. Global Change Biology. 15, 2803–2824 (2009). doi:10.1111/j.1365-2486.2009.02109.x.

Straszburg B, Turner RK, Fisher B et al. Reducing emissions from deforestation – the combined incentives mechanism and empirical simulations. Global Environmental Change. 19, 265–278 (2009). doi:10.1016/j.gloenvcha.2008.11.004.

Tollefson J. Deforestation emissions on the rise Amazon study suggests denser forest yields will mean more carbon release. Nature (2009). doi:10.1038/news.2009.752.

Torras M. The total economic value of Amazonian deforestation, 1978–1993. Ecological Economics. 33, 283–297 (2000). doi:10.1016/S0921-8009(99)00149-4.

Torres AB, Skutsch M. Splitting the difference: A proposal for benefit sharing in Reduced Emissions from Deforestation and Forest Degradation (REDD+). Forests 3, 137–154 (2012). doi:10.3390/f3010137.

UNDP (United Nations Development Programme). The Brazilian human development atlas 2013. Brasilia: UNDP (2013).

UNFCCC (United Nations Framework Convention on Climate Change). Reducing emissions from deforestation in developing countries: Approaches to stimulate action. Bonn: UNFCCC (2005).

UNFCCC (United Nations Framework Convention on Climate Change). Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Bonn: UNFCCC (2011).

UNFCCC (United Nations Framework Convention on Climate Change). Report of the Conference of the Parties on its eighteenth session, held in Doha from 26 November to 8 December 2012. Bonn: UNFCCC (2013).

van der Werf GR, Morton DC, DeFries RS et al. CO₂ emissions from forest loss. Nature Geoscience. 2, 737–738 (2009). doi:10.1038/ngeo671.

Veríssimo A, Rolla A, Souto Maior APC et al. Protected areas in the Brazilian Amazon: Challenges and opportunities. Belem and Sao Paulo: Imazon and ISA (2011).

Zadeh L. Similarity relations and fuzzy orderings. Information Sciences. 3, 177–200 (1971). doi:10.1016/S0020-0255(71)80005-1.