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Regrowing forests contribution to law compliance and carbon storage in private properties of the Brazilian Amazon

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ABSTRACT

The viability of the climate pledges made by Brazil at the COP21 in Paris, 2015, heavily depends on the success of the country policies related to forest governance. Particularly, there are high expectations that the enforcement of the Brazilian Forest Code (BFC) will drive large-scale forest recovery and carbon mitigation. In this study, we quantified the potential role that ongoing forest regeneration may play in offsetting deficits from private properties with less vegetation cover than determined by the BFC, considering different law implementation settings. Focusing on the Amazon Biome, we overlaid property level data from a mandatory registry (≈ 250,000 properties) onto land cover maps to quantify on-site forest deficit offsets by ongoing forest recovery. Similarly, we estimated the share of regrowing forests in private properties potentially eligible for off-site deficit compensation (i.e. via market-based forest certificates trade). Regrowing forests could reduce, on-site, 3.2 Mha of forests deficits, decreasing non-compliance from private properties by 35%. Likewise, forest certificates availability increased by 3.4 Mha when we included regrowing forests in the calculations. This means an increase in the forest certificate offer-demand ratio from 0.9 to 2.0. On the one hand, trading certificates issued from recovering forests may represent a low-cost strategy for compliance with the BFC, a pathway for achieving restoration targets, and an additional source of income for landholders. To meet this potential, it is necessary to better conceptualize second-growth forests, advancing the poor definitions presented by the BFC, and offer an operational basis for their protection. On the other hand, including regrowing forests' certificates in compensation schemes may further restrain the potential of the trading mechanism for conservation of unprotected old-growth forests and lead to positive net carbon emissions. We highlight that the BFC implementation must be carefully regulated to maximize synergies between compliance and forest resources conservation and enhancement.

1. Introduction

Forest conservation and forest restoration are key strategies for mitigating the impacts of deforestation on biodiversity, soil, water quality and carbon stocks depletion (Banks-Leite et al., 2014; Barlow et al., 2007; Martin et al., 2013; Zhao et al., 2013). Hence, the rise of a global agenda on forest restoration has motivated many countries to scale-up forest recovery initiatives (Chazdon et al., 2017). Recent examples are international conventions such as the Aichi Targets, setting a restoration target of at least 15% of degraded ecosystems (Jørgensen, 2013), and the Bonn Challenge, targeting 350 Mha of forest restoration globally by 2030 (Bonn challenge, 2017).

Chazdon et al. (2016) estimated that, if left to regrow, in 40 years regrowing forests (RF) in Latin America could offset two decades of fossil fuels and industrial carbon dioxide emissions from the region. Brazil alone accounts for 75% of the carbon storage potential of young

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to medium age second-growth forests of all tropical Latin America (Chazdon et al., 2016). Focusing on the Brazilian Amazon, Aguiar et al. (2016) demonstrated that RFs may turn the Amazon into a net carbon sink by 2020, if, in addition to continued deforestation reduction, second-growth forests are expanded and protected.

Aware of this mitigation opportunity, Brazil pledged to restore 12 Mha of forests by 2030 at the COP21 (Nationally Determined Contribution, NDC - ratified at the UNFCCC COP Paris 21) (Brasil, 2015). However, achieving this target depends on the implementation of interrelated sectorial policies involving different stakeholders, as well as legislation and market developments (Brancalion et al., 2016b; Lazos-Chavero et al., 2016). Chief among policies are the recently revised Brazilian Native Vegetation Protection Law (Law N. 12651/2012), commonly referred to as Brazilian Forest Code (BFC) (Brasil, 2012), and the National Plan for Native Vegetation Recovery – PLANAVEG, launched in 2017 (Brasil, 2017).

In 2014, an assessment mapped over 17 Mha of secondary vegetation (in this article used as a synonym of regrowing forests) in the Brazilian Amazon Biome, inside public and private lands (INPE, 2014a). However, very often, RFs are a temporary component of the landscape, quickly reincorporated into productive land. Between 2008 and 2012, 25% of RF areas in the Amazon were re-cleared while their total cover increased, suggesting that the short-life of this land cover may impair its long-term potential for carbon mitigation (Aguiar et al., 2016). Underlying land use systems and heterogeneous actors strongly influence RFs trajectories (Lambin and Meyfroidt, 2010). In the Amazon, RFs appeared as a transitional cover with the purpose of ecological restoration in traditional agricultural systems, as revegetation in abandoned, degraded pastures or as a by-product of agricultural intensification (Costa, 2016). Therefore, RFs are multifaceted components of land use systems, and competition for land associated with the lack of specific legislation regulating their protection, threaten the persistence and co-benefits of forest recovery (Barbier et al., 2010; Carvalho et al., 2019; Vieira et al., 2014).

The BFC regulates the conservation of native vegetation in private lands. With 54% of the Brazilian Amazon forests located inside private properties, landholder's compliance with the BFC is strategic for forest conservation and restoration. Recent studies have calculated forest deficits (i.e. forest cover falling behind with the BFC requirements) and forest extent apt for issuing certificates (which may be used for off-site deficit compensation) for rural properties (Brito, 2017; Freitas et al., 2017b; Micol et al., 2013; Nunes et al., 2016; Soares-Filho et al., 2014). These studies indicated that BFC compliance levels (i.e. landholdings degree of agreement to legal conservation requirements) and forest balances (i.e. regionally aggregated difference between potential forest certificates availability and deficits) vary in intensity and spatial distribution.

The forest balance of a federal state is an indicator of its potential role as buyer or provider of forest certificates eligible for trade via a market-based mechanism for BFC deficits offsetting. In this context, state-level regulatory setups are crucial (Freitas et al., 2017b); they impose different restrictions for trade, delimiting the size and appeal of the market, with consequences for economic gains and conservation additionality. Currently, the implications of using different offsetting mechanisms foreseen by the BFC are under evaluation by state governments and sectors of the civil society (especially by the academia and NGOs), with regards to market territorial restrictions, protection status of the traded forest certificates and prioritization of vulnerable areas (Freitas et al., 2017b; Gasparinetti and Vilela, 2018; Soares-Filho et al., 2016). However, less attention has been given to the eligibility and potential contribution of adding RFs to the BFC balance and the consequences for conservation. Brito (2017) found that in the state of Pará, 30% of forests apt for issuing tradable certificates likely come from regrowing forest areas, indicating the need to investigate possible implications for related policies.

In this paper, we bring this discussion forward and investigate the potential contribution of RFs to law compliance and conservation under the BFC in the Brazilian Amazon. Our specific goals are: (1) To assess the current compliance with the BFC on property-level, including and excluding RFs of landholdings' forest stocks; (2) to evaluate the implications of alternative regulatory setups of BFC implementation, including and excluding RFs, for forest conservation and carbon storage. The paper is organized as follows. First, we detail central aspects of the BFC to contextualize our analysis. Then we present the methods for achieving goals 1 and 2, followed by the results and discussion of our findings under the perspective of our guiding questions (see next section) and previous research on the topic. We also discuss the challenges and implications of implementing the proposed setups in the context of the Brazilian Amazon and make suggestions for future work.

1.1. Pathways to compliance with the Brazilian Forest Code: including forest regrowth

In 1965 the BFC instituted two conservation categories inside private lands, the Legal Reserve (LR) and the Permanent Protection Area (PPA) (table S1) (BRAZIL, 1965). The PPAs define strict protection zones inside the properties (i.e. riparian buffer zones and steep terrain). The LRs represent a property set-aside for native vegetation protection, defined as 80% of the landholding in forestlands of the Amazon biome (table S2) since an addendum made to the BFC in 1996 (Law MP 1.511/1996). However, the BFC was never properly enforced, which, in combination with conflicting land governance, led to massive noncompliance among landholders (Sparovek et al., 2012). The ineffectiveness of the law motivated its revision, aiming to create instruments to give noncompliant farmers access to laxed conditions to regularize their situation – a lengthy and controversial process that mobilized the civil society and was marked by conflicts between conservationists and the agribusiness sector. The revised BFC, promulgated in 2012 (Brasil, 2012), weakened restoration requirements for noncompliant landholders and granted amnesty to most irregular deforestation prior to 2008 (Soares-Filho et al., 2014).

The 2012 BFC created two sets of rules, not mutually exclusive, to address conservation and compliance in private properties (table S2). The first regulates the conservation of forest remnants. The second specifies the minimum requirements noncompliant landholders must conform to become law-abiding. As a first step, landholders must submit georeferenced information of property boundaries to a countrywide land registry (i.e. Environmental Rural Registry - CAR, Portuguese acronym) planned to support the BFC monitoring and enforcement. Next, the roadmap to compliance should be detailed in a 20 years length plan for environmental regulation (i.e. PRADA, acronym in Portuguese) (table S1) (Brancalion et al., 2016a) with strategies including on-site (i.e. forest recovery) or off-site compensation (Oakleaf et al., 2017). The PRADA must conform to the Program for Environmental Regulation (table S1; i.e. PRA, Portuguese acronym), a state level legislation guiding the application of the BFC, ideally tailored to maximize law compliance and lateral benefits of the law implementation in each federal state (table S3). If regulated and enforced, the BFC may promote on-site forest recovery through either native or mixed species forest reestablishment, and off-site forest recovery or forest conservation when the compensation pathway is chosen for compliance. Areas deforested before 2008 could either be recovered on-site or compensated off-site, but on-site forest reestablishment is mandatory for areas deforested after 2008 (Brasil, 2012).

Although off-site compensation precedes the 2012 BFC (e.g. prior to 2012, noncompliant farmers could acquire properties with exceeding forest to solve their deficits), the current version of the BFC institutionalized tradable certificates of private protected and unprotected forests framed within Environmental Reserve Quotas (table S1; i.e. CRA, Portuguese acronym), that is, eligible to be used for off-site compensation. The CRA mechanism was created to be a cost-effective strategy for deficit compensation through the acquisition of forest certificates based on predefined duration contracts. Landholders can indistinctively use old-growth and secondary vegetation, at any stage of recovery, to compose their properties' LRs (Article 46, Item I of the Law N. 12767/2012). A priori, tradable certificates may also be issued from regrowing vegetation areas, unless state PRAs explicitly oppose, as it is the example of Mato Grosso do Sul (Mato Grosso do Sul State Decree 14,722 of 2015).

In 2017 a federal plan named PLANAVEG was launched (Brasil, 2017), with the aim of enabling the 12 Mha restoration target under the terms of the BFC and aligned with the Brazilian NDC (Celentano et al., 2017). Policy implementation is strategic for achieving the NDC's targets, as Brazil's pledges are not conditioned to international funding. It will be necessary to set a baseline for old-growth and regrowing forests on private rural landholdings from which to estimate the policies' contribution to forest expansion. This information is crucial to guide the regulation and execution of mitigation plans based on the BFC.

Yet, despite their promising role, RFs are poorly addressed by the BFC and other pieces of environmental legislation in Brazil (Vieira et al., 2014). The BFC does not provide a definition of regrowing forests, nor clarifies how to monitor and enforce their protection. In addition, state-level regulations make superficial mentions to recovering forests, their definition and protection status and eligibility to compose LRs or to be used as compensation assets (table S3). No technical guidance is provided on how to identify such regrowing forests (e.g. temporal or biophysical criteria), except for the state of Pará (State Law IN-08 of 2015). As legal definitions are vague, landholders may fear ambiguous interpretations of the BFC concerning the use and potential protection of RFs for compliance with the BFC or show resistance to engage in new alternatives for compliance (Pacheco et al., 2017).

As a first step to include forest regrowth in the discussion about the BFC implementation, it is important to understand where RFs may contribute the most to the BFC compliance and how it may interfere with the offer and demand for forest certificates, either increasing competition with unprotected old-growth forest (OGF) surplus or as a compensation choice in states with limited certificate offer. Dependent upon the CRA trade regulatory settings, the increased offer of certificates issued from regrowing forest areas may decrease the appeal of the CRA market for certificates issued from unprotected old-growth – carbon rich – forest areas. Therefore, we designed this analysis to consider plausible outcomes of different regulatory settings, implementable by the states PRAs, to better understand the potential role of RFs for law compliance, forest conservation and carbon storage. The guiding research questions were:

(1) How does the inclusion of RFs in LRs changes the BFC forest balance? How much LR deficit can be offset by on-site regeneration?
(2) How much do certificates issued from OGF and RFs contribute to BFC compliance under different regulatory setups of CRA market restriction, excluding or including ongoing regeneration from LRs and from forest certificates?
(3) How much forest carbon would be offset and protected under different regulatory setups of CRA market restriction, excluding or including ongoing regeneration from LRs and from forest certificates?

2. Materials and methods

2.1. Study area

We focused on private rural properties in the Amazon Biome which intersects the nine federal states composing the Brazilian Legal Amazon (BLA) (Fig. 1a). Most of the study area is covered by humid tropical forest, but significant portions are covered by savannas or grasslands (figure 1b – Non-Forest class). Forest loss advances from East to West and South to North, along major roads, concentrated in the states of Pará (PA), Mato Grosso (MT) and Rondônia (RO). Eighty percent of the original forest cover is standing, and 22% of the cleared area is covered by secondary vegetation with different levels of recovery (INPE, 2014a, INPE, 2014b).

2.2. Estimating forest deficits and forests apt for issuing certificates at property level

We quantified forest deficits and forest cover eligible for issuing certificates (i.e. CRAs) in rural properties, based on the conservation and regularization (compliance) requirements established by the revised BFC (Brasil, 2012) (table S2). For each property, we divided forest stocks in three categories (a) LR non-eligible for issuing CRAs, (b) LR eligible for issuing CRAs (i.e. protected private forest), and (c) forest surplus exceeding the 80% LR requirements, eligible for issuing CRAs or for conversion to other land uses (i.e. unprotected forest surplus) (see table S1 for definitions of forest stocks categories). We also identified and divided forest shortfall (deficit) in two categories: (d) LR deficit qualified for on-site or off-site offsetting, and (e) post-2008 deforestation, where on-site forest reestablishment is mandatory (table S2, figure S1). First, we estimated the five categories (a–e) mentioned above considering only OGF stocks inside properties. Next, we calculated the contribution of regrowing forests to the BFC balance including RFs areas in forest stocks. From that we estimated how much of the area deforested after 2008 is currently regrowing and how much additional on-site forest regeneration is required to achieve LRs compliance with the BFC.

LRs are placed by landowners at their determination, contingent on government approval. However, for this study, we mapped LRs based on forest extent inside properties, identified by overlaying land cover maps with property boundaries. We did not distinguish between forests located in LRs and in PPAs, meaning all forest stocks add up to LRs, which is aligned with Art. 15 of the BFC that made admissible the inclusion of PPAs in LRs to reduce landholders' deficits. We did not calculate PPAs deficits, which have a specific location at environmentally fragile areas inside properties as they could not always be captured by the spatial resolution used in our study (e.g. riparian protected areas may be wide as 5 m, while our analysis spatial resolution is of 100 m).

We applied a collection of spatial datasets, resampled to a 100-meters resolution, including individual property boundaries, forest and land use cover with 2014 as a base-year. We downloaded individual rural properties included in the CAR (SICAR, 2017) before December 2016. Current regulations determine that all the landholders must register their properties before December 31st, 2019, to compose a provisional CAR. One important disadvantage of the CAR data is that, at this provisional stage, there are no impediments to the inclusion of false or conflicting information (e.g. overlapping properties, double registry). Therefore, after downloading the dataset, we removed inconsistencies that led to the reduction of properties included in the study from *n-Initial* = 420,778 to *n-Final* = 255,224 (figure S1) covering 15% of the Amazon biome. We also collected information on protected areas, indigenous lands, and military areas – considered as public areas destined to conservation (Fig. 1a, table S4), and consolidated areas for agriculture (FUNAI, 2017; MMA, 2017b). These were used to calculate the varying BFC conservation requirements for the individual properties depending on their location and the municipality forest protection level. (figure S1; table S1-S2 and-S4).

To quantify OGF area per property, we used old-growth forest cover and deforestation data (Fig. 1b; table S4) annually provided by the National Institute for Space Research (INPE) through its deforestation monitoring program (PRODES) since 2000 (INPE, 2014b). We distinguished between deforestation occurring before and after 2008, the year established as a threshold to grant access to relaxed terms for compliance according to the BFC (e.g. amnesty for small landholders, access to compensation via forest certificates – CRA, see table S2, "RL – Regularization Regime").

RFs cover was also obtained from INPE, through the TerraClass

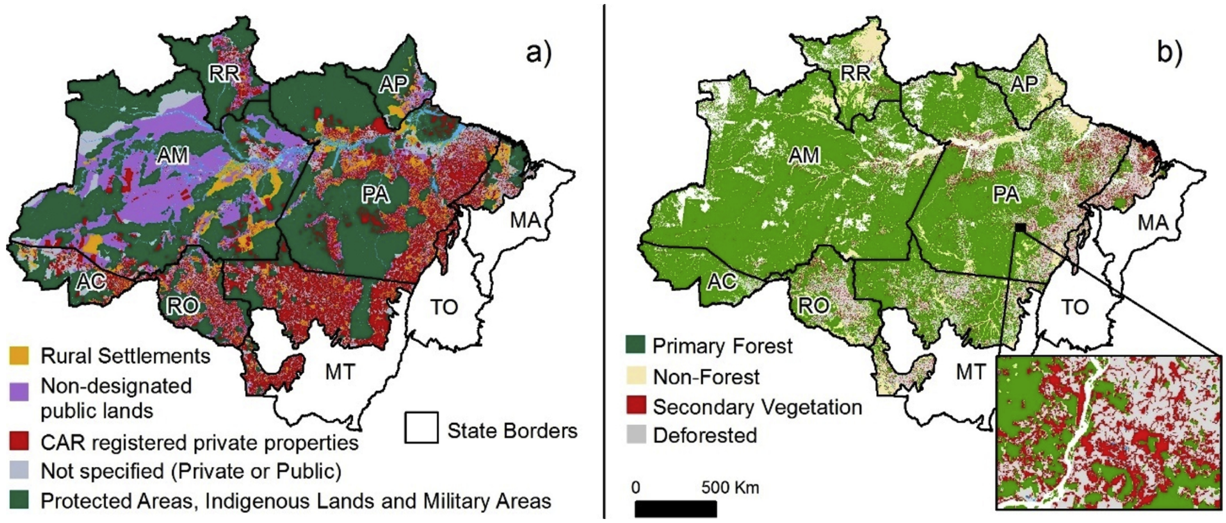

Fig. 1. Study area (a) Land Categories and (b) Forest Cover, old-growth and secondary– detailed view showing secondary vegetation spatial patterns; AC = Acre; AM = Amazonas; AP = Amapá; MA = Maranhão; MT = Mato Grosso; PA = Pará; RO = Rondônia; RR = Roraima; TO = Tocantins. Data sources: FUNAI, 2017; MMA, 2017b; INCRA, 2017; INPE, 2014a, INPE, 2014b.

project (INPE, 2014a). This project mapped post-deforestation land use and cover, including "secondary vegetation" and "pasture covered by forest regrowth" classes, for the Brazilian Amazon for five time-steps (e.g. 2004, 2008, 2010, 2012, and 2014). We used this information to derive RFs cover area and age (i.e. annual landscape permanence time of forest regrowth per pixel) in the Amazon. Supplementary table S4 details our dataset. We only considered forestlands, and excluded properties overlaying savannah or natural grasslands from our analysis, using the PRODES forest-non-forest mask as reference. This decision was made due to the absence of spatial information on land use and cover for vegetation types not included in the current monitoring systems (INPE, 2014a, INPE, 2014b).

We conducted one additional BFC balance analysis excluding secondary vegetation mapped with less than 5 years of prevalence in the landscape by 2014 To avoid the inclusion of fallow lands mapped as "secondary vegetation" by TerraClass. We used a 5-years temporal criterion based on studies which have identified that for some regions of the Amazon, the average permanence time of RF in the landscape is 5 years (Aguiar et al., 2012; Müller et al., 2016; Schwartz et al., 2017).

2.3. Designing alternative regulatory setups

To support the discussion on the impact of including RF certificates in a CRA market, we considered eight different regulatory setups (Fig. 2; see table S5 for a description of the eight regulatory setups applied). This exercise allowed us to understand the impact of different regulations on compliance and conservation additionality under market implementation. These setups combine three variables: (a) the eligibility of certificates issued from RFs; (b) the spatial coverage of the market (i.e. either restricted to federal state boundaries or open for trade within the biome); and, (c) the protection status of forest certificates (i.e. from protected private forests or from unprotected forest surplus).

In a self-regulating market the CRAs issued from unprotected private forests would have higher prices than those issued from protected private forests which, by definition, do not allow alternative land uses, hence have very low opportunity costs. Therefore, we assumed that CRAs issued from protected forests would be absorbed first by the market, in detriment of unprotected, more expensive CRAs. We used the following hierarchy to calculate the BFC balance for our market regulatory setups: old-growth protected forest → regrowing protected forest → old-growth unprotected forest → regrowing unprotected forest.

2.4. Carbon storage quantification and sensitivity analysis

We estimated current (actual) carbon stocks in OGFs and RFs and the potential carbon sequestration by RFs and forest deficits recovery; these values supported a discussion about the potential of the BFC for private forests carbon protection and sequestration under the implementation of the proposed market regulatory setups.

We used above and belowground biomass maps provided by the Third Brazilian Emissions Inventory (Brasil, 2016) as a reference to extract average forest carbon density (tons per hectare) for each landholding. The inventory maps provide original biomass values, expected to occur in undisturbed forests. The biomass estimates are based on a large compilation of plot level and literature data made spatially explicit using geostatistical methods. Other carbon pools such as understory, fine litter and soil carbon were not included.

Total carbon stocks were estimated for each of the private forest categories (i.e. protected forest not eligible for issuing CRAs, protected forest eligible for issuing CRAs and unprotected forests) -, and deficits (i.e. deficits offsetable on-site or off-site and deficits from post-2008 deforestation). To calculate total carbon stocks in OGFs and the potential carbon sequestration by RFs and deficit restoration we multiplied the biomass density by the forest cover or deficit extent. We transformed biomass values to carbon content using a conversion factor of 0.5. Current carbon stocks in RFs were obtained as described by Eq. (1), where pristine "carbon" density values were multiplied by an annual biomass accumulation rate "R" of 1.2% (Lennox et al. 2018) and by RFs age "i" values obtained by overlaying the bi-annual Terra Class maps.

$$\sum_{i=1}^{n} Carbon * R * Age_i \quad (1)$$

Following, we estimate carbon stocks protection and sequestration potential under the different regulations of the CRA market. CRA units are measured in hectares being equivalent on their offsetting purpose but may differ in terms of carbon storage potential. To address this source of uncertainty, we conducted a sensitivity analysis of carbon storage potential of CRAs. We performed 1000 random selections of properties with available certificates adding up to the area required to offset LR deficits in each regulatory setup and reported the mean, maximum and minimum respective carbon stocks from the combinations. The same was done for estimating the carbon sequestration

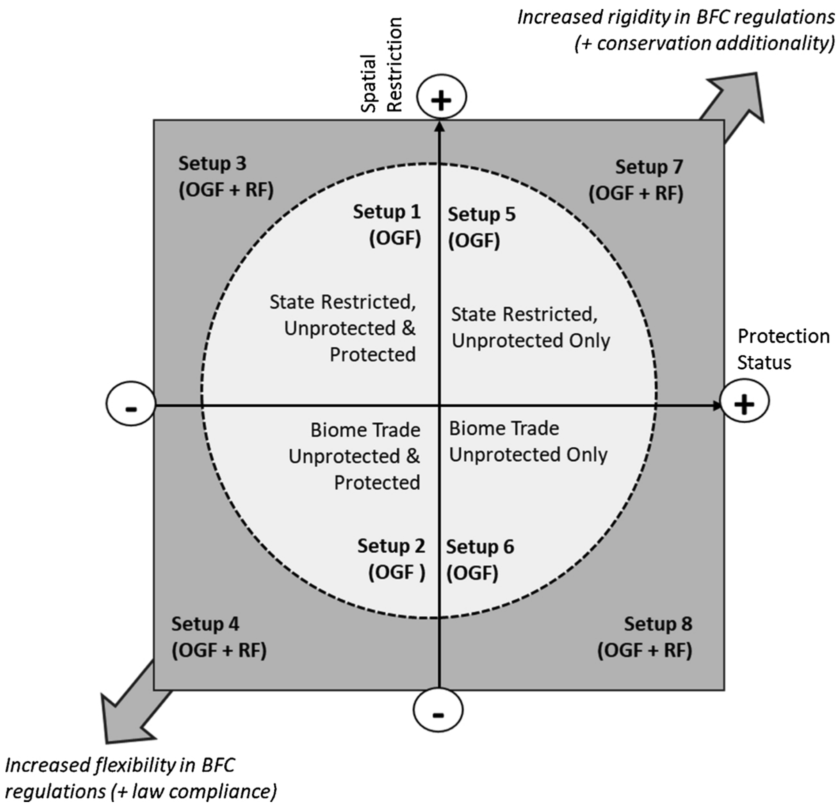

Fig. 2. Combination of spatial and conservation criteria assessed by the regulatory setups for a forest certificate compensation mechanism. *X* axis describes the protection status of forest apt for compensation: on the left, both protected and unprotected forests are allowed, on the right, only unprotected forests; *Y* axis describes the spatial coverage allowed for each regulatory setup: on the bottom, certificate trade is biome-wide, while on the top supply is restricted to state boundaries. The inner circle represents the settings excluding RFs. Large arrows point to the increase in either rigidity or flexibility in trade regulations with outcomes for law compliance and conservation additionality.

potential by properties restoring remaining LR deficits if, according to the regulatory setup, the CRA demand is not covered by certificates availability. Finally, we evaluated the net carbon stocks protection resulting from each of the eight regulatory setups considering two additionality baselines. Baseline 1 considers the demand for certificates issued from unprotected forests as BFC additionality. Baseline 2 considers the demand for certificates issued from unprotected forests, the carbon sequestration from the remaining LR deficits and any protection of regrowing forests as BFC additionality. Results were expressed in carbon dioxide (CO_2) values.

3. Results

3.1. BFC balance at property level excluding and including regrowing forests

We estimated that regrowing forests reduced, on-site, 3.2 Mha of LRs forest deficits. This represents a 35% decrease in offset requirements for private properties analyzed by this study (Fig. 3). Likewise, protected LR eligible for issuing CRAs increased by 3.4 Mha when we included RFs in calculations, adding up to 12 Mha (Fig. 3; Table 1). Finally, including RF areas increased by 0.5 Mha the share of unprotected forests - eligible for legal deforestation in private properties (e.g. located in properties that have over 80% of forest cover and no deforestation since 2008). Most vegetation cover is not apt for compensation under the BFC (24.5 Mha considering only OGFs, and 27.5 Mha considering OGFs and RF areas) (Table 1; Fig. 3). By 2014, one quarter of areas deforested after 2008 were regrowing vegetation (figure S2b) representing a 0.4 Mha reduction in deficits that are non-eligible for offset via extra-property compensation. Restricting our analysis to RFs with a permanence time equal to or higher than 5 years (figure S2a) noticeably decreased RFs contribution to BFC compliance (Table 1; Fig. 3).

OGFs (protected and unprotected) apt for CRA surpass LR deficits in six states (AC, AM, AP, PA, RO, RR); in these states, LR deficit could be totally offset via certificate trade within state borders, without additional certificates issued from RF areas (Fig. 4a). For MT, MA and TO, LR deficits exceed the availability of protected and unprotected CRAs, and regularization will require forest recovery or the acquisition of forest certificates outside state borders. If included, certificates issued from RFs could turn the forest balance positive in MT but would not suffice in TO and MA (Fig. 4b). RFs are mainly concentrated in states with higher forest deficits (MT, MA, PA and RO), and a large deficit reduction could be achieved by conserving RFs areas as LR. Despite having a positive balance, PA has the second largest on-site forest deficit in the Amazon and could increase law compliance by 43% with the inclusion of RFs in LR (1.46 Mha). Deficits reduction were also high in in RO, MT, MA and TO, in relative and absolute numbers. Among the states with less deficits, including RFs in the forest balance calculation substantially reduced the percentage of deficits for RR, AM and AP (Fig. 4a-b).

3.2. Regulatory setups results including and excluding regrowing forests

Fig. 5 illustrates the outcomes of different market regulatory setups (Fig. 2, table S4) for law compliance and conservation additionality. As a rule, a less-restricted market shifted the balance between supply and demand, towards certificate excess. Regulatory setup 3 included OGFs and RFs and hence started with less deficits to offset (4.4 Mha) than regulatory setup 1 (7.1 Mha) meeting most demand for certificates (98%) - even being state constrained -, in comparison to its equivalent (setup 1) which excluded RFs (75%). Regulatory setups 1 and 3 offered some additionality and absorbed 0.8 Mha and 0.5 Mha of unprotected forest certificates, respectively. Regulatory setups 2 and 4 also included protected forests apt for CRAs and did not impose any geographical constraint (i.e. offsetting allowed across the biome). In both setups CRA demand was fully met, indicating that the inclusion of apt protected forests in combination with a biome-wide forest trading scheme counteracts conservation additionality regardless of the inclusion of RFs.

To prioritize additionality, regulatory setups 5 to 8 limit off-site deficit compensation to the acquisition of certificates issued from

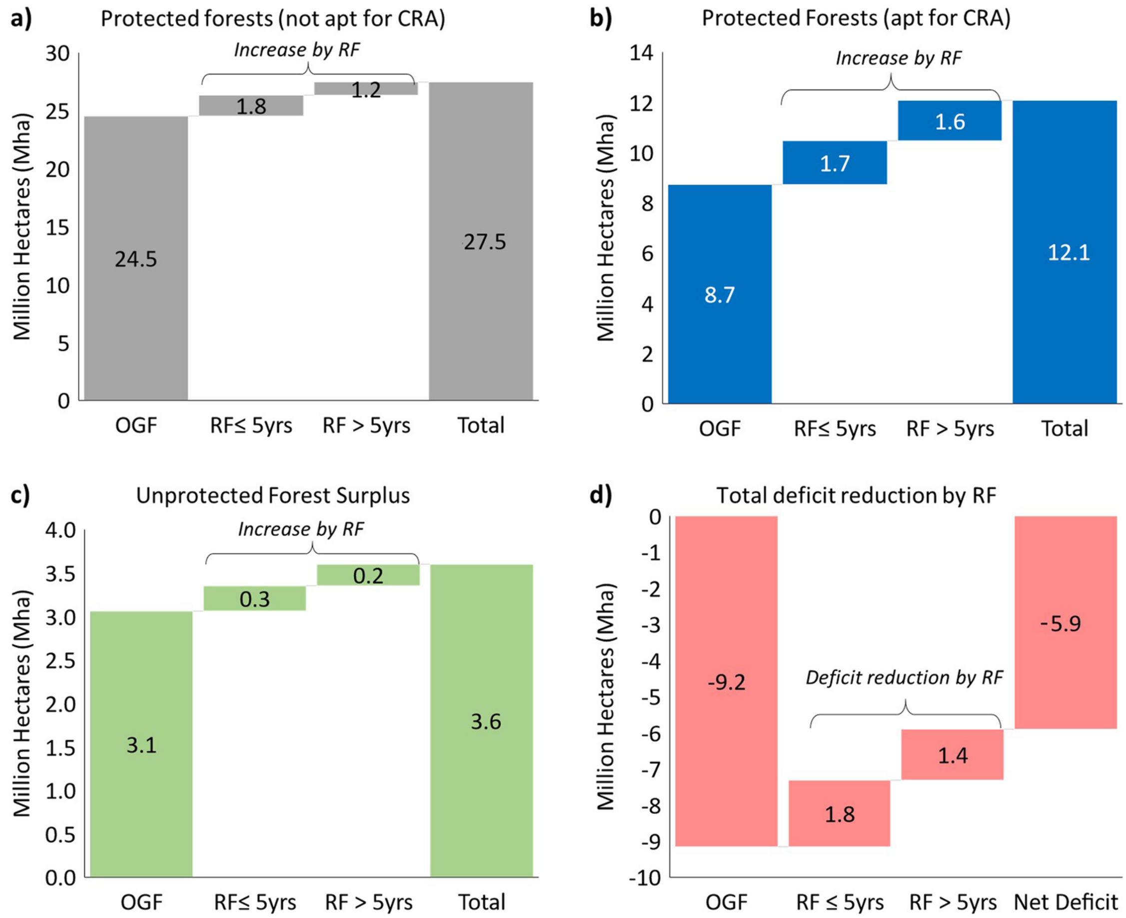

Fig. 3. Increase in area by forest category (a–c) and deficit reduction (d) after including regrowing forests in the forest balance calculations; (d) includes both LR deficits and post-2008 deforestation deficits.

unprotected forest surplus. Despite limiting certificates to unprotected surplus, regulatory setup 5 is unable to absorb the full certificate supply (26% of deficit offset) and, after exhausting compensation possibilities, would require 6.9 Mha of on-site restoration of to achieve full compliance. In this case, opening the trade for the biome (setup 6) would benefit law compliance (69% of deficit offset) and create more opportunities for conservation of unprotected surplus. Finally, regulatory setups 7 and 8 show the potential for an increase in law compliance after the inclusion of RFs certificates. Again, if trade is restricted to certificates from unprotected surplus then a biome-wide market would be able to fully absorb the OGFs and RFs surplus.

3.3. Old-growth and regrowing forests carbon storage quantification

OGF hold the equivalent to 20.7 $PgCO_2e$, while, by 2014, RFs stored 0.2 $PgCO_2e$. If left to regrow, stocks of ongoing forest regrowth could reach 3.8 $PgCO_2e$ (table S6). Most OGF carbon stocks are, in theory, protected by law (91.0%) and are associated with forests not apt (65.5%) or apt for issuing CRAs (25.5%); the remainder (9.0%) are associated with forests eligible for alternative uses (unprotected surplus). If governed by the BFC, RFs potential carbon would be split between non-eligible (41.4%) eligible for compensation (49.6%) and unprotected surplus forests (8.9%).

If the baseline to analyze forest conservation additionality is the increase of protection above the minimum BFC requirement (i.e. 80%), then only regulatory setups 6 and 8 would be able to fully protect the carbon stocks in forest surplus (table S7). All other setups made private properties a net source of carbon, as unprotected forest surplus was not fully assimilated by a CRA market, being left vulnerable to deforestation (table S8). However, if, in addition to forest surplus protection, we consider the attainable (potential) carbon stocks in protected RFs and the recovery of the remaining LR deficits as BFC enforcement

Table 1
Legal reserve (LR), forest categories and deficits classification in million hectares (Mha). (OGF) refers to calculations excluding regrowth; (RF) refers to the contribution of regrowing forests; (RF ≥ 5 yr) refers to the contribution of regrowing forests with permanence time equal or above 5 years.

Forest	Class	OGF	RF	RF ≥ 5 yr	Total (OGF + RF)	Total (OGF + RF > 5 yr)
Forest Categories	Protected forests (not apt for CRA)	24.5	3.0	1.8	27.5	26.3
	Protected forests (apt for CRA)	8.7	3.4	1.7	12.1	10.4
	Sub-Total (Protected)	***33.2***	***6.0***	***3.5***	***39.6***	***36.8***
	Unprotected forest surplus	3.1	0.6	0.3	3.6	3.4
	Total	**36.3**	**6.9**	**3.8**	**43.2**	**40.2**
Deficit	LR deficits (apt for off-site compensation)	7.5			4.6	5.7
	Post-2008 deforestation deficits	1.7			1.3	1.6
	Regrowing in post-2008 deforestation areas		0.4	0.1		

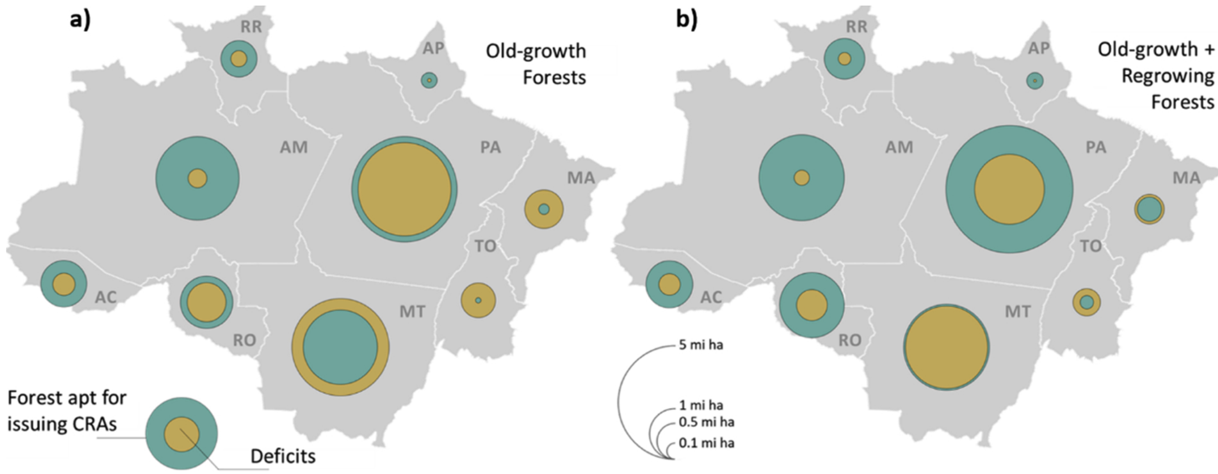

Fig. 4. Forest balance for the analyzed properties per state. The figure does not include forests not apt for issuing certificates. Mustard areas encircling blue areas means the total deficit is higher than the availability of forests apt for CRAs, and the opposite means that apt forest area is higher. Circle sizes indicate absolute area in Mha; (a) forest balance including OGFs only; (b) forest balance including OGFs and RF areas by 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

additionality, then most regulatory setups would present a positive balance with scenario 8 leading to the net protection of 5.0 $PgCO_2e$ (table S7). On the other extreme, for setups 1–4, not even the protection of current carbon stocks in RFs and the recovery of remaining LR deficits would be enough to compensate for the eventual deforestation of unprotected OGF, leading to a negative balance (table S7). A full account of carbon storage for each regulatory setup and different categories for each federal state can be found in supplementary tables 8a-b.

4. Discussion

In this paper we use property-level data to provide the first comprehensive overview of regrowing vegetation potential contribution to compliance with the BFC, contextualizing the socio-environmental relevance that RFs may gain under the BFC implementation. Over 0.4 Mha of forests cleared after 2008 are recovering and could offset 24.7% of the post-2008 deforestation deficit for selected properties (Table 1). An effective implementation of the BFC, supported by the validation of the CAR, should allow the separation between regrowth taking place on properties eligible for off-site compensation and over post-2008 deforested areas, and enforce the protection of RFs where on-site recovery is mandatory. Additionally, if RFs had the same protection status as OGFs, the BFC enforcement could secure the conservation of 6.3 Mha of forests recovering on farms with forest area below conservation requirements (Table 1). This amount exceeds the 4.8 Mha of forest expansion planned to take place in the Amazon (BRASIL, 2017),

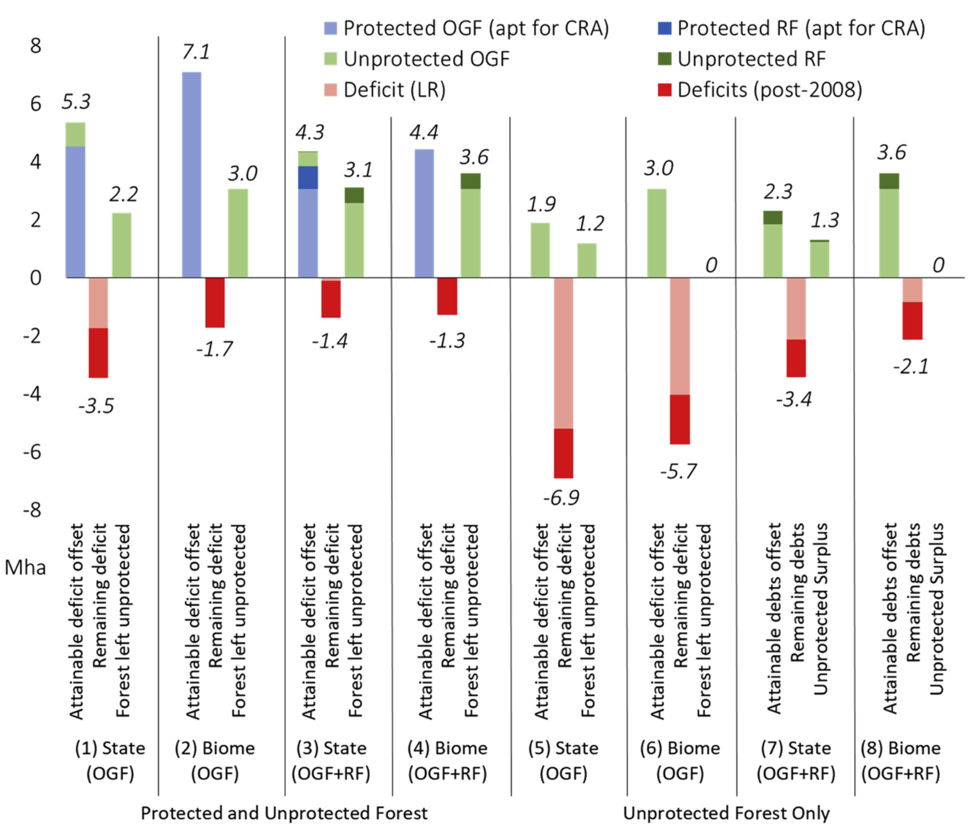

Fig. 5. Effects of tested market regulations on law compliance. *Attainable deficit offset* shows the maximum deficit reduction that can be expected within each setup, with colors highlighting forest stock categories that contributed to compensation. *Remaining deficits* are LR forest shortages that could not be offset given the market regulations. *Forest left unprotected* equals the amount of forest surplus that would not be assimilated by the market being left unprotected (see table S2 for forest stock categories). As regulatory setups 1–2, 5–6 exclude on-site regeneration from LRs, the initial demand for forest certificates totaled 7.1 Mha. Regulatory setups 3–4 and 7–8 include RFs in LRs, which resulted in a lower demand for forest certificates (4.4 Mha). (OGF) refers to setups in which only old-growth forests were considered in the BFC balance calculations; (OGF + RF) refers to setups in which old-growth forests and RF were considered in the BFC balance calculations.

which emphasizes the huge potential that a careful regularization (and enforcement) of RFs protection may have for promoting large scale forest restoration. However, current federal and state legislations do not make clear if and how RFs located in properties with LRs below the 80% cap should be protected by the BFC (table S3).

An excessively flexible CRA market may represent a missed opportunity for the protection of 1.9 PgCO2e stored in unprotected OGFs (table S7). Our results show that the inclusion of RFs in LRs can decrease deficits on-site, which, further combined with lenient CRA trade regulations has the potential to fully solve offsetable deficits, at the expenses of unprotected OGF conservation (setups 2–4, Fig. 5, table S7). This reinforces that regulations should be based on an understanding of the potential role a state may play as a supplier or buyer of CRA (Gasparinetti and Vilela, 2018) and, ideally, prioritize deficit compensation with OGF surplus in detriment of protected or RF certificates. States with high CRA offer and little demand (e.g. Amazonas) should restrict the market to the state area, but issue OGF certificates to be traded with states with high demand for CRAs (e.g. Mato Grosso). Such strategy could make the CRA market a more attractive option for landholders with use rights over unprotected OGFs to negotiate their surpluses. Additional programs for payment for ecosystem services might also be a promising alternative to compensate OGF conservation that can easily be implemented using the CRA trade platform (Soares-Filho et al., 2016).

As Freitas et al. (2017a), we found that private properties are critical for the conservation of OGF carbon stocks in the Brazilian Amazon, stressing the importance of BFC compliance. Despite the expressive contribution of RFs for the increase in BFC compliance, we found that current (actual) carbon stocks in RFs are nearly negligible when compared to carbon storage of OGFs and add little change to the regulatory setups carbon balance. This is mostly due to the young age of RFs (Figure S2a). Important to highlight, the lack of a longer time series of RFs age information likely led to an underestimation of our carbon sequestration estimates in RFs. However, if we consider the attainable carbon storage by RFs, their future contribution would be expressive, leading to a threefold increase in the protection of carbon stocks in setup 8, baseline 2, for example (table S7).

Our results are consistent with previous studies, which found an imbalance between forest certificates offer and demand (i.e. deficits), possibly leading to an oversupply of forest certificates under a biome-wide market setup. Still, these assessments used different methods, datasets and assumptions, making direct comparisons tricky (table S8). First, previous estimates of the BFC balance either excluded RF (Freitas et al., 2017b; Soares-Filho et al., 2016) or did not discriminate it from OGFs (Nunes et al., 2016; Soares-Filho, 2013), whereas we make this distinction explicit and highlight the implications of a differentiation between old-growth and secondary vegetation. Second, we covered less area than most analysis, as only properties registered within the CAR were included. Other studies circumvented this limitation simulating properties for the remainder of the non-registered area (Freitas et al., 2017b; Micol et al., 2013) or using other spatial units as proxies for properties (Martini et al., 2015; Soares-Filho et al., 2014). This explains why our estimated CRA offer and forest deficits are smaller than calculated by other studies (table S9).

We found a smaller certificate “offer-demand ratio” than previous research (table S9). This is likely because we assessed rural settlement properties’ individually (i.e. they are included if registered within the CAR), while other studies calculated the forest balance for whole settlements as units. Depending on the premise of the study (i.e. if settlements can supply certificates for the CRA market), rural settlements add substantial area to the pool of protected forests apt for compensation, and very little to deficits (Brito, 2017). In addition, the full inclusion of rural settlements by other studies partially explains the higher proportion of protected forests apt for compensation than unprotected surplus in previous reports in comparison to this study (Micol et al., 2013; Nunes et al., 2016; Soares-Filho et al., 2014) (table S9).

There are high uncertainties regarding the lawfulness of CAR entries located in public non-designated areas, which later may not be recognized as private (e.g. might be designated as indigenous or protected areas). This means that we might have overestimated unprotected surpluses from properties registered in public lands, especially properties located in remote, forested areas. Other studies dealt with this limitation either excluding the full surplus of states with large tracts of non-designated public lands (Soares-Filho et al., 2014) or blocking the simulation of properties in areas with more than 95% of forest cover (Freitas et al., 2017b). Different to these analyses we decided to include all the CAR entries to support the discussion based on the most accurate property level information available but highlight the respective uncertainties inherent to the data.

4.1. Challenges for implementation

Recent research supports the hypothesis that landholders might use ongoing forest-recovery to solve their deficits under certain conditions (Pacheco et al., 2017). In the Brazilian Amazon, regrowth usually takes place on marginal lands, where expected returns are sufficient to drive deforestation, but actual profits do not compensate production costs (Costa, 2016). These areas may present a high aptitude for natural (passive) regeneration, which needs less investment compared to active restoration strategies required to recover very degraded ecosystems. In fact, a recent policy brief assessed that 60% of forest deficits in the Amazon have high potential for recovery through natural regeneration (MMA, 2017a). If provided with the necessary incentives (i.e. facilitated access to credit lines, participation in complementary PES schemes), a large share of RF could be preserved at low costs. In this regard, synergies between agriculture and environmental policies are expected and could be beneficial. Synergistically with the BFC enforcement, the Low Carbon Agriculture Program created a credit line to support LR and APP recovery in rural properties, aligned with the objectives of the PLANAVEG and the Brazilian NDC. However, in 2017 only 1% (US $4 M) of the available resources was granted for this purpose. Therefore, the protection of regrowing vegetation depends upon the opportunity costs of lands where regrowth is taking place compared to the perceived noncompliance costs (i.e. credit restriction, fines). If the opportunity costs exceed the perceived compliance costs, it is not reasonable to expect that regrowing areas will be spared, as discussed by Aguiar et al. (2016).

The BFC still lacks mechanisms to support the protection of recovering forests (Garcia et al., 2016; Metzger et al., 2010) making state legislations key instruments to enable restoration targets. First, it is necessary to provide a comprehensive definition of second-growth forests to be protected, supported by forestry and ecological parameters. Such parameters should ideally support monitoring systems using remote sensing products to allow law enforcement and avoid conversion of second-growth forests. The protected status of second-growth forests should also be sensitive to social actors’ practices distinguishing fallowing from land abandonment, to avoid the imposition of complicated licensing schemes on smallholders practicing swidden agriculture, that depend on cyclic forest regrowth, and avoid negative social impacts (Aguiar et al., 2016). A revision of the state-level PRAs showed a few legislations already place second-growth forests as native vegetation, differentiating them from degraded lands, but only the state of Pará details which second-growth forests should be protected and clearly establishes that issuing CRAs from RFs is allowed (table S3). Therefore, state laws should also regulate the use of RFs on LRs and compensation schemes to avoid competition with OGFs in the CRA market.

Despite the potential availability of apt RFs, we argue that a massive inflow of certificates issued from RFs to a CRA market is unlikely under any of the analyzed regulatory setups. The increasing scarcity of land for agricultural expansion, combined with the legal uncertainty of RFs protection and a saturated CRA market (e.g. setups 3–4), may direct landholders to use current secondary forests to expand productive area. With less land available, it is doubtful that farmers will source unprotected OGF, let alone their RF surplus for trade at an oversupplied market offering small prices for certificates. This suggests that inequality reduction and income redistribution may be a limited cobenefit of a CRA market in states where smallholder forest certificates offer is dominated by RFs, such as TO and MA (figure S3). Freitas et al. (2017b) suggest that one alternative to promote social welfare through the BFC implementation would be to restrict the market to smallholdings. This could be one example of a policy tailored to target smallholders, less responsive to past policies directed to reduce deforestation (Godar et al., 2014; Richards and VanWey, 2016). Other factors limiting farmers adherence to the certificate market could be land tenure insecurity (Brito, 2017) or the lack of knowledge about the system (Rasmussen et al., 2016).

4.2. Study limitations and recommendations for future research

The BFC balance and market regulatory setups analyzed by this study are intended to be illustrative of the potential RFs offer to increase law compliance and carbon storage. However, there are no guarantees that RFs mapped by TerraClass are suitable for supporting a successful forest restoration plan. Mapping RFs is a central challenge (Caviglia-Harris et al., 2014), and despite being a big step forward for vegetation regrowth monitoring, the TerraClass product has limitations. TerraClass does not rely on information about successional status or land use history to detect forest cover expansion. For example, Nunes et al. (2016) found that large areas of RFs mapped in 2010 had been deforested only two years before, which is incompatible with the advanced stage of recovery TerraClass claims to detect (Almeida et al., 2016). Research relying on long-term time-series of satellite data could offer more consistency and allows to track indicators of RFs successional stage, such as time since abandonment (Carreiras et al., 2014; Müller et al., 2016).

We calculated LR forest deficits based on an accumulated clear-cut deforestation map, which does not include forest losses due to degradation processes that may also require restoration. Between 2007 and 2013 OGF degradation from fires or logging affected nearly twice the (clear-cut) deforested area in the Brazilian Amazon (INPE, 2014c). This makes degradation processes a non-negligible source of carbon as well as a potential sink under an efficient forest governance scenario (Aguiar et al., 2016). However, as we lack up-to-date information on forest degradation, as well as regrowth dynamics following forest degradation, this remains an information gap to be addressed by future studies.

Forthcoming improvements of the CAR dataset may impact future assessments of the BFC balance. The CAR, as made public by the Brazilian Government, does not include property ownership information. Such data is important to accurately assess the extent of forest deficits and eligible area for issuing CRAs as landowners may purchase multiple properties to offset deficits from landholdings with LR area below the required cap. We stress that a thorough policy evaluation will benefit from property ownership data transparency. This holds true not only for BFC analyzes but also for related policies (e.g. Soy Moratorium) (Gollnow et al., 2018). Additionally, the CAR validation should solve current data inconsistencies (i.e. overlapping properties, duplications or false geometries) and allow the inclusion of all properties submitted to the SICAR system (SICAR, 2017) in BFC assessments.

In this study we mapped ongoing recovery potential contribution to law compliance, OGFs and RFs (and associated carbon stocks) conservation. However, despite the enthusiasm on the potential offered by passive (natural) forest recovery (Crouzeilles et al., 2017) an effective cross-sector implementation of the BFC (with other policies covering forest recovery and climate change) would strongly benefit from an investigation of synergic combinations of OGFs and RFs conservation and forest restoration based on indicators at multiple scales. For example, several recovering forest-patches may have been abandoned due to an advanced stage of soil degradation, and, therefore, could require more intervention than passive restoration offers. On that matter, Arroyo-Rodriguez et al. (2017) stressed that forest succession is driven by numerous factors interacting across local, landscape and regional levels. Future strategies for large-scale forest recovery should consider the synergies between land use and intensity history, forest connectivity, law compliance, carbon storage potential, topography and ecoregional conservation status.

5. Conclusions

Geospatial information on property level have been enabling rigorous examinations of land use policies, including the BFC. Building up on previous detailed assessments our analysis shed light on an important aspect of the BFC law implementation: the contribution of ongoing forest recovery to the offer of forest certificates and forest deficits offsets across properties in the Brazilian Amazon. Our findings suggest that RFs may play an important role on deficit offsetting and forest certificates supply. Most important, policy outcomes differed drastically among the regulatory setups of the forest certificate trade mechanism here analyzed. Our results call attention for the need to explicitly include regrowing forests in BFC balance assessments, to support the design of state specific policies to maximize synergies between BFC law compliance, conservation additionality and forest recovery in highly degraded ecosystems.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2019.104163.

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