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Article

The Scope for Reducing Emissions from Forestry and Agriculture in the Brazilian Amazon

Jan Börner * and Sven Wunder

Center for International Forestry Research (CIFOR), Rua do Russel, 450/sala 601, CEP 22.210-010, Rio de Janeiro, Brazil; E-Mail: s.wunder@cgiar.org

* Author to whom correspondence should be addressed; E-Mail: j.borner@cgiar.org;
Tel.: +55-21-2285-3341; Fax: +55-21-2285-0447.

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Abstract: Reducing emissions from agriculture, forestry, and other land uses is considered an essential ingredient of an effective strategy to mitigate global warming. Required changes in land use and forestry, however, often imply foregoing returns from locally more attractive resource use strategies. We assess and compare the prospects of mitigating climate change through emission reductions from forestry and agriculture in the Brazilian Amazon. We use official statistics, literature, and case study material from both old and new colonization frontiers to identify the scope for emission reductions, in terms of potential additionality, opportunity costs, technological complexity, transaction costs, and risks of economic and environmental spillover effects. Our findings point to a comparative advantage in the Brazilian Amazon of forest conservation-based over land-use modifying mitigation options, especially in terms of higher potential additionality in emission reductions. Low-cost mitigation options do exist also in use-modifying agriculture and forestry, but tend to be technologically complex thus requiring more costly intervention schemes. Our review points to a series of regional development deficits that may come to hamper attempts to tap into the large-scale climate change mitigation potential often associated with the Amazon. Low-hanging fruits for mitigation do exist, but must be carefully identified based on the performance indicators we discuss.

Keywords: climate change mitigation; technology adoption; opportunity costs; Latin America

1. Introduction

Under the emissions from agriculture, forestry and other land uses (AFOLU), reducing emissions from deforestation and forest degradation (REDD+) is expected to tap the large mitigation potential of conserving and better managing the world's forests, predominantly in tropical countries. Recent emission data suggest that forest loss contributes less to global anthropogenic greenhouse gas (GHG) emissions than had been estimated in the Intergovernmental Panel on Climate Change (IPCC) 2007 assessment report [1,2], but AFOLU emissions from tropical countries, including methane (CH_4) and nitrous oxide (N_2O) predominantly from agricultural land, still represent 31% of total global anthropogenic GHG emissions [3]. The relative importance of emissions from agriculture has therefore spurred renewed interest in agriculture-based climate change mitigation.

In 2007, FAO's The State of Food and Agriculture report emphasized the large potential for encouraging farmers to provide ecosystem services, including climate change mitigation, using payments for environmental services (PES) in agriculture as the key instrument. Several analysts have thus called for a whole-landscape perspective to AFOLU-based climate change mitigation as a response to the diverse interrelated factors that contribute to emissions from agricultural and forested land [3,4].

Operationalizing whole landscape management could essentially involve two types of interventions: (1) reducing agricultural expansion, increasing cropland retirement, and forest conservation; *versus* (2) changing production technologies and practices. Accordingly, Zilberman *et al.* [5] distinguished between "land-diversion schemes" where land is set aside for conservation, and "working-land schemes" that change production practices and technologies to achieve mitigation objectives. In the following, we employ the related terms "*use-restricting*" versus "*use-modifying*" to distinguish between the two intervention types.

In tropical countries, current mitigation initiatives rely preferably on use-restricting, often forest- or forestry-based interventions [6]. Notable exceptions are use-modifying afforestation and reforestation (A/R) schemes strategies. However, even forestry-based mitigation has been ridden with obstacles. A/R initiatives as the only AFOLU measure eligible under the Clean Development Mechanism (CDM) of the Kyoto Protocol, account for only 39 out of 3,379 registered projects approved since the CDM's inception [7]. Complicated rules and high transaction costs have been binding constraints, and pilot experiences were often confined to the voluntary market [8].

Beyond assessing the biophysical mitigation potential, we thus obviously need to understand potential implementation barriers to alternative AFOLU-based mitigation options in concrete contexts, before we can consider starting points for action. This paper seeks to identify possible low-hanging fruits for climate change mitigation among dominant AFOLU activities and popular alternatives in the Brazilian Amazon region. Based on this scoping assessment, we point to some implications for the design of intervention strategies.

A key criterion for setting priorities among alternative mitigation options is cost-effectiveness. AFOLU-based mitigation cost-effectiveness can be defined as follows:

$$CE = (BP - L)/(OC + IC) \tag{1}$$

where CE = cost-effectiveness; BP = biophysical mitigation potential (tCO_2); L = leakage (tCO_2); OC = opportunity costs (\$); and IC = implementation costs (\$). All variables on the right-hand side of Equation (1) are subject to measurement and other uncertainties. Ideally, a mitigation option would thus:

(1) Come with high biophysical potential for emission reductions;
(2) Be adoptable at low opportunity costs and low risk of economic failure;
(3) Be carried out at low implementation costs;
(4) And disseminated with low risk of negative spillover effects, e.g., leakage.

Hence, a holistic assessment of mitigation potential goes beyond the biophysical and technological characteristics of different mitigation options; it is also inherently related to intervention design and the local context.

The paper is organized as follows: Section 2 provides a short overview of the Amazon region, and the Brazilian Amazon in particular, and presents the methodologies and data sources used. In Section 3, results are presented according the four intervention criteria sketched above. Section 4 concludes with a discussion of implications.

2. Study Area, Methods and Data

The Amazon forest is the largest continuous tropical rainforest on the planet. Between 1989 and 2009, a forest area equivalent to the size of Germany (357 thousand square kilometers) was converted to pastures and agricultural crops in the Brazilian Amazon alone. Here, carbon emissions from deforestation were for 1998–2007 estimated to account for 24% of global carbon emissions from land-use change [9], but have reduced considerably after 2004 as deforestation dropped sharply [10]. Enteric methane emissions from its 57 million cattle herd also contribute substantially to agricultural GHG emissions in the region. In countries with large Amazon territories (Bolivia, Brazil, Colombia, Ecuador, and Peru), combined AFOLU emissions account for over 83% of total GHG emissions, thus representing the single most important sector for climate change mitigation in the region [11].

Land-cover and land-use change in the Amazon have historically been most dynamic in Brazil, with cattle pasture expansion being by far the most important driver of forest loss [12]. Apart from cattle ranching, commercial agriculture, small-scale slash-and-burn farming, wildfires, and timber extraction have shown to be significant sources of emission through deforestation, forest degradation, and the use of fire for land preparation [9,13–16].

Considerable research has been done not only on the prospects of use-restricting conservation schemes in the Amazon, but also on potential use-modifying technological fixes to high GHG emissions, e.g., on intensified cattle production, minimum-tillage cropping, agro-forestry, sustainable forest management, and reduced impact logging. An important part of this research remains confined to the grey literature, which has thus also been consulted for this study. Yet, very few *in situ* experiments of agricultural innovations exist, and average yield or benefit-cost ratio estimates from controlled field trials seldom allow for realistic comparisons with on-farm established technologies.

As a result of this bias towards controlled field trials, cost-benefit analyses often suggest technological innovations to be both economically (e.g., per-hectare profits) and environmentally (e.g., per-hectare emissions) superior to established practices. In practice, however, adoption rates remain low, such as in the case of agro-forestry systems. Meanwhile, according to the latest Brazilian Agricultural Census in 2006, some technological innovations such as no-till cropping quickly disseminated among commercial farms over the whole region, and now predominate over traditional soil preparation practices. In other words, technological change does happen in the Brazilian Amazon, but currently our analytical means to fully understand and predict it based on economic and environmental indicators are rather limited.

In what follows, we thus identify broad-based tendencies (best bets) with respect to the four mitigation option characteristics outlined above, based on the available literature and secondary data. For each AFOLU mitigation option, we proceed as follows. We first derive indicators of the biophysical mitigation potential of different land-use and technology transitions. Second, transitions with likely emission reduction potentials are then scrutinized for foregone profits or opportunity costs. Third, we establish a simple conceptual framework explaining the cost of implementing these interventions. Finally, we briefly discuss likely spillover effects for selected options.

3. Results

3.1. Biophysical Mitigation Potential

Assessing the mitigation potential of alternative AFOLU options first requires looking at envisaged changes in carbon stocks, as well as other emission sources. AFOLU alternatives can differ in terms of carbon stored in the below- and above-ground biomass that vary over time due to land-cover change, growth, fire, and harvest/management cycles. Biomass burning and decomposition cause emissions, whereas biomass growth removes carbon from the atmosphere. Land use and land-use change also affect the gas exchanges between soil and atmosphere and cause emissions, e.g., through biological processes and fossil energy use in primary production phases and further up the value chain.

Due to climatic and, biogeochemical characteristics, and a variable history of human interventions, below- and above-ground biomass is highly heterogeneous across the region. Above-ground live biomass in dense forests is estimated at on average 276 t/ha (approximately 138 tC), but below 50 t/ha in young secondary forests and savanna-type ecosystems [17,18]. Closed natural forests dominate the Amazonian landscape in the Central and Western Amazon, whereas agriculture-pasture-forest mosaics are typical landscape features in the southern and eastern parts. Annual and semi-permanent bush crops can hold up to 5.3 t/ha in their above-ground biomass, whereas permanent tree plantations such as oil palm can reach 57 t/ha [19] (Table 1).

Below-ground biomass density of natural vegetation differs primarily as a result of soil and climatic conditions. Nepstad *et al.* [20] have shown that evergreen forests in the Eastern Amazon have developed particularly deep and biomass-rich root systems in response to seasonal droughts that are more pronounced than in the Western Amazon. The largest soil carbon pool, however, is soil organic matter. For a range of land-use systems in the Eastern Amazon, Sommer *et al.* [21] found an average soil organic matter content of 185 t/ha (~90% of all below-ground carbon pools in up to 6 m depth) reaching a minimum of 139 t/ha under oil palm plantations.

Across the Amazon Biome, it is thus evident that the removal of above-ground biomass during forest conversion to agricultural land represents the most drastic change in carbon stocks. Soil carbon changes, e.g., through root removal under mechanization or decomposition of soil organic matter under repeated cropping cycles are also significant, but not as sizable—at least within the observed time horizons. Both above- and below-ground carbon stocks can recover naturally through vegetation re-growth, but biomass accumulation rates depend on previous land uses [22]. Major agriculture-induced changes in GHG emissions vary depending on environmental and management conditions and result from enteric fermentation, and soil-biological processes that lead to nitrous oxide (N_2O) and methane (CH_4) emissions from soils [23–25].

Table 1 shows the best-bet biophysical mitigation potential for transitions between the most prominent AFOLU options in the Brazilian Amazon. Column headers are natural reference vegetation types (REF) and currently dominant business-as-usual (BAU) land uses, whereas potential alternative land uses (ALT) options are listed in the rows. Some increasingly adopted land-use alternatives are labeled 'TREND'. Table cell entries indicate the climate change mitigation potential of moving from BAU to ALT/TREND land uses, expressed by changes in above- (AC) and below-ground (BC) carbon stocks, and other emissions (OE). Cell colors represent an overall best-bet evaluation of mitigation potential based on the reviewed literature (see table legend for explanation). For example, each row of the column named "fallow-based annual cropping under slash-and-burn" represents a potential alternative land-use option. Dark green in the row called 'fire-free fallow-based annual cropping' depicts a clear and high biophysical mitigation effect of moving from slash-and-burn cropping to a fire-free alternative. Grey colors depict unfeasible mitigation options.

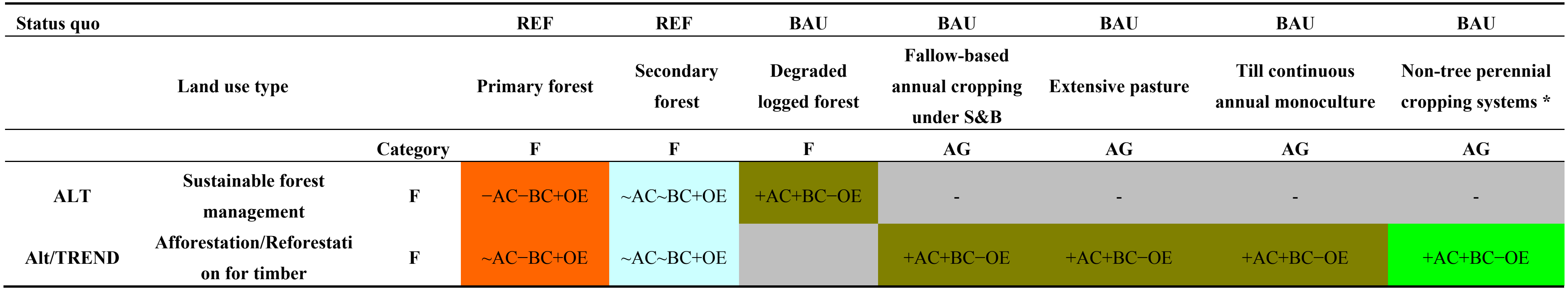
As expected, we find practically all use-restricting mitigation options that involve either avoiding agricultural expansion or abandoning existing agricultural land uses to exhibit high per-hectare mitigation potential. This is primarily due to the high above-ground carbon stock of primary forests, and the vegetation regeneration potential in the tropical forest biome. Reduced expansion of pastures clearly stands out as the single most important large-scale mitigation option, though potentials for avoided expansion of soy beans, fallow-based slash-and-burn (S&B) agriculture, and avoided logging are also high [15,26,27]. While per-hectare emissions from forest conversion to perennial cash-crops can also be large, the direct contribution of permanent crops to agricultural expansion is very small in the Brazilian Amazon [28].

Among the use-modifying mitigation options features the elimination of fire as a land preparation method from slash-and-burn cultivation as a potentially large opportunity with multiple co-benefits, such as the reduction of emissions through accidental fires [9,23,29]. A/R as well as fruit-tree or oil palm plantations represent potentially high per-hectare carbon stock gains as well as reductions in CH_4 and N_2O emissions vis-à-vis baselines of continuous agricultural cropping or pastures [30,31]. Agro-forestry systems, too, may yield high per-hectare carbon gains depending on tree densities, but integration with livestock or the most common annual and semi-perennial staple and cash-crops will typically result in lower overall biomass gains than under purely tree-based systems.

Table 1. Best-bet biophysical mitigation potential of commonly proposed mitigation options in the Brazilian Amazon (sources cited in text).

Status quo			**REF**	**REF**	**BAU**	**BAU**	**BAU**	**BAU**	**BAU**
	Land use type		**Primary forest**	**Secondary forest**	**Degraded logged forest**	**Fallow-based annual cropping under S&B**	**Extensive pasture**	**Till continuous annual monoculture**	**Non-tree perennial cropping systems***
		Category	**F**	**F**	**F**	**AG**	**AG**	**AG**	**AG**
Above ground C (Δ against forest)[1]			160	(−56%)	(−48%)	(−94%)	(−98%)	(−98%)	(−97%)
Below-ground C (Δ against forest)			197	(~)	(~)	(~)	(+/−)	(−)	(−)
Other GHG emissions			-	-	Decay + post-harvest	Fire use, decay, post-harvest	Fire use, enteric fermentation, post-cull	Fossil fuel use, nitrification, post-harvest	Nitrification, post-harvest
ALT	**Primary forest conservation**	**F**	-	-	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE
ALT	**Set-aside land for forest restoration**	**F**	-	-	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE
TREND	**No-till continuous annual monoculture**	**AG**	−AC−BC+OE	−AC−BC+OE	−AC−BC+OE	−AC−BC−OE	−AC−BC~OE	+AC+BC−OE	−AC−BC~OE
TREND	**Integrated crop-pasture systems**	**AG**	−AC−BC+OE	−AC−BC+OE	−AC−BC+OE	−AC−BC−OE	~AC−BC~OE	+AC+BC−OE	−AC−BC~OE
ALT	**Fire-free fallow-based annual cropping**	**AG**	−AC−BC+OE	−AC−BC+OE	−AC−BC+OE	+AC~BC−OE	+AC+BC~OE	+AC+BC−OE	+AC+BC~OE
ALT	**Intensified pastures**	**AG**	−AC−BC+OE	−AC−BC+OE	−AC−BC+OE	−AC~BC−OE	+AC+BC−OE	+AC+BC−OE	−AC−BC~OE
ALT	**No-till continuous Multi-crop systems**	**AG**	−AC−BC+OE	−AC−BC+OE	−AC−BC+OE	−AC~BC−OE	~AC−BC~OE	+AC+BC~OE	−AC−BC~OE
ALT	**Agro-forestry**	**AG/F**	−AC−BC+OE	~AC~BC+OE	−AC−BC+OE	+AC~BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC~OE
ALT/TREND	**Tree/Fruit tree systems**	**F**	−AC−BC+OE	~AC~BC+OE	−AC−BC+OE	+AC~BC−OE	+AC+BC~OE	+AC+BC−OE	+AC+BC~OE

Table 1. *Cont.*



Status quo			**REF**	**REF**	**BAU**	**BAU**	**BAU**	**BAU**	**BAU**
	Land use type		**Primary forest**	**Secondary forest**	**Degraded logged forest**	**Fallow-based annual cropping under S&B**	**Extensive pasture**	**Till continuous annual monoculture**	**Non-tree perennial cropping systems ***
		Category	**F**	**F**	**F**	**AG**	**AG**	**AG**	**AG**
ALT	**Sustainable forest management**	**F**	−AC−BC+OE	~AC~BC+OE	+AC+BC−OE	-	-	-	-
Alt/TREND	**Afforestation/Reforestation for timber**	**F**	~AC−BC+OE	~AC~BC+OE		+AC+BC−OE	+AC+BC−OE	+AC+BC−OE	+AC+BC−OE

AC = above-ground carbon stock; BC = below ground carbon stock; OE = other emissions, e.g., reduced N_2O, CH_4; [1] See also [32]; 🟧 = No C gains; 🟦 = Unclear, context dependent; 🟩 = Context dependent, probably positive per ha potential; 🟩 = Most probably positive per ha potential, limited potential scale; 🟩 = Positive per-hectare potential (<50 t), large-scale potential; 🟫 = Highly positive per hectare potential (>50 t), large scale potential; ⬜ = Not a feasible option.

Low to moderate per-hectare emission reductions, though on potentially large areas, could be achieved through changes in the management of pastures and continuous annual crop production systems (e.g., soy beans). Extensive pastures in the Amazon region are frequently burned to reduce bush encroachment [33,34]. Fire use can be avoided on well-managed intensified pastures, and small gains in above- and below-ground biomass are possible [35]. Increased stocking rates may, however, partially offset emission reductions through higher per-hectare CH_4 emissions from enteric fermentation.

Cerri *et al.* [25], moreover, highlight the mitigation potential of no-tillage versus conventional continuous annual cropping, especially through its positive impact on soil organic matter. In no-tillage systems, crops such as soy beans are planted directly without prior tillage-based land preparation. N_2O and emissions from fossil fuel burning tend to increase under no-till, but not to the extent of compromising the net positive mitigation potential. Due to positive effects on soil quality conservation and private farm profitability there is, however, already a fast adoption of no-till in Brazil, so that interventions towards a transition to no-till may not always qualify as a genuinely additional mitigation option (see also next section).

Mitigation initiatives could thus clearly draw on a range of use-modifying and especially use-restricting mitigation options with large biophysical mitigation potentials, in absolute and/or per-hectare terms. Among use-modifying options, only tree-based systems (oil palm or fruit trees, such as citrus and native Amazonian species) can compete with use-restricting options in terms of per-hectare mitigation potential, but both pasture intensification and no-till farming could potentially bring about substantial absolute emission reductions if implemented at large scales. In general, converting primary or old secondary forests to other land uses bear no or only ambiguous potential for carbon stock gains and involves long carbon payback periods due to high emissions during conversion. Promoting the replacement of natural vegetation is thus not considered a viable mitigation option. The attractiveness of mitigation options that replace productive land uses, however, depends crucially on the economic conditions under which AFOLU-based mitigation is promoted, which we will explore next.

3.2. Opportunity Costs and Other Adoption Barriers

Opportunity costs, among other factors to be discussed below, represent a fundamental barrier to the adoption of innovative land-use systems and technologies [36]. Nonetheless, specifically for carbon credits to be earned, a fundamental eligibility criterion e.g., under the CDM has been financial additionality, *i.e.*, economic activities that are *per se* profitable and would likely be adopted under a business-as-usual scenario are generally not eligible. Under REDD or Nationally Appropriate Mitigation Actions (NAMA), however, less restrictive eligibility criteria may be adopted to allow for more flexibility. As a result, positive opportunity costs (*i.e.*, the forgone profits of abandoning the first-best land-use alternative or technology) may cease to be necessary conditions for international support measures.

3.2.1. Opportunity Costs

A straightforward method to estimating the opportunity costs of switching from one to another AFOLU option is to compare standardized performance measures, such as per-hectare net present values, which can be established through cost-benefit analyses. A major shortcoming of this approach is that it ignores potential constraints on the availability of production factors, such as labor and capital. Similarly, market access limitations tend to condition farmers' land-use decisions at economically and institutionally poorly developed forest margins [37]. These caveats of standard opportunity cost analysis are particularly relevant for the assessment of use-modifying mitigation options, which tend to differ considerably from BAU land uses in terms of labor and capital requirements, as well as profit risk. Use-restricting mitigation options, on the other hand, typically free up production factors for other activities, and thus entail less potential pitfalls for cost-benefit assessments.

Adopting use-modifying land uses also usually requires specific management skills, and may be perceived by farmers as riskier, at least in the adoption stage [38–40]. While use-restricting mitigation options do not require sophisticated management skills, new risks or costs may arise if food security is compromised. Use restriction may increase farmers' dependence on uncertain or expensive external purchases of basic consumption items. Hence, mitigation options, especially use-modifying ones, could appear profitable based on standard opportunity cost analyses, but would still remain unattractive for farmers under conditions that often prevail in forest environments, such as the Amazon region. Methods certainly exist to incorporate most farm-level constraints to technology adoption in advanced versions of opportunity-cost analyses, but data requirements are often a limiting factor.

Following the approach in the previous section, Table 2 classifies potentially promising mitigation options in terms of their likely opportunity costs and technological complexity (see table legend). As expected, we find use-restricting mitigation options to generally exhibit positive opportunity costs. Several studies have estimated the cost of forest conservation and setting aside agricultural land for the Brazilian Amazon in both case-studies and regional assessments [13,14,41,42]. For forest conservation, findings generally point to relatively low opportunity costs (below US$5 per ton of avoided CO_2 emission), especially if extensive cattle ranching or slash-and-burn agriculture dominate BAU land uses. However, when high-value cash crops dominate the land-use mix, or when valuable timber species make intensive logging particularly attractive, opportunity costs can be considerably higher. Likewise, forest conservation and land set-asides become substantially more expensive per unit of avoided emission in areas with low natural biomass densities. Clearly, positive opportunity costs (orange areas in Table 2) of use-restricting mitigation options thus clearly feature among the key adoption barriers to be overcome by mitigation initiatives.

For a range of mitigation options, either no clear evidence could be established from the reviewed literature, or credible information was missing altogether (light blue colors in Table 2). This applies, in particular, for two of the most promising use-modifying mitigation options in the Brazilian Amazon, namely no-till cropping and pasture intensification.

Comparative studies eventually find no-till soybean production to be slightly less profitable on a per-hectare basis than conventional till-based production [25,43,44]. However, they generally ignore the long-term soil quality enhancing effects of no-till. The ongoing transition trend from till to no-till commercial annual crop production in the soy bean sector suggests that many farmers seemingly perceive benefits from adopting no-till even without external support. According to the 2006 national agricultural census, farms using minimum or no-till cultivation now outnumber those using conventional tillage in the region.

Table 2. Best-bet opportunity costs and technological change requirements of promising mitigation options in the Brazilian Amazon (sources cited in text).

		BAU	**BAU**	**BAU**	**BAU**
Status quo	**Land-use type**	**Degraded logged forest**	**Fallow-based annual cropping under S&B**	**Extensive pasture**	**Till continuous annual monoculture**
	US$ NPV/ha	-	206	39–59	171
ALT	**Primary forest conservation**	🟧 -	🟧 -	🟧 -	🟧 -
ALT	**Set-aside land for forest restoration**	🟧 -	🟧 -	🟧 -	🟧 -
TREND	**No-till continuous annual monoculture**	-	-	-	🟦 TC
TREND	**Integrated crop-pasture systems**	-	-	-	🟦 TC++
ALT	**Fire-free fallow-based annual cropping**	-	🟧 TC	-	-
ALT	**Intensified pastures**	-	-	🟦 TC+	🟦 TC++
ALT	**No-till continuous Multi-crop systems**	-	-	-	🟦 TC+
ALT	**Agro-forestry**	-	🟩 TC++	🟩 TC++	🟩 TC++
ALT/ TREND	**Tree/Fruit tree-based systems**	-	🟩 TC++	🟩 TC++	🟩 TC++
ALT	**Sustainable forest management**	🟦 TC	-	-	-
TREND	**Afforestation/Reforestation for timber**	-	🟩 TC++	🟩 TC++	🟩 TC++

🟧 = Clear loss per ha; 🟦 = Unclear (variable prices, costs, research gap); 🟩 = Clear gain per ha; TC = Simple technological change required (same system, light management changes); TC+ = Complex technological change required (same system, different crops and/or inputs); TC++ = Very complex technology change (different system and/or crops and inputs).

For the case of pasture intensification, Fearnside [45] argues that fertilizer costs could eventually render intensive cattle ranching less profitable than conventional extensive ranching. Based on secondary data from several Amazon sites, Costa [46] suggests that pasture intensification is altogether less profitable than extensive ranching. Rueda *et al.* [47], on the other hand, found intensification of beef cattle ranching to be a profitable strategy, at least in the Western Amazon. Similar findings are summarized by Faminow [48] for the Eastern Amazon. Profitability thus varies with agronomic conditions and the sign of the opportunity costs of pasture intensification remains ambiguous.

Switching from slash-and-burn agriculture to fire-free fallow-based annual cropping clearly exhibits positive opportunity costs, unless a full technological package including fertilizer application and extended cropping periods is adopted only under the fire-free land preparation option [49,50]. If fertilization was adopted under slash-and-burn, the potential yield increase of fire-free agriculture, and thus the economic advantage vis-à-vis fire-free land preparation, vanishes [51].

Profitability estimates of tree-based mitigation options, such as agro-forestry, fruit, and timber species plantations generally hinge on the choice of crop and tree species, as well as discount rates, because at least a part of the returns accrues only after several years. Plantation forestry is widespread in Brazil, but primarily outside the Amazon region [52,53]. Experiments with plantation forests in the Brazilian Amazon have, nonetheless, yielded similarly high annual productivity rates as in other climate zones [54,55]. Based on standard cost-benefit analyses of plantation forestry systems, the Brazilian Agricultural Research Center (EMBRAPA) suggests comparatively high per-hectare profitability for plantations of commercial tree species, such as eucalyptus and pine [56]. Several studies also suggest extraordinary high returns to agro-forestry in Amazonian settings [57,58]. A recent Amazon-wide in-depth review of smallholder experiences with agro-forestry and tree plantations, however, suggests that adopters have often realized less than one third of expected profits under on-farm conditions, allegedly due to the poor adaptation of forestry projects to local conditions [59].

Finally, Holmes *et al.* [60] found sustainable forest management (SFM) to be potentially more profitable than conventional logging, but results are sensible to cost assumptions. In a review of logging cost studies, Pokorny and Steinbrenner [61] did not find clear evidence in favor of reduced impact logging, and only a clearly superior price paid for certified timber from SFM could make a significant difference. Yet currently, prices for certified timber in Brazil are only marginally higher than for conventionally produced timber, including because of the high market supply of illegally harvested commercialized timber [62].

We thus find only use-restricting, and at least one of the use-modifying mitigation options (fire-free fallow based agriculture), to exhibit clearly positive opportunity costs as prime adoption barriers. But, beyond opportunity costs, research has pointed to a series of other farm-level obstacles to the wide-spread adoption of mitigation options, which we discuss next.

3.2.2. Other Adoption Obstacles

Provided that all potential opportunity costs are compensated for, use-restricting mitigation initiatives should face relatively few economic farm/firm-level adoption barriers. Neither avoiding deforestation nor other set-aside conservation options, such as land retirement, require specific skills, market access, or production factor reallocation. Thus, once opportunity costs are addressed, only social factors, such as mistrust or cultural attachment to traditional modes of production, could potentially hamper adoption. Possible constraints to the implementation of direct compensation-based mitigation initiatives will be discussed in the next section.

With regard to use-modifying mitigation options, a host of empirical studies points to considerable adoption barriers that apply to smallholder settings in particular. For the case of fire-free land preparation, Börner *et al.* [14,50] suggest aversion to price and production risks as a major impediment to the adoption of fertilizers. Fertilizers are a key input requirement for profitable fire-free staple crop production, e.g., based on mechanical mulching. Subsidizing machine services or insurance against risks could thus potentially remove a major adoption barrier.

For smallholder settings in the Western Brazilian Amazon, Vosti *et al.* [63] point to up-front investment needs, multiple initial years of negative cash-flow, and uncertain demand as key barriers barring the wider adoption of otherwise profitable agro-forestry options. In a review of 108 running agro-forestry systems in the Brazilian Amazon, Smith *et al.* [64] emphasized the high diversity of locally developed fruit-tree based systems, but pointed to very limited marketing opportunities as a key barrier to their wider dissemination. This notion was confirmed by Hoch *et al.* [65], who reviewed smallholder forestry experiences in several Amazon countries and found, in addition, externally promoted forestry systems to be ill-adapted to local conditions, skills and economic needs.

Large-scale commercial tree and perennial crop plantations, e.g., fruit trees and oil palms, often owe their establishment in the Brazilian Amazon to incentives through subsidized credit programs [66]. In the long term, their economic viability as well as their potential to become major deforestation drivers will, among others, depend on further agro-industry development and the removal of land tenure insecurities in the region [67].

Adoption rates of integrated crop-pasture systems are still low according to census data, but equally high in the Amazon than in the rest of Brazil, thus indicating no particular comparative disadvantage. Yet, wherever extensive cattle production has advanced into remote locations with poor transport infrastructure, limited access for farm machinery and transport means can represent serious adoption constraints for crop components in crop-pasture systems. The same essentially applies for the introduction of trees into pasture systems.

Beyond financial analysis, few studies have looked into the determinants of adoption of pasture intensification in the Brazilian Amazon. Apart from inefficient extension strategies, Faminow (1998) identified a mismatch between technology packages and farmer needs as a reason for low adoption rates, in particular, for smallholders. The tendencies to keep cattle more as an insurance than a productive asset, or as an alibi land use to occupy illegally deforested land for land market speculation, also qualify as relevant explanatory factors for the dominance of extensive systems among all producer types [12,68].

The adoption of mitigation options in the Brazilian Amazon is thus limited not only by opportunity costs (for use-restricting and some use-modifying options), but also by a diverse set of context- and technology-related factors (primarily for use-modifying options). The implications of these multiple adoption barriers for the design and economic competitiveness of mitigation initiatives are discussed in the following section.

3.3. Policy Implementation Costs

Opportunity costs, technological complexity, and risks jointly imply that higher adoption rates of AFOLU-based climate change mitigation options will not come about without systematically planned interventions. Such interventions can take the form of direct incentives, such as payments for environmental services, but the adoption of mitigation options may also be induced by disincentive-based measures, such as regulations and standards, or integrated conservation and development programs that enable forestry or agricultural production with low carbon footprints (see [69] for an overview of intervention options).

Implementing such programmatic measures results in costs, which are here very broadly termed "implementation costs". For incentive-based and enablement measures we define implementation costs as all costs that are not incentive proper, *i.e.*, payments or in-kind benefits to providers that are intended to compensate for opportunity costs or enable mitigation action are excluded. Implementation costs thus include all items covered under the term "transaction costs" in the literature on project-based mitigation initiatives, *i.e.*, costs related to search and information, design, monitoring, and enforcement [70]. For disincentive-based measures, we understand implementation costs to cover all intervention-related costs, excluding potential fine revenues.

Although each intervention comes with particular implementation challenges, implementation costs tend to be strongly determined by two factors: the intervention context and the technological complexity of the mitigation option.

3.3.1. Intervention Context

Intervention context-related implementation costs arise from the need to interact with the target population, *i.e.*, land users. Examples of such interactions are regular control and enforcement field visits, technology dissemination and extension campaigns, or contract establishment and field-based monitoring in the case of payment schemes. The cost of interactions with land users depends critically on the total mitigation potential of landholdings and the costs of field-based operations in the target region.

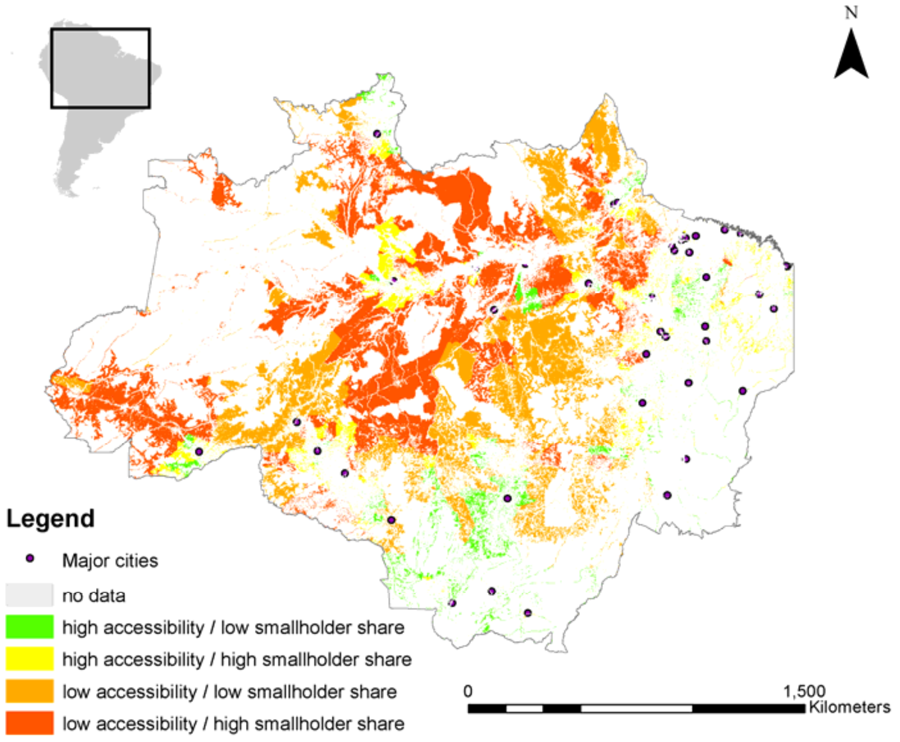
Given the land-based nature of AFOLU-based mitigation, attending a small number of medium-to-large landholders would thus generally appear implementation cost wise more attractive than dealing with a large number of smallholders with lower mitigation benefits per provider. As a caveat, a few large landholders might also find it easier to organize and bargain effectively for higher compensations, to the detriment of cost-effectiveness in implementation.

Many remote Amazon forest margins suffer from poor access conditions and a limited presence of the State. Land tenure rights are often unclear, and illegal economic activity, such as emission-intensive deforestation and predatory logging, are frequent [71]. Mitigation initiatives can be hampered under these conditions and requires additional costly safeguards. Effective monitoring generally requires a spatially explicit land register, which often hinges on previously clarified land tenure.

Established agricultural colonization areas in the Amazon, on the other hand, may boast more intervention-friendly infrastructure conditions and better defined tenure rights, but may also exhibit higher rural population densities, and thus smaller-sized farms, depending on settlement history.

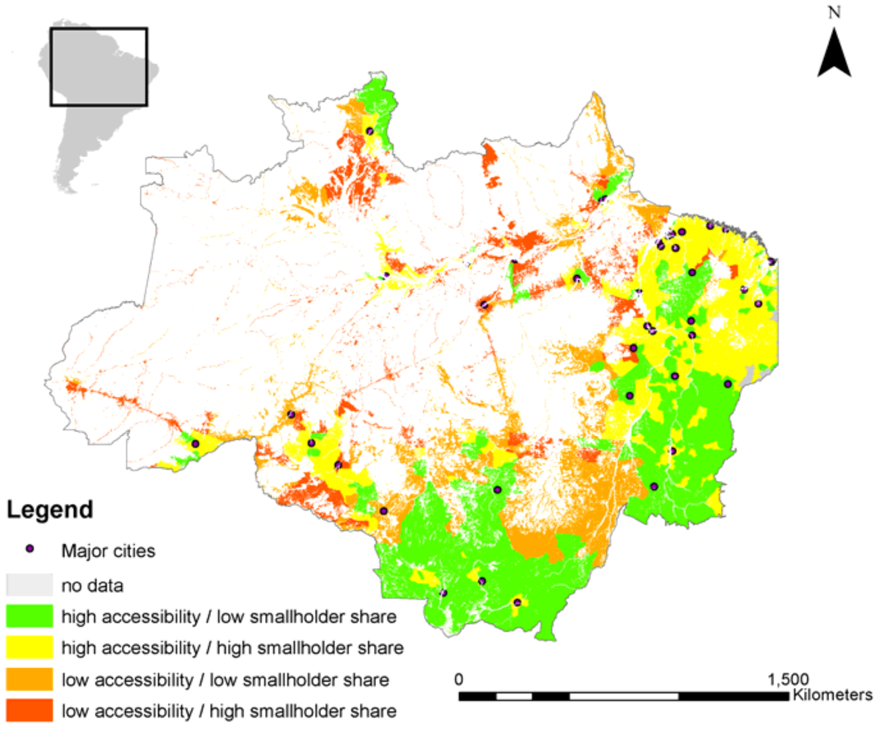
Figures 1 and 2 visualize these two dimensions of contextual implementation costs through secondary data overlays. Figure 1 depicts "new forest frontiers", *i.e.*, areas threatened by deforestation until 2050 according to simulation studies [72]. Based on travel time estimates obtained through accessibility mapping [73], high (above-average) and low (below-average) accessibility zones were defined and further divided according to their share of land under land holdings below 100 ha—considered smallholdings in the context of the Brazilian Amazon—using agricultural census data.

Figure 1. Contextual determinants of implementation costs in projected threatened forests of the Brazilian Amazon.



Sources: Soares-Filho *et al.* [72]; IBGE Agricultural Census 2006, Nelson [73].

Figure 2. Contextual determinants of implementation costs in non-forest and deforested areas in the Brazilian Amazon.



Sources: Soares-Filho *et al.* [72]; IBGE Agricultural Census 2006, Nelson [73].

According to Figure 1, high context-related implementation cost factors (low accessibility, high smallholder share) clearly dominate a large potential intervention zone for forest conservation (*i.e.*, REDD) mitigation initiatives. Recent reductions in historical deforestation rates from 27.8 thousand km^2 in 2004 to below 10 thousand km^2 after 2008 (according to the Brazilian Space Agency INPE) may cast doubt on the predicted extent of future deforestation. Opportunities for REDD in the Brazilian Amazon remain nonetheless sizable area wise. Börner *et al.* [41] show that in roughly two thirds of this area, tenure rights are either unclear or pending documentation in spatially explicit registers, suggesting the need for considerable up-front investments for effective mitigation action. Some pilot REDD projects, such as the Juma Sustainable Development Reserve Project, have thus targeted well-delimited protected areas, in which residents can legally engage in subsistence farming and some forest uses. Self-reported program implementation costs are nonetheless quite high (over 40% of costs are not incentive-proper), even under clear property right conditions, due to the high costs of field intensive community support measures in a remote and sparsely populated environment [32,74].

Figure 2 illustrates the spatial distribution of our two intervention cost indicators for deforested and natural non-forest areas in the Brazilian Amazon. Although these areas may contain old secondary forests, the average biomass carbon content of current land covers is considerably lower here than in the areas shown in Figure 1 [17]. Figure 2 thus delimits potential target zones for initiatives that promote use-modifying agricultural mitigation options, land retirement, or reforestation and afforestation schemes.

Figure 2 clearly suggests a large proportion of high accessibility zones with medium and large landholdings dominating the occupied land in most municipalities. Field-based operations under these conditions will thus often be considerably less cost-intensive contributing to lower overall implementation costs.

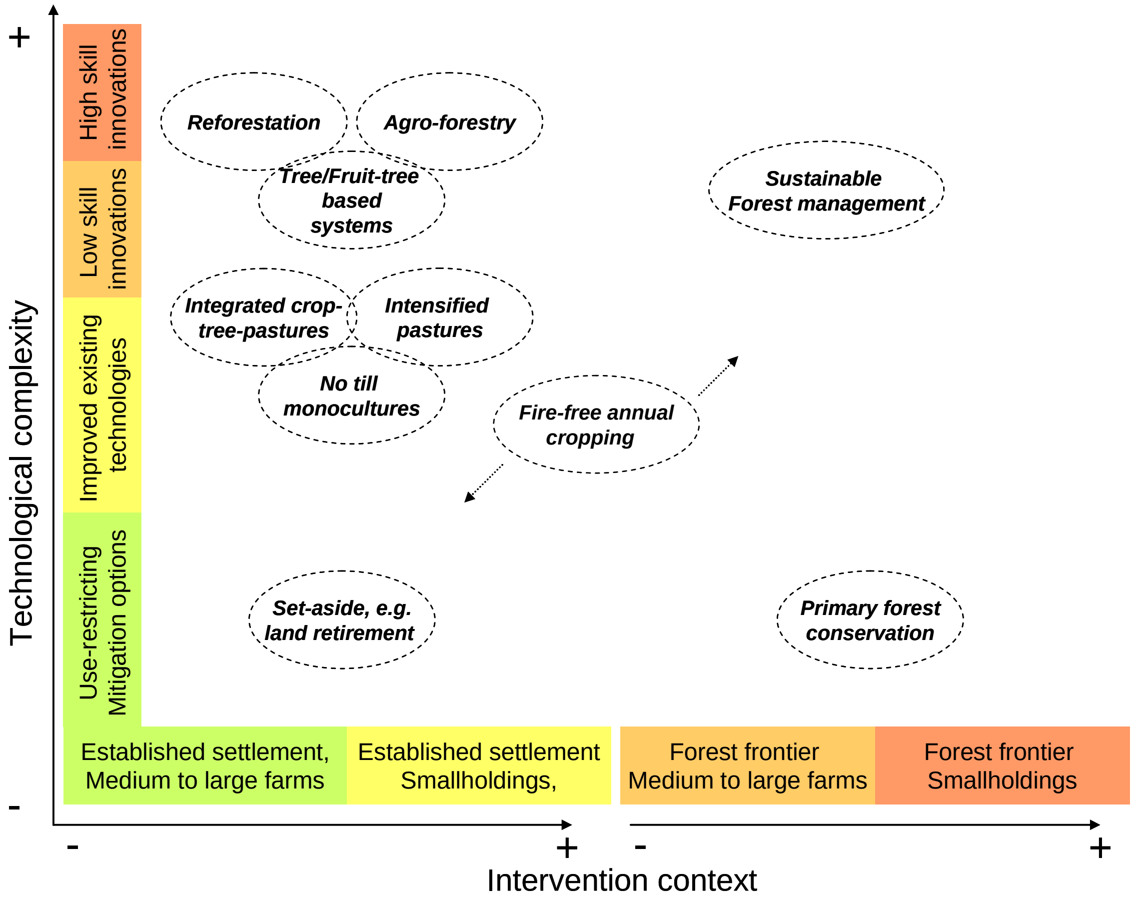
3.3.2. Technological Complexity

When mitigation options are technologically complex, substantial intervention costs arise from the need to overcome gaps in user (*i.e.*, mitigation provider) skills and knowledge. Use-restricting mitigation options, such as forest conservation and land set-aside, arguably require substantially lower user skills than changes to existing techniques (e.g., to no-till) or the adoption of completely new technology packages (e.g., agro-forestry).

Additional costs arise when mitigation implementation is not remotely detectable. Monitoring distinct land-cover change, as in the case of reforestation, land retirement, and forest conservation, can usually be widely accomplished by remote sensing techniques. More subtle changes, such as the adoption of no-till land preparation techniques, will have to rely on more sophisticated and field-based measuring, reporting, and verification methods, which will be more costly.

Figure 3 spans a stylized implementation cost plane for the mitigation options identified in the previous section, according to their technological complexity and the implementation cost related indicators discussed above. Location categories on the horizontal axis are not continuous, as indicated by the two separate first axes.

Figure 3. Key implementation cost dimensions for selected mitigation options in the Brazilian Amazon.



Opportunities for primary forest conservation are thought to be abundant in forest frontier regions with high forest cover and dynamic land-use change. Retiring agricultural land, on the other hand, may be a more frequent option in established settlement, *i.e.*, “old frontiers”, of the Amazon, where soil productivity loss is a common phenomenon [75,76]. Both these use-restricting mitigation options require comparatively little user knowledge and low technology-related implementation costs.

Technological fixes to existing agricultural practices, such as tree-crop integration, intensified pastures, and no-till land preparation play a role primarily for commercially oriented producers, which tend to be located more in established agricultural areas than at forest frontiers, because they often depend on closeness to output, input and labor markets. This is also the most promising intervention context for reforestation and intensive fruit tree or agro-forestry systems, which for most farmers in the Amazon still represent complete technological innovations. Introducing these knowledge-intensive mitigation options will require considerably more interaction with providers, e.g., through repeated extension efforts. The same essentially applies for attempts to substitute predatory logging by sustainable forest management, which generally involves more sophisticated management skills.

Several technologically complex alternatives to fire-free annual crop production exist for fallow-based smallholder agriculture, but the use of fire is common across the whole Amazon region. Related mitigation opportunities are thus as abundant in old as they are in new forest frontiers, where interventions would nonetheless suffer higher context-related implementation costs.

Hence, low opportunity costs and technological simplicity of use-restricting mitigation options, particularly forest conservation, may often have to be balanced against the high cost of operating at remote forest frontiers, or interacting with a disproportionately large number of land users (red areas in Figure 1). Land retirement or conservation of smaller forest remnants in established agricultural zones are thus not generally unattractive as AFOLU-based climate change mitigation options.

3.4. Economic and Environmental Spillover Risks

Mitigation incentives inevitably affect farmers' land-use decisions, which could create environmental spillover effects in three ways. First, the adoption of mitigation measures could itself produce unintended externalities on non-carbon environmental services, e.g., when carbon forestry projects introduce fast-growing monoculture plantations that negatively affect biodiversity and groundwater reserves [77] (*i.e.*, *losing other services*). Second, agricultural mitigation options could become so profitable that they are expanded into previously unused land, such as natural forests (*overshooting adoption scale*). And third, mitigation incentives can cause price effects and factor movements that shift spatial pressures triggering unintended land-use change outside the mitigation scheme (*leakage*).

In the context of the Amazon, spillover effects have above all been addressed in modeling exercises [14,78–82]. These suggest that incentives for both forest conservation (at forest frontiers) and land retirement (old frontiers) could be competitive strategies for carbon mitigation at conservative offset prices. However, liquidity-providing payments or subsidized credits and increased land scarcity were shown to eventually increase farmers' input-intensive cash-crop production, at the expense of annual staple crops in the Eastern Amazon [14]. The resulting additional use of agrochemicals and fertilizers could potentially result in increased water pollution, as an example of "losing other services" that is increasingly becoming relevant in the Brazilian Amazon [83].

Intensifying land use through land-intensive technologies (mechanization, fertilizers) has often been proposed as a way to produce more on less agricultural land, thus sparing forests—known also as the Borlaug hypothesis [84]. However, at the local scale, more rather than less deforestation could occur. Börner *et al.* [14] show for an old frontier region in the Eastern Amazon how intensification through mechanization can result in cropland expansion, due to relaxed labor constraints. Cattaneo [82] suggests that regional "overshooting adoption scales" is likely to occur for practically all but the most labor-intensive technological changes. Amazon model simulations thus generally predict that new capital-intensive technologies can lead to *increased* forest loss. A global compilation of case studies by Angelsen and Kaimowitz [85] shows that deforestation impacts are scenario-dependent, but agricultural innovations more often than not cause locally higher deforestation, even when the innovative technology allegedly is "land-sparing".

The third spillover effect (leakage) is particular relevant for use-restricting conservation schemes, since they can "push" economic activities from restricted into non-target areas. Model-based leakage estimates for one of the first REDD projects in the Amazon, the Noel Kempff project in Bolivia, ranged between 2%–42%—*i.e.*, at worst almost half of reduced logging would be compensated through increased demand elsewhere [86]. These large ranges illustrate the uncertainties involved in quantifying leakage effects. Expected leakage under REDD would depend on various parameters of flexibility in output and production-factor markets: generally, the more flexible the economy is, the more it will succeed in substituting production in space, and thus likely raise leakage.

Implementers of mitigation initiatives thus generally need to worry about spillover effects that can reduce the cost-effectiveness of their interventions either through reduced mitigation effectiveness (leakage or overshooting adoption scale) or by causing the loss of other environmental services. Addressing spillover effects requires extra implementation costs that accrue, for example, in the form of additional monitoring needs to quantify leakage outside project boundaries, or efforts to enforce regulations on land and agricultural input intensity to minimize undesired agricultural expansion or negative externalities.

4. Discussion and Conclusions

We have assessed for the Brazilian Amazon region the bio-physical and economic scope of agriculture (usually, use-modifying) and forestry (predominantly, use-restricting) based mitigation options, in terms of four interrelated performance indicators: bio-physical mitigation potential, opportunity costs and other adoption barriers, implementation costs, and spillover effects. We saw that neither scores equally high on all four accounts; tradeoffs exist between these dimensions, with important implications for the cost-effectiveness and feasibility of currently popular mitigation schemes, such as REDD+. Table 3 summarizes our findings for a selected set of promising and frequently discussed mitigation options and highlights (grey), where high uncertainty about performance indicators suggests future research needs. Mitigation options that exhibit clear adoption trends in the Amazon, such as no-till farming are excluded here as they tend to lack financial additionality.

Avoiding primary forest loss does clearly provide the largest mitigation benefits on a per-hectare basis, provided mitigation initiatives can target forests that are truly threatened. But the lion's share of projected future deforestation lies in areas with low accessibility. Most of these areas exhibit poor institutional and transport infrastructure, with unclear and conflicting tenure rights featuring among the most prominent barriers to cost-effective mitigation actions [41,87]. Incipient REDD projects are thus almost generally forced to invest in establishing basic preconditions for mitigation actions, including leakage control, leading to delays in project implementation and costs [88]. Assessments purely focused on biophysical mitigation potential and opportunity costs thus probably overestimate the mitigation potential at forest frontiers vis-à-vis opportunities in old frontier areas; except for the limited amount of threatened frontier land under well-established property right regimes, such as extractive reserves or protected areas.

The bio-physical mitigation potential of land retirement, as the other major use-restricting mitigation option, can also be high due to rapid re-growth of secondary vegetation, especially where tree root systems have not been removed by mechanical land preparation. The large areas of low productivity pastures in the Brazilian Amazon as well as extensively used mosaic landscapes resulting from fallow-based farming represent key target areas for land retirement with low opportunity costs. Like primary forest conservation, land retirement potentially displaces other activities, and is thus prone to leakage effects. In the more intervention-friendly environment of old frontiers, land retirement may, nonetheless, represent an area-wise more abundant mitigation option than primary forest conservation.

Table 3. Summary of performance indicators and related research needs for selected mitigation options (grey color suggests research needs).

Mitigation option	Bio-physical mitigation potential per ha (BP)	Opportunity costs (OC)	Implementation cost (IC)	Leakage and spillover effects (L)
Primary forest conservation	Very high at most forest frontiers	Many low cost options	Low technological complexity, but high operational costs at new frontiers	High leakage risk
Retiring extensive pastures	High	Low cost options, especially where pastures are degraded	Low technological complexity and low operational costs in old frontiers	High leakage risk
Sustainable forest management	Medium to high depending on BAU	Medium under currently low prices for certified timber	High technological complexity and high operational costs at new frontiers	Low
Reforesting extensive pastures	High	Low or negative depending on species choice and risk profile	Medium to high technological complexity and low operational costs in old frontier areas	Medium
Intensifying extensive pastures	Medium	Low to medium depending on state of existing pastures	Low to medium technological complexity and low operational costs in old frontiers areas	Low
Integrating trees in crops and pastures	Medium to high depending on tree density	Low or negative depending on tree species and market access	Medium to high technological complexity and low operational costs in old frontier areas	Low
Avoiding fire use in annual crop production	Medium to high	Medium depending on crop types and risk profiles	Low to medium technological complexity and low operational costs in old frontiers areas	Low

Most of the remaining use-modifying mitigation options in Table 3 exhibit lower per-hectare mitigation potential than the two use-restricting options at the top of the table. Apart from "reforesting extensive pastures" all these options are agricultural, but not usually of the type that is associated with a high risk of causing negative spillover effects on other environmental services. Although many of these agricultural mitigation options may exhibit low or even negative opportunity costs in standard cost-benefit analyses, their adoption rate remains low. Adoption research, especially in the agro-forestry literature, suggests several reasons for this apparent paradox [38,65,89]. First, most technological alternatives to business-as-usual land uses perform less well in practice than in experiment station settings. Second, many popular agricultural mitigation options are indeed technologically more complex, and may thus be perceived as inaccessible or riskier from a farmer's point of view. And third, even in what we termed “old frontiers”, limited market access often prevents farmers, especially smallholders, from capturing prices that justify investments into more climate-smart production systems.

Only the first and second of these three reasons for low adoption rates would appear amendable by project-based mitigation initiatives, whereas the latter requires broader State-led interventions towards infrastructure, public services, and economic development. Past experiences documented in the literature on integrated conservation and development projects (ICDP), as well as recent research on smallholder forestry in the Amazon, suggest that the dissemination of forestry and agricultural innovations is a cost- and time-intensive endeavor with high risks of failure [90–93].

In the context of the Brazilian Amazon, based on our best-bet assessment we thus primarily see scope for two distinct, but not mutually exclusive pathways to land-use based climate change mitigation:

The first, ‘*spatially targeted use-restriction*’, requires an intervention strategy focused on (a) limiting the expansion of extensive and low opportunity cost land uses, such as conventional cattle ranching, in forest frontier areas; and (b) the retirement of unproductive agricultural and pasture land, some of which now lies in the old frontiers of the Brazilian Amazon.

The second, “*technology-specific use modification*”, would concentrate on locally facilitating the adoption of technological innovations in both agriculture and forestry. This may involve the technological adaptation of promising mitigation options to local conditions, such as pasture intensification, or the participatory refinement of traditional production systems, e.g., slash-and-burn agriculture, towards a lower carbon footprint.

Our review of performance factors for mitigation options suggests that low-hanging fruits for both strategies exist in the region, but probably only to a limited extent, and often located in separate target regions (Figures 1 and 2). Our assessment here is nothing but a first regional scoping, which would need to be supplemented by context- and case-specific estimates of service gains and cost of AFOLU-based mitigation initiatives. The increasing number of REDD pilot schemes, of course, also reflects current donor fashions, but suggests equally that forest conservation still has an edge over alternative mitigation options in the Amazon. Managing leakage, non-additionality and non-permanence risks thus represents an important challenge for climate change mitigation in the Amazon.

We identify research needs above all with respect to the opportunity costs and adoption barriers of technological innovations under representative on-farm conditions. In general, very little empirical evidence exists on the costs of implementing mitigation schemes and accompanying policy measures under spatially heterogeneous institutional and accessibility conditions. This includes, among others, economically motivated analyses of land use change that take economic and environmental policies (and their effects on activity displacement, *i.e.*, leakage) explicitly into account.

In any case, however, distinct State-supported interventions in various sectors are required to tap into the potentially large absolute bio-physical potential for climate change mitigation in the Amazon. For example, minimizing leakage from forest conservation and land retirement schemes requires enhancing forest law enforcement on private and unprotected State land, which accounts for the major share of historical and projected future forest loss. In addition, land registration and tenure regulation campaigns are also needed to allow for more effective law enforcement and the establishment of conditional mitigation incentive schemes.

Likewise, agriculture and forestry in the Brazilian Amazon are unlikely to leapfrog onto a technologically more sustainable development path at larger scales without additional public spending for regionally targeted and actor-specific agricultural research and extension. Cases of profitable technological innovations, like no-tillage practices that disseminate without targeted interventions, represent exceptions that may eventually benefit from positive spillover effects once a critical mass of adopters is reached. Promoting general technological development in these sectors comes, nonetheless, also at the risk of causing additional pressure on other environmental services. Well-designed land-use regulations and their effective enforcement thus represent *sine qua non* conditions for achieving substantial emission reductions in the region. Agriculture and forest-based climate change mitigation in the Amazon poses a challenge not only for developers of project-based carbon schemes. Often much broader development deficits must be addressed to allow for local interventions to cost-effectively promote concrete mitigation options.

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Conflict of Interest

The authors declare to have no conflict of interest.

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