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Carbon payments can cost-effectively improve logging sustainability in the Amazon

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ABSTRACT

Selective logging is pervasive across the tropics and unsustainable logging depletes forest biodiversity and carbon stocks. Improving the sustainability of logging will be crucial for meeting climate targets. Carbon-based payment for ecosystem service schemes, including REDD+, give economic value to standing forests and can protect them from degradation, but only if the revenue from carbon payments is greater than the opportunity cost of forgone or reduced logging. We currently lack understanding of whether carbon payments are feasible for protecting Amazonian forests from logging, despite the Amazon holding the largest unexploited timber reserves and an expanding logging sector. Using financial data and inventories of >660,000 trees covering 52,000 ha of Brazilian forest concessions, we estimate the carbon price required to protect forests from logging. We estimate that a carbon price of $7.90 per tCO$_2$ is sufficient to match the opportunity costs of all logging and fund protection of primary forest. Alternatively, improving the sustainability of logging operations by ensuring a greater proportion of trees are left uncut requires only slightly higher investments of $7.97–10.45 per tCO$_2$. These prices fall well below the current compliance market rate and demonstrate a cost-effective opportunity to safeguard large tracts of the Amazon rainforest from further degradation.

1. Introduction

Tropical forests support globally important biodiversity and carbon stocks, but are being deforested and degraded at alarming rates (Hansen et al., 2013; Vancutsem et al., 2021). The key driver of tropical forest degradation is selective logging (Hosonuma et al., 2012; Houghton et al., 2012; Pearson et al., 2017), which covers an area of at least 403 million hectares worldwide (Blaser et al., 2011) and is responsible for 6% of tropical greenhouse gas emissions (Ellis et al., 2019). Forests logged sustainably can retain significant proportions of their carbon stocks and harbour high species richness (Putz et al., 2012), yet most selective logging is done unsustainably (Edwards et al., 2014a; Bousfield et al., 2020) and a mentality that prioritises profit over the environment prevails. High-value tree species are often preferentially logged at high intensities, leading them to become extremely rare or commercially extinct (Richardson and Peres, 2016), and forests become increasingly depleted with each harvest (Piponiot et al., 2019). However, large timber demand makes selective logging an important economic activity in many tropical economies and balancing sustainable economic production with global climate targets and biodiversity protection remains a critical challenge.

Carbon-based payments for ecosystem service schemes, such as the REDD+ (Reducing Emissions from Deforestation and Degradation) programme, seek to achieve the balance between development and conservation by giving tangible economic value to standing forests. Placing value on carbon retention provides economic incentives for selective loggers to reduce their emissions through improved logging practice (eg. RIL-C) (Ellis et al., 2019) or forgoing logging entirely, provided carbon payments can meet or exceed the opportunity cost of doing so (Fisher et al., 2011, 2014).

In Malaysian Borneo, the high carbon prices required to meet logging opportunity costs (US$22–28 per tCO$_2$) means carbon payments are not a cost-effective conservation measure (Fisher et al., 2011), while in Cambodia, carbon payments can cost-effectively prevent logging at prices of US$2.43-$4.27 per tCO$_2$[15]. In sub-Saharan Africa, carbon payments could fund more sustainable logging management regimes for US $4.40-$25.90 per tCO$_2$ (Ndjondo et al., 2014). We currently lack an understanding of carbon payment feasibility in the Amazon, where

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forest structure and composition differs significantly from South-east Asia (Fisher et al., 2014). Amazonian forests consist of many low-value tree species and small numbers of rare, high-value species that are targeted by logging. Due to this heavily skewed value structure, permitting a low level of logging whilst restricting the extent and intensity of harvest could significantly reduce the opportunity cost of protection, whilst still providing carbon and biodiversity benefits (Fisher et al., 2014). Preventing the commercial extinction of target species requires the retention of many more individuals (Richardson and Peres, 2016; Zarin et al., 2007), and carbon markets may play a major role in facilitating this transition to more sustainable harvests (Salzman et al., 2018).

Here, we tackle the key question of whether carbon payments can viably protect Amazonian forest by preventing all logging or by improving logging sustainability. We focus on the Brazilian Amazon, where approximately 35 million hectares of public forest are available to be designated for timber harvest with 1.6 million hectares having already been granted as forest concessions (Sist et al., 2021). We use detailed financial data and spatial harvest simulations for multiple logging concessions to calculate the opportunity cost and carbon breakeven price of forgoing logging entirely as well as improving logging sustainability. We do so to understand the cost-effectiveness of the following objectives: (1) forgoing logging entirely to protect undisturbed primary forests; (2) restricting harvest to higher-value species and preventing harvest of lower-value timber classes; and (3) reducing extraction intensity of higher-value timber species, while preventing logging of lower-value species.

2. Material and methods

2.1. Study site

We focused on seven logging concessions located throughout the Brazilian Amazon (Bousfield et al., 2021) and spanning a broad spectrum of forest structure profiles. Extensive pre-harvest inventories were undertaken by the logging companies whereby all trees ≥40 cm DBH representing commercially viable species were georeferenced and tagged. The forest inventories across the seven concessions provide us with specific attribute data for >660,000 individual trees spanning ~52,000 ha of undisturbed Amazonian forest.

2.2. Simulating new forests

For each concession, we simulated 100 new spatially explicit forests based on the original tree distributions within each concession. Each simulated forest contained a new tree species community, where species aggregation patterns, tree DBH and harvestable volumes were reproduced based on models of the original species-specific spatial and size distributions and DBH-volume relationships (see SOM Methods in Bousfield et al., 2021) (Bousfield et al., 2021). Harvest simulations were subsequently conducted on each simulated forest.

2.3. Simulating full and restricted harvests

We simulated a business-as-usual logging harvest for all concessions as well as a number of restricted harvests whereby carbon payments were used to protect certain trees from harvest.

2.3.1. Business-as-usual logging

To calculate the opportunity cost of forgoing selective logging entirely in the concession, we simulated a full harvest of all profitable timber within the concession according to legal restrictions. The volumetric amount of profitable timber varied between concessions, with harvests spanning a wide range of intensities from 5 to 20 m^3 ha^{-1}.

2.3.2. Restricting harvest with carbon payments

We simulated three harvest restriction scenarios whereby carbon payments would be used to protect trees that would otherwise have been harvested.

Objective 1: Preventing logging entirely - all trees within the concession were protected from logging, retaining the whole concession as unlogged primary forest.

Objective 2: Preventing logging of certain species based on value classes - tree species were grouped into four decreasing timber value classes (very high: Class I, high: Class II, medium: Class III and low: Class IV) based on their market sale price (Bousfield et al., 2021). Species-specific timber values were obtained from actual transaction prices based on financial records of a Brazilian logging company based at one of the study sites (AMATA) and timber transaction details recorded by IBAMA. Consecutive harvests were then simulated with logging prevented for an increasing number of value classes, with Class IV being the first to be restricted (i.e., logging permitted for Classes I, II and III), then Classes III and IV restricted (logging permitted for Classes I and II), then Classes II, II and IV restricted (logging permitted for Class I only) and finally all Classes restricted (i.e. no harvest).

Objective 3: Reducing extraction intensity of higher-value timber species, while restricting logging of lower-value species - Assuming loggers would have a greater desire to harvest higher than lower value stems (due to higher economic returns), we tested the carbon prices required to spare increasing proportions of each tree species in the higher value timber classes from logging (from the legally required 10% up to 90%) whilst also restricting the logging of all trees in the lower value classes. For this we used two baseline scenarios: (1) logging permitted in Classes I and II (no logging of Classes III and IV), with increasing proportions of trees of each species in Classes I and II also spared from harvest; (2) logging permitted in Class I only (no logging of Classes II, III and IV), with increasing proportions of trees of each species in Class I also spared from harvest.

Harvests were simulated on all 100 modelled forests from each of the seven concessions. The resulting profit from each harvest and the carbon emitted was then estimated and compared with the full harvest baseline to calculate the opportunity cost of harvest and the total amount of carbon saved. The breakeven carbon price required to make forest protection through compensatory carbon payments a financially viable alternative to business-as-usual logging was then estimated.

2.4. Estimating carbon stocks and emissions

2.4.1. Estimating carbon stocks in unlogged primary forest

To estimate the mean carbon stock per hectare in each of our concessions prior to any logging activity, we used plot inventory data from the RADAMBRASIL (1973–1983) network that comprehensively mapped forests in 2719 1-ha (20 × 500 m) tree plots throughout Brazilian Amazonia. All trees with a CBH ≥100 cm (i.e., DBH ≥31.8 cm) were sampled, except for arborescent palms, and tree genera identified by experienced parabotanists.

Using the DBH, location and genus-specific wood density (Chave et al., 2009), we calculated the above-ground biomass (AGB) of all trees in each 1-ha plot using the allometric equations developed by Chave et al. (2014) through the R package BIOMASS (R é jou-M é chain et al., 2017). We used genus-level rather than species-level tree identification due to higher taxonomic certainty at the genus level for all RADAMBRASIL tree plots (Peres et al., 2016). Below-ground biomass (BGB) was estimated to be 0.235 that of the AGB (Mokany et al., 2006), which was added to the AGB to give the total biomass (tonnes) in each plot. Following Peres et al. (2016), we then accounted for the additional biomass contribution of trees 10–31.8 cm DBH based on empirical observations within the Brazilian Amazon (10–31.8 cm DBH trees account for 94% of the aboveground tree biomass represented by large trees >31.8 cm DBH) before converting total biomass to total carbon content (tC) using the standard factor of 0.47 (IPCC, 2006).

To estimate the mean carbon stock per hectare in each concession, the primary vegetation type of the concession was identified as per each RADAMBRASIL survey. We then took the nearest 50 RADAMBRASIL plots of the same primary vegetation type and calculated a mean biomass and carbon stock per hectare from these plots, which was then assigned to each concession.

2.4.2. *Estimating carbon emitted during harvests*

The carbon pools considered during our harvest simulations were carbon loss (above- and below-ground) of trees harvested, carbon loss through residual damage during harvest and carbon loss through the creation of logging road infrastructure. For simplicity, and to follow the previous literature (Pearson et al., 2017; Warren-Thomas et al., 2018; Griscom et al., 2014; Zalman et al., 2019), we assumed the carbon within harvested trees to be emitted fully at the time of harvest, focusing on committed emissions and following the IPCC Tier 1 assumption that all carbon extracted is emitted at the time of felling. We did not include soil carbon loss due to lack of data and highly variable findings of the impact of logging on soil carbon (Johnson and Curtis, 2001; James and Harrison, 2016; Riutta et al., 2021).

2.4.3. *Carbon stock of felled trees*

We calculated the AGB (t) of each tree felled during the harvest using the BIOMASS package (R é jou-M é chain et al., 2017) and allometric equations developed by Chave et al. (2014). Below-ground biomass of each tree was estimated to be 0.235 that of the AGB (Mokany et al., 2006). Total below and above-ground biomass were multiplied by 0.47 (IPCC, 2006) to predict the total carbon content of each tree in tC. The carbon stock lost during harvest was therefore estimated as the sum of the total carbon stored in all trees harvested.

2.4.4. *Residual damage*

Residual damage of the surrounding tree stand is commonplace in selective logging operations. We used the linear model ($r = 0.43$, $P < 0.01$) developed by Sist & Ferreira (Sist and Ferreira, 2007) based on empirical field measurements of residual damage in a Brazilian logging concession implementing reduced impact logging (RIL) techniques to estimate residual damage. The percentage of the forest stand killed during harvest (*y*) based on the logging intensity (*x*, in m^3ha^{-1}) was therefore calculated as:

$$y = 0.43x + 6.8 \tag{1}$$

To estimate the total carbon lost across the harvest through residual damage during logging, the percentage residual damage was multiplied by the total pre-harvest carbon (tC) estimate for the concession.

2.4.5. *Road network emissions*

We used spatial maps of road networks in one of the concessions (JM.i – AMATA) to estimate the percentage of road cover per hectare of logged forest. We divided the road map into three road types: Primary access roads, secondary roads and tertiary roads and assigned them an average width of 15 m, 8 m and 5 m, respectively (based on communications with AMATA). We calculated the total road area in the concession and divided this by the total area logged to calculate the percentage road cover per hectare of logged forest. We estimated percentage road cover to be 1.58%, which is consistent with the literature, and close to the median global estimate of 1.7% (Kleinschroth and Healey, 2017). We assumed that all trees >10 cm DBH overlapping the road network were destroyed during its creation, therefore estimating the total carbon lost during road construction to be 1.58% of the total area logged (in hectares) multiplied by the average carbon stock per hectare (tC) in the concession.

2.4.6. *Total carbon emitted during harvest*

We estimated the total carbon (TC) emitted through logging harvest *h* as:

$$TC_h = \sum CF_n + RD_h + RN_h \tag{2}$$

where CF_n is the total carbon stored in *n* trees felled during harvest *h*, RD_h is the total carbon lost through residual damage during harvest *h*, and RN_h is the total carbon lost through creation of a road network to facilitate harvest *h*.

2.5. *Estimating the net profit of harvest*

We used detailed financial records from one of the concessions (JM.i-AMATA) as well as public logging price data (IBAMA, 2017) to estimate the costs and returns of harvests across all seven concessions. All concessions were assumed to market FSC-certified processed sawnwood and employ RIL techniques during harvest, as declared in the concession contracts with the Brazilian Forestry Service (SFB). We adopted the profit calculations used in Bousfield et al. (Bousfield et al., 2021) and estimated the net profit (P) of a harvest *h* as:

$$P_h = \left(\sum_{1}^{x} R_x - C_x \right) - HC_h \tag{3}$$

where R_x represents the revenue of harvested tree *x*, C_x is the direct costs associated with harvesting tree *x* (including the cost of felling, processing and stumpage fees), whereas HC_h is the harvest costs incurred throughout harvest *h* (including wages, tree inventory, road construction, skidding and log transport). All calculations were made in Brazilian Real (R$) and then converted into US Dollars (USD$) based on the average exchange rate for 2018 (1 R$ = 0.28 USD$). See supplementary information for a more detailed breakdown of revenue and cost calculations.

2.6. *Calculating a breakeven carbon price*

Opportunity costs were defined as the forgone profits of logging all profitable timber within the concession. We simulated full business-as-usual harvests of all profitable timber (up to the legal maximum of 30 m^3 ha^{-1}, but harvest intensities varied between concessions based on available timber), as well as restricted timber harvests, estimating the profit made and carbon emitted during each harvest and using these figures to calculate the breakeven carbon price (BE_x - US$ per tCO_2) of each type of restricted harvest as:

$$BE_x = \frac{(P_x - P_y) + T_y}{3.67 \times (C_x - C_y)} \tag{4}$$

where P_x is the net profit generated under a full business-as-usual harvest *x*, P_y is the net profit generated under restricted harvest *y*, T_y is the total REDD + project implementation and transaction costs (estimated at $1.17/$tCO_2$ after accounting for inflation) (Olsen and Bishop, 2009), 3.67 the conversion factor from tC to tCO_2, C_x the carbon emitted during full business-as-usual harvest *x* and C_y the carbon emitted during restricted harvest *y*.

3. Results

3.1. *Preventing logging entirely*

Undertaking a full harvest of all profitable timber within concessions in accordance with Brazilian Law resulted in an average remaining carbon stock of 128.4 ± 14.2 tC per hectare. This equates to 78.6 ± 6.5% of the original pre-harvest forest carbon stock (163.3 ± 9.7 tC per hectare). The carbon price (in 2018 US$) required to cover the opportunity cost of the full logging harvest and protect the forest from logging averaged $7.90 ± 1.88 per tCO_2 across the concessions (Fig. 1). Concessions showed considerable variation in carbon breakeven prices

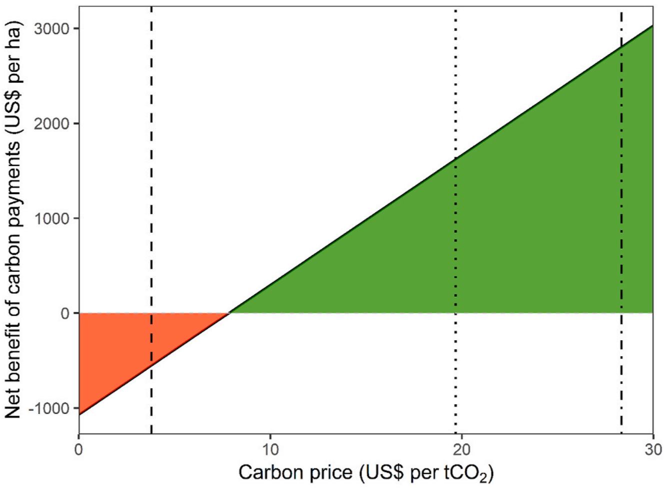

Fig. 1. The opportunity cost of forgoing logging in public logging concessions in the Brazilian Amazon. Where no carbon finance is used, forgoing logging carries an opportunity cost of ~$1071 per hectare. This opportunity cost is eliminated when carbon finance is used at a carbon price of $7.90 per tCO_2. Areas shaded in red represent carbon prices at which the opportunity cost of not harvesting is greater than the revenue provided through carbon finance, areas shaded in green represent carbon prices at which the opportunity cost of forgoing logging is exceeded and income from carbon payments generates greater returns than logging. Dashed line represents the voluntary market carbon price in 2019 (US$3.80), dotted line represents the 5-year average EU ETS carbon market price (US$19.68), and dot-dashed line represents the 2020 EU ETS average (US$28.33). These carbon prices equate to net benefits of carbon payments of -$551, $1621, and $2803 per ha, respectively.

(from $4.85–10.42 per tCO_2) due to the varying opportunity costs that reflect the spatial variation in the value of pre-harvest timber stocks (Figure S1).

3.2. *Preventing logging of certain species based on value classes*

Restricting logging of Class IV, such that only individuals in timber value Classes I, II and III were logged, maintained on average 84.9 ± 3.7% of the original forest carbon stocks. Further restrictions saved only marginally more of the original forest carbon stock, with logging only Class I and II individuals retaining 86.9 ± 3.6% and logging only Class I individuals retaining 90.5 ± 1.6% (Fig. 2a). Preventing logging of Classes III and IV, such that only Classes I and II were logged, resulted in an average carbon breakeven price of $7.97 ± 1.08 per tCO_2 (Fig. 2b). Logging Classes I, II and III (protecting Class IV) was 12.6% more expensive than logging only Classes I and II, whilst logging Class I only (protecting Classes II, III and IV) was 19.8% more expensive. Preventing logging entirely (i.e., sparing all timber trees across all value classes) thus remained the cheapest option at $7.90 ± 1.88 per tCO_2.

3.3. *Reducing extraction intensity of higher-value timber species, while preventing logging of lower-value species*

Increasing the proportion of individuals from species in the higher value classes spared from harvest, whilst restricting logging to only higher value species in Classes I and II (Scenario 1) or only Class I (Scenario 2) resulted in an increase in retained carbon stocks in both scenarios. As expected, remaining carbon stocks were higher when logging of only Class I species was permitted (scenario 2) than when logging was permitted for both Classes I and II (scenario 1) (Fig. 3a and b).

Increasing the percentage of individuals in the highest value classes spared from harvest required increasingly high carbon payments up to 80% retention. At lower proportions of higher-value individuals spared (up to 60%), carbon breakeven prices were consistently lower in scenario 1 (logging of Classes I and II) than in scenario 2 (Class I only logged): $9.44 ± 1.45 versus $10.01 ± 2.10 per tCO_2 at 50% retention. The breakeven price for increased retention of higher-value individuals thus ranged from $8.23–10.46 per tCO_2 (Fig. 3c and d).

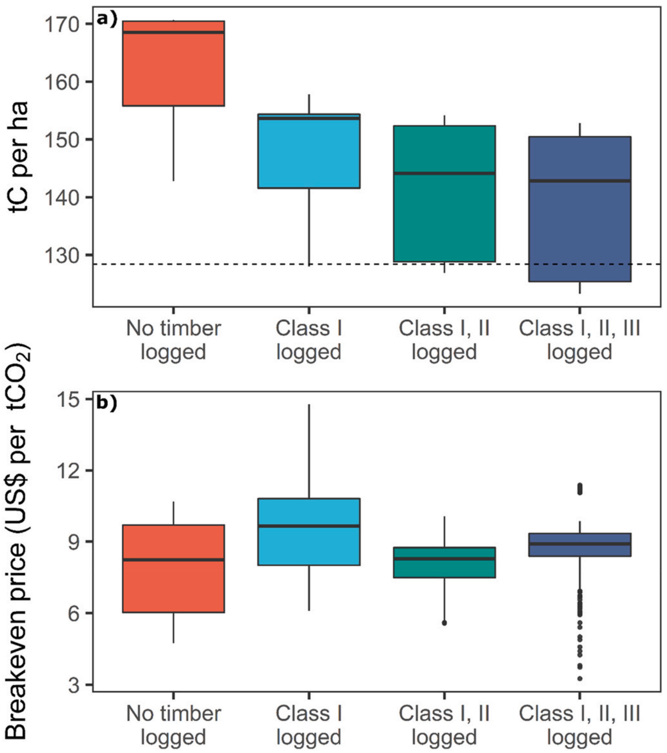

Fig. 2. Remaining carbon stocks (tC per hectare) (a) and breakeven carbon price (US$ per tCO_2) (b) for different levels of forest protection based on timber value classes, averaged across the seven concessions examined. Species were divided into four value classes based on market sale prices and timber sparing strategies were assessed, including no logging, logging only the most valuable species (Class I), logging the two most valuable species classes (Class I, II) and logging the three most valuable species classes (Class I, II, III). Central bar shows median, box shows upper and lower quartiles, whiskers extend to 1.5 × the inter-quartile range, and outliers are presented as dots. Dashed grey line represents the mean remaining carbon stock (tC per ha) of a forest where all profitable timber has been logged (up to the legal maximum harvest of 30 m^3ha^{-1}).

4. Discussion

Our simulations demonstrate that the least expensive carbon payment option to reduce the environmental damage of Amazonian logging is to prevent logging entirely, requiring payments of US$7.90 ± 1.88 per tCO_2. However, if some logging must occur — for instance, because governments would prioritise supporting downstream wood-related businesses — then permitting logging of higher-value timber species only (and sparing individuals in Classes III and IV) requires just a 12.6% higher investment whilst retaining 87% of forest carbon stocks. To alleviate significant logging pressure on populations of high-value timber tree species, only $8.59 per tCO_2 could cover the opportunity cost of sparing 30% of these individuals, while again discontinuing logging of lower-value species entirely.

4.1. *Protecting forest from all logging is cost effective*

Our estimates for the cost of protecting areas of the Brazilian Amazon from logging are considerably lower than previous estimates for Borneo ($22–$28 per tCO_2) (Fisher et al., 2011), where the opportunity costs of

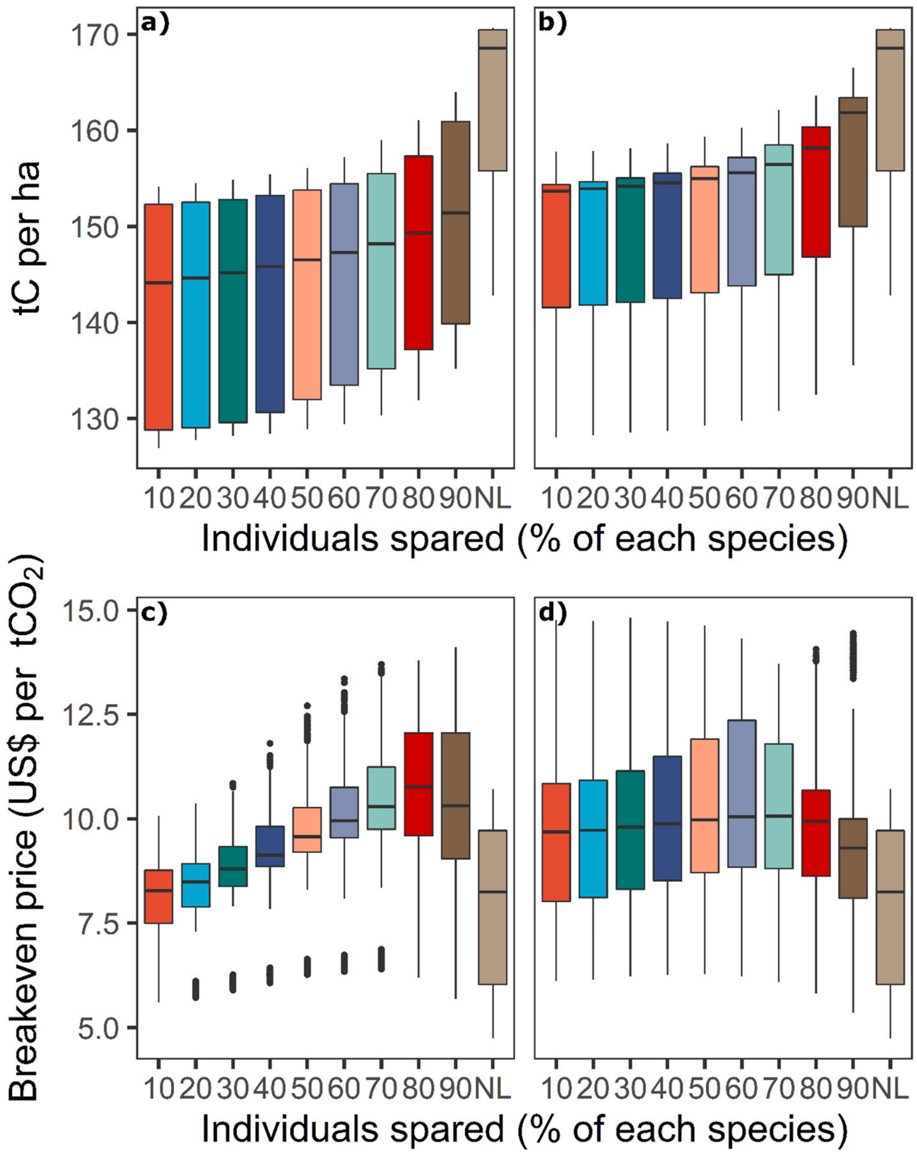

Fig. 3. Remaining carbon stocks (tC per hectare) (a, b) and breakeven carbon price (US$ per tCO_2) (c,d) for different levels of forest protection where logging is restricted to higher-value classes only (I or I and II) whilst sparing from harvest an increasing proportion (10–90%) of individuals from each species in these classes, averaged across the seven concessions examined. (a, c) Logging permitted for Classes I and II only (scenario 1), with increasing proportions (10–90%) of individuals of each species in Classes I and II spared from harvest. (b, d) Logging permitted for Class I only (scenario 2), with increasing proportions (10–90%) of individuals of each species in Class I spared from harvest. Central bar shows median, box shows upper and lower quartiles, whiskers extend to 1.5 × the inter-quartile range, outliers presented as dots. NL represents scenario where no logging occurs.

forgoing higher intensity logging than in the Amazon (Ruslandi Venter and Putz, 2011) increase the required breakeven carbon price. In Cambodia, estimates were slightly lower ($4.27 per tCO_2) (Warren--Thomas et al., 2018) than those found here, but were based on farm-gate timber prices for unprocessed timber, which points to lower profitability (and smaller opportunity costs) than the processed, FSC-certified timber products sold on the domestic and international markets we modelled (Kollert and Lagan, 2007). Our breakeven estimates also fall within the range of previous estimates for improved timber management in Gabon, where carbon payments could be leveraged to lengthen cutting cycles and increase minimum cutting diameters for US$4.40–25.90 (Ndjondo et al., 2014).

The carbon price of protection in Asia rises dramatically when also considering the opportunity cost of land conversion to agriculture ($46–48 and $30–51 per tCO_2 for Borneo and Cambodia, respectively), whereas forest conversion is prohibited in Brazilian public forest reserves. Our breakeven prices are therefore enough to protect forests entirely from legal logging or clearance, although additional costs may be incurred in enforcing the protection of these areas from illegal activities (estimated at $1.17–3.51 ha^{-1} $year^{-1}$) (Nepstad et al., 2009). These breakeven prices fall well below the 2020 average EU ETS carbon market price of US$28.33 ± 4.21 per tCO_2 (5-year average = $19.68 ± 11.69) and the US Government's social cost of carbon ($51 per tCO_2), making Amazonian forest protection a cost-effective investment in the compliance carbon market. However, average REDD + carbon prices paid in the voluntary market in 2019 were lower at ~$3.80 per tCO_2, making forest protection currently too expensive for the voluntary market.

Logging concessions in public forests currently cover 1.6 million hectares of the Brazilian Amazon. Using our predicted carbon retention and breakeven prices, carbon payment projects that fully protect these concessions from logging at a price of $7.90 per tCO_2 would avoid logging-related carbon losses of ~55.92 million tC at a total cost of ~ $1.62 billion. With logging concessions set to expand across Brazil, full protection of the 35 million hectares of public forest open to gazettement as concessions (Sist et al., 2021) could avoid carbon losses of ~1.22 PgC whilst generating ~$35.47 billion for the Brazilian economy. This carbon saving is roughly twice the net AGB carbon loss for the entire Brazilian Amazon between 2010 and 2019 due to deforestation and degradation (Qin et al., 2021). These estimates are based on simulations covering a range of different Amazonian forest structure profiles and timber densities, but should be treated with caution as they may still overlook the complex spatial variation in carbon and timber stocks across the Brazilian Amazon. Furthermore, widespread reduction of timber production could increase reliance on higher-emission building materials, such as steel or cement (Davis et al., 2018), and lead to significant job losses in the timber sector.

In addition to carbon retention, significant biodiversity benefits could be achieved through carbon payments that restrict logging entirely. Firstly, primary forests are irreplaceable for sustaining tropical biodiversity (Gibson et al., 2011). Furthermore, when no logging occurs, no road networks are created. Logging roads cause forest cover losses of 0.6–8% within concessions (Kleinschroth and Healey, 2017), facilitate further ecological exploitation through improved access for hunters and illegal loggers (Poulsen et al., 2011; Wilkie et al., 2000), and increase edge effects (Edwards et al., 2017). In the Brazilian Amazon, 95% of deforestation occurs <5 km from roads (Barber et al., 2014), demonstrating the significant benefit of full forest protection through carbon payments in avoiding further deforestation and forest degradation.

4.2. *Improving the sustainability of logging operations using carbon payments*

Whilst forgoing logging entirely represents the cheapest and most optimal option for carbon stock and biodiversity protection, policymakers may require some logging activities to meet timber demand and create jobs. Using carbon payments to prevent the logging of lower-value timber stocks still represented a cost-effective option only \$0.07 per tCO_2 more expensive than full forest protection, well below the 2020 EU compliance market price with the added benefit of providing jobs and income. Reducing logging intensity using carbon payments also offers a pathway for biodiversity conservation whilst permitting low levels of economic extraction. Well-managed selectively logged forests can still retain significant amounts of biodiversity (Putz et al., 2012), especially when RIL techniques are employed (Bicknell et al., 2014), whilst lower logging intensities result in smaller declines in species richness amongst mammals, amphibians, invertebrates, and forest-specialist birds (Burivalova et al., 2014). Nevertheless, permitting low-intensity logging would still lead to forest degradation, including extensive road networks to facilitate extraction, fragmentation of the canopy, and residual damage to the forest (Bousfield et al., 2020). Methods to prevent such degradation, and their resultant costs, would have to be considered and included during design and implementation of any carbon payment scheme.

Undertaking post-logging silvicultural interventions, such as liberation cutting and enrichment planting, could provide further biodiversity and carbon benefits whilst improving the long-term sustainability of timber harvests (Cerullo and Edwards, 2019). Alternatively, using carbon payments to protect areas of high ecological value within the concession from logging would improve conservation outcomes for old-growth specialists (Edwards et al., 2014b).

When logging focuses on high-value timber species, harvests tend to be demographically unsustainable (i.e., high grading), leading to significant changes in forest community composition (Richardson and Peres, 2016). In addition to preventing the logging of lower-value trees, carbon payments could also protect a proportion of higher-value, typically rare species (Fisher et al., 2014). Increasing the proportion of each species in value Class I and II left unharvested from the legal minimum (10%) to 30% would require an additional carbon payment of \$0.62 per tCO_2, and to 50% an additional \$1.47 per tCO_2. A small additional investment to restrict extraction levels of high-value timber species would prevent functional homogenisation of the remaining tree community, with potential knock-on effects for biodiversity (Richardson and Peres, 2016; Tabarelli et al., 2012), and retain a greater proportion of standing timber beyond the first harvest (Pereira et al., 2002).

4.3. *Study caveats*

Our simulations have four caveats. Firstly, we base our opportunity cost estimations on large FSC-certified concessions marketing high-quality, processed timber pointing to high profitability (Kollert and Lagan, 2007)' whilst our residual damage estimates are based on RIL harvest methods (Sist and Ferreira, 2007) that cause less canopy damage than conventional logging methods (Pereira et al., 2002; West et al., 2014). Where logging operations market lower-quality or unprocessed timber harvested with conventional logging techniques, opportunity costs will likely be lower whilst carbon emissions are greater, thus resulting in cheaper breakeven carbon prices. Secondly, we assume maximising profitability to be the only driver of land-use decision-making by concessionaires, but this does not capture the influence of non-carbon ecosystem services (e.g., water provisioning), cultural attachment to forests (Watson et al., 2018; Rozzi, 2012), or governmental policies. Thirdly, we simulate outcomes for Brazilian public forests concessions, and do not include community forests or land owned by indigenous groups. Whilst forest management in such areas can be sustainable and profitable (Humphries et al., 2012), and rates of degradation are often reduced (Sze et al., 2021), our economic and yield data do not allow us to address the potential of REDD + to work in these areas. Finally, we considered harvest emissions through loss of live biomass carbon, but did not account for associated emissions from heavy machinery and vehicles (Pearson et al., 2017), additional damage through skid trails construction (Goodman et al., 2019), or changes to forest soil carbon (Riutta et al., 2021). These would likely increase carbon emissions saved under restricted harvests, meaning our breakeven carbon prices may be slightly overestimated.

More broadly, REDD+ and carbon payment projects are complex. Large-scale reduction of logging activities in public forests through REDD + could restrict timber supply, encouraging leakage to meet demand via the expansion of timber plantations (particularly in Brazil's species-rich cerrado woodlands) (Stickler et al., 2009) and logging activities elsewhere (West et al., 2020). Moreover, ensuring the longevity of a project (at least the 35-year logging cycle) is difficult, and strong enforcement would be needed to prevent illegal loggers from harvesting the trees protected by carbon payments (Nasi et al., 2011). Monitoring, reporting, and verification of carbon credits can be costly and difficult to set up (K ö hl et al., 2020), whilst carbon credit payments must be transparent and avoid marginalising local people.

5. REDD + roll-out and conclusions

Despite the clear ecological benefits of using carbon payments to protect vast tracts of Amazonian forest, there are additional policy barriers to ensuring the success of carbon projects. Currently, the Brazilian government does not permit such projects in national forest concessions (Azevedo-Ramos et al., 2015) and imposes a minimum tax on the concessionaire regardless of whether any logging occurs. Without this minimum tax the cost of fully protecting primary forest drops to \$7.06 per tCO_2. Understandably, governments may not view logging activities purely through the lens of economic production, but also through tax income and job provision or, alternatively, as detrimental to their climate goals. The minimum tax imposed by the government could therefore be waved for carbon projects if guarantees were made for investment of the carbon payments into local economies. Indeed, regional or national governments could themselves set up carbon payment projects instead of allocating land to concessionaires. This would significantly reduce opportunity costs and provide the government a chance to contribute towards climate targets and invest in local communities and economies.

In conclusion, we have demonstrated that full protection of forest allocated for selective logging in the Brazilian Amazon is cost-effective under realistic carbon payment scenarios. Full protection of intact forests represents the most beneficial option for ecological and climate goals, as primary forests are irreplaceable for protecting biodiversity and store large carbon stocks. Alternatively, if some level of logging is to occur to meet timber supply and support economies, carbon payments remain a cost-effective way of restricting the intensity of logging, improving logging sustainability and maintaining significant (although still reduced) biodiversity and carbon, at only a small additional cost. If viewed as an opportunity to provide investment into local communities whilst contributing to long-term climate goals, REDD + projects in public forest concessions represent a cost-effective opportunity to protect the hyper-diverse biodiversity and extensive carbon supported by the Brazilian Amazon.

Credit author statement

Christopher Bousfield: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft.; **Mike Massam**: Resources, Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing.; **Carlos Peres**: Resources, Data curation, Writing – review & editing.; **David Edwards**: Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115094.

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