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# Land-sharing logging is more profitable than land sparing in the Brazilian Amazon

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## Abstract

Selective logging is pervasive across the tropics and a key driver of forest degradation. Two competing harvest management strategies have been proposed: Land sharing via low-intensity logging throughout a concession; and high-intensity land-sparing logging across a smaller area, protecting part of the concession as primary forest. Empirical research points to land sparing being more optimal for maintaining biodiversity and carbon, especially under secure land tenure, but a key question for forest-based economies is how each strategy affects the profitability of logging. We combine detailed financial data with harvest simulations to assess the profitability of land-sharing and land-sparing logging in the Brazilian Amazon. Under business-as-usual, land-sharing is significantly more profitable than land-sparing logging, whether sparing is conducted in a single block or targeting the highest-density timber stocks, highlighting a conflict between economic and conservation priorities. Land-sharing logging is also more profitable than hybrid strategies whereby a mix of land-sharing and land-sparing logging is employed. Conservation-based restrictions that apply quotas on species in different size classes reduces the opportunity cost of land sparing, but even under tight restrictions land sharing remains more profitable and land sparing often returns a loss. Additional financial incentives, including timber certification schemes and carbon-based payment for ecosystem services, are needed to bridge the opportunity cost of land-sparing logging and minimise ecological damage to tropical rainforests.

**Keywords:** land-sparing versus land-sharing logging, tropical forest, forest degradation, REDD+, Amazon.

## Introduction

Over 403 million hectares of tropical forest are committed to selective logging [1], with the expansion of logging set to continue to meet increasing demand from growing populations, increased urbanisation, and consumerism [2,3]. Yet the tropics are home to two-thirds of global biodiversity [4] and key carbon stocks [5]. As the most powerful force of tropical forest degradation [6, 7], selective logging is responsible for 6% of tropical greenhouse gas emissions [8] and reductions in forest-interior biodiversity [9, 10].

To minimize ecological damage, governments, certification schemes (e.g. Forest Stewardship Council- FSC, Programme for the Endorsement of Forest Certification- PEFC), and emerging carbon-based payments for ecosystem service schemes (e.g. REDD+) mandate or incentivise implementation of improved logging practices. Adoption of Reduced Impact Logging (RIL) [11] to reduce residual damage and soil compaction [12], enhance biomass recovery [13] and lessen biodiversity losses [14] is one example, whilst legally restricting maximum harvest intensities [15] and minimum cutting diameters [16] also contributes towards improving sustainability.

The spatial arrangement of logging within a concession—embodied by the land-sharing and land-sparing paradigm [17, 18]—can also generate varied environmental outcomes. Under land sharing, low-intensity timber extraction is implemented throughout the entire forest concession, whereas under land sparing, smaller areas of a concession are harvested at high intensity allowing the remainder to be protected as unlogged forest. In Borneo, more bird, dung beetle and ant species have higher abundance under land-sparing regimes [17], while in the Amazon, a mixed strategy would benefit understorey butterflies [19] and high sensitivity of dung beetles to even low-intensity logging suggests that land-sparing logging would be beneficial [20]. More broadly, pan-tropical modelling suggests that land sparing would benefit both biodiversity and forest carbon under secure land tenure scenarios [21]. Conversely, it has been suggested that better conservation outcomes can instead be achieved through focusing on improved logging management strategies (e.g. RIL) [22], or that mixed strategies can better achieve all forest stakeholder objectives [23].

A crucial knowledge gap is whether land-sparing or land-sharing logging yields higher net profitability, underpinning attempts to identify an optimal balance between more sustainable economic production and environmental protection. Financial incentives are strong drivers of ecological exploitation [24], with the potential opportunity costs of implementing either land-sharing or land-sparing logging, plus the impacts of increasingly stringent harvest regulations [25, 26], likely the core driver of harvest strategy. Thus, improved understanding of the profitability of timber extraction strategies can underpin appropriate incentives for improved logging practice, and associated policy and sustainable development goals.

Here, we focus on the Brazilian Amazon, which has the largest unexploited timber reserves globally, with an estimated 1.2 billion $m^3$ of profitable timber valued at over $15.4 billion [27]. Currently, 55 forest reserves covering over 30 million hectares in the Brazilian Amazon—an area roughly the size of Germany—are slated for timber extraction, of which 1.5 million hectares have already been granted as forest concessions. We use spatial maps of >660,000 adult trees across seven Amazonian logging concessions spanning 52,000 ha and detailed financial data from concessionaires and the Brazilian Institute of Environment and Natural Resources (IBAMA) to generate harvest simulations. Using our simulations, we estimate the profits associated with land-sparing, land-sharing and hybrid harvest strategies, under varying conservation scenarios that restrict yields or access to harvestable tree species.

## Methods

### Study Sites

We used seven logging concessions located throughout the Brazilian Amazon as study sites. (Figure 1). These sites span a broad spectrum of forest structure profiles, including high basal-area closed-canopy stands and lower basal-area stands containing high densities of natural canopy gaps. The *terra firme* forests store large amounts of carbon, contain diverse canopy tree communities reaching heights of up to 50m and support extensive biodiversity. Annual rainfall across sites ranges from 2005-3324mm and the max elevation is 236m.

Extensive pre-harvest forest inventories were carried out in each concession, where all trees ≥40 cm DBH representing commercially viable species were georeferenced and tagged. These forest inventories provide us with specific attribute data for >660,000 individual trees, including species, size and geo-location, spanning a total of ~52,000 ha of undisturbed Amazonian forest.

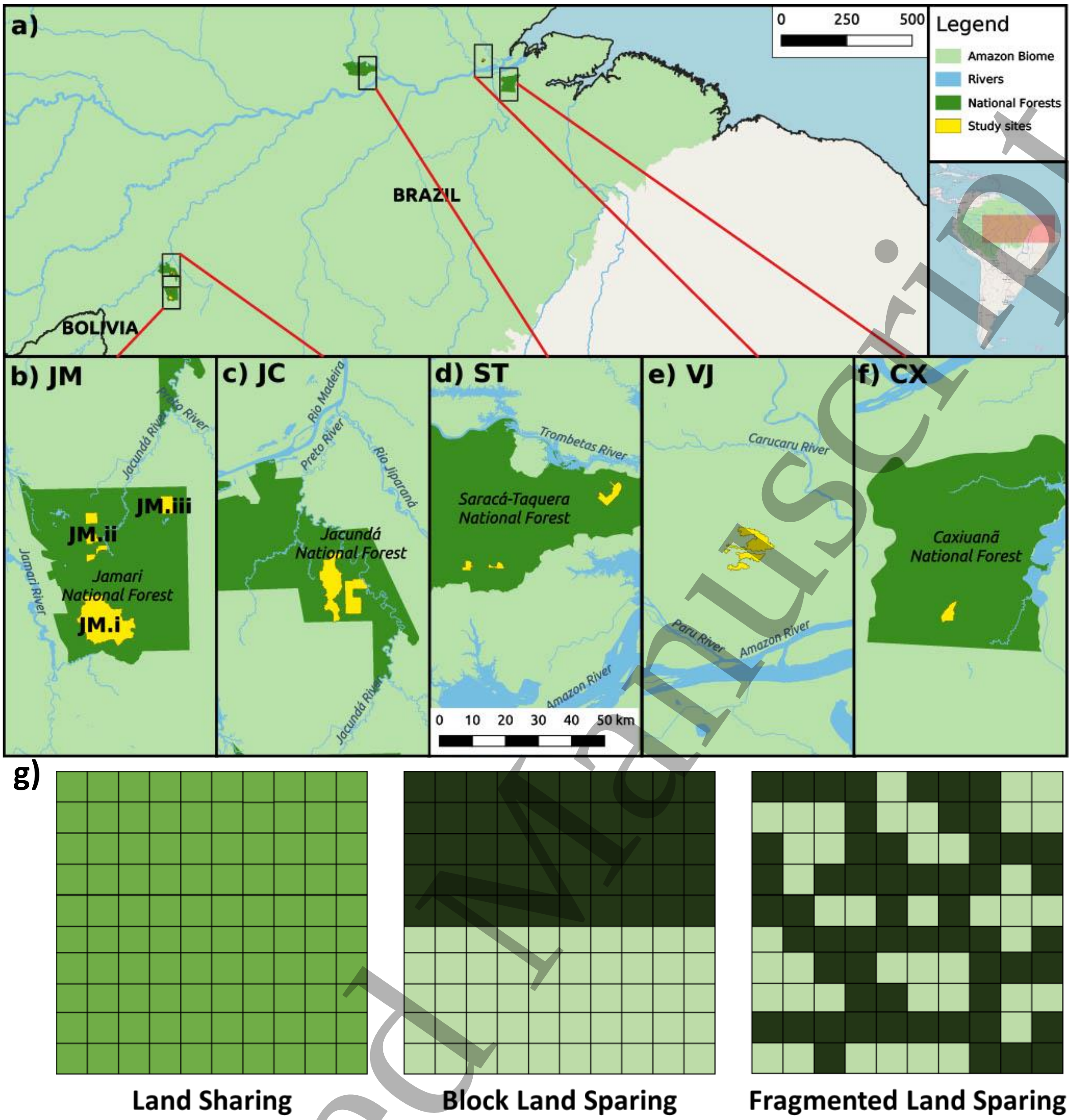


**Figure 1.** Concession map and harvest strategies. a) Map of studied logging concessions within the Brazilian Amazon. b) Three are located in the Jamari National Forest (JM.i, JM.ii, JM.iii) in Rondônia; c) one is located within the Jacundá National Forest (JC) in Rondônia; d) one in the Saracá-Taquera (ST) National Forest Pará (one concession in several locations); e) one in the Jari Valley region (VJ), Pará; f) and one in Caxiuanã (CX) National Forest, Pará. Concession areas are marked in yellow, whilst dark green areas depict the boundaries of the National Forests. g) Three alternative logging harvest strategies. Land-sharing involves low-intensity logging throughout the entire concession (mid-green squares) whilst land-sparing involves high intensity logging throughout part of the concession (pale green squares), whilst setting aside the remaining area of unlogged primary forest for conservation (dark-green squares). Here two forms of land sparing are simulated: block land-sparing, where retention of large contiguous areas of unlogged primary forest is prioritised; and fragmented land-sparing, where only the most valuable forest areas are prioritised for harvesting.

## Harvest Simulations

### *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 community of trees, in which species aggregation patterns, tree volumes and DBH were reproduced based on models of the original species-specific spatial and size distributions and DBH-volume relationships (SOM Methods 1). Harvest simulations were subsequently conducted on each simulated forest. Harvests were also simulated on the original concessions, but we present the results from the simulated forests as they exhibit the same patterns.

### *Simulating Harvests*

Under all scenarios, harvests were simulated following legal guidelines. The most common and/or valuable commercially viable species were included in the pool of trees available for harvest (>200 species), leaving protected species, non-marketable species, and trees <50 cm DBH unharvested (in accordance with Brazilian law) [28]. The harvest quota in terms of basal area density for land-sharing and land-sparing comparisons was 20 $m^3$ $ha^{-1}$, as is typical in National Forests such as the concessions studied here, but intensities of 10 $m^3$ $ha^{-1}$ and 30 $m^3$ $ha^{-1}$ were also simulated.

### *Land-sharing under business-as-usual*

To simulate land-sharing harvests, we created a function that divided the concession up into 25-hectare grid cells, and then harvested the most valuable standing tree in each cell in a continuous cycle until the average harvest intensity reached the pre-assigned quota.

### *Land-sparing under business-as-usual*

To simulate land-sparing harvests, two different functions representing different harvest priorities were used (Figure 1). The first is 'Block land-sparing', where harvesting prioritises maintaining a large area of spatially contiguous unlogged forest by restricting the harvest to a single block of intensively logged forest. Here, concessions were divided into 25-hectare grid cells, with harvesting starting in one corner of the concession and fanning out to adjacent grid cells. All harvestable trees in each harvested cell were taken until the average quota was met, thereby sparing the rest of the concession as contiguous primary forest. The second is 'Fragmented land-sparing', in which areas of the greatest economic value are targeted for harvesting. This function divided the concession into 25-hectare grid cells, then ranked cells by the total value of all trees within the cell. All harvestable trees in the most valuable cells were harvested until the total volume logged reached the harvest quota.

We undertook sensitivity analysis to test the impact of future scenarios of variable transport and infrastructure costs, as well as reduced stumpage fees on the profitability of both land-sparing and land-sharing logging (SOM Methods 2).

### *Hybrid harvest strategies*

We tested the profitability of a mixed range of hybrid harvest strategies, whereby differing proportions of the concession were allocated to land sharing and land sparing harvests. For this scenario, we randomly selected 10 forests from each concession to undergo each level of a mixed strategy (i.e. from 100% sharing and 0% sparing, to 0% sharing and 100% sparing in increments of 1%) and calculated the resulting profits from each mixed strategy. We used only block-sparing as the land sparing method in this scenario (not fragmented sparing), as this represents the purest form of land sparing which would be implemented within a mixed strategy to achieve ecological benefits.

## *Conservation Measures*

We tested the effect of increased conservation-based restrictions on the profitability of each harvest method by re-running harvest simulations requiring minimum percentages of all species to be protected from harvest. We tested two different conservation measures:

***Scenario 1: Protection of the smallest adult trees***. Requirement to protect up to 60% of all adult trees (>50 cm DBH) of each species, allowing harvesting of the largest trees to permit higher incomes and promote retention of adult trees for future harvest [29].

***Scenario 2: Protection of the largest adult trees***. Requirement to protect up to 50% of the largest trees of each species, to maintain forest structure and the key ecological roles fulfilled by large trees [30, 31], including seed production, habitat provision [16] and carbon storage [32].

For each iteration of the conservation-restriction harvests, we randomly selected 10 of the 100 simulated forests for each concession to undergo logging under each level of restriction (i.e. from 1-60% protection at 10 $m^3$ $ha^{-1}$, 10 random forests were selected for each proportional protection, totalling 600 simulated harvests per concession). The maximum protected percentage varied between harvest intensities to ensure the required harvest quota could still be met.

## Profit calculations

The net revenue accrued from each harvest was calculated using species-specific timber prices, extraction costs and yield data. Our detailed revenue and cost data came from AMATA (JM.i), a sustainable timber harvesting company responsible for timber harvest in the Jamari National Forest, Rondônia. AMATA's cost data was reprojected on to the other concessions for profit estimations (whilst controlling for concession size or volume output). All but one of the concessions are located in National Forests and form part of the ongoing initiative by the Brazilian Government to award logging concessions on public forested lands [33]. We thus assumed they would market similar wood products at similar prices and incur similar harvest costs as FSC-certified forest concessions. Average selling prices for commercial timber species present in other concessions but not sold by AMATA were obtained through IBAMAs Document of Forest Origin [34] and price transformed to match the premium charged by AMATA for high quality, FSC-certified timber (SOM Methods 3).

### *Revenue*

Gross revenue per tree was calculated using species-specific timber prices and yield data. Revenue considered the wastage of wood in the sawmill processing phase and was calculated for each individual tree ($R_x$) thus:

$$R_x = \sum_{1}^{x} V_x O_y P_y \qquad \textit{Eq. 1}$$

Where $V_x$ is the total volume of the logged tree *x*, $O_y$ is the proportional output yield after processing of species *y*, and $P_y$ is the sale price per $m^3$ of processed wood for species *y*.

### *Costs*

Detailed harvesting costs were divided into direct costs associated with tree felling and harvest costs incurred throughout the harvest.

***Direct Costs***

Direct costs were calculated per $m^3$ of timber and included contractually agreed government stumpage fees, costs of felling and sawmill costs. Direct harvest costs were calculated for each tree ($C_x$) thus:

$$C_x = \sum_{1}^{x} V_x \left(S_y + Cf\right) + V_x O_y M_y \qquad \textit{Eq. 2}$$

Where $V_x$ is the total volume of the logged tree *x*, $S_y$ is the stumpage fee per $m^3$ for species *y*, Cf is the cost of felling per $m^3$, $O_y$ is the output yield after processing of species *y*, and $M_y$ is the cost of operating the sawmill per $m^3$ of processed wood produced for species *y*.

***Harvest Costs***

Harvest costs were calculated as a total cost across the concession and included administration (wages), conducting a full forest census, road network construction, skidding and roundlog transport. These costs were calculated post-harvest for harvest *h* thus:

$$HC_h = CA_x + CE_s + RC_x + SK_x + LT_x \qquad \textit{Eq. 3}$$

Where $CA_x$ is the total administrative costs (including wages) for *x* $m^3$ of timber harvested, $CE_s$ is the total cost of conducting a full tree census of a concession *s* hectares in size, $RC_x$ is the total road construction cost for *x* $m^3$ of timber harvested (weighted for each harvest method- SOM 4), $SK_x$ is the total cost of skidding for *x* $m^3$ of timber harvested, and $LT_x$ is the total cost of roundlog transport for *x* $m^3$ of timber harvested.

***Profit***

The total profit (P) from harvest *h* was calculated as such:

$$P_h = \left(\sum_{1}^{x} R_x - C_x\right) - HC_h \qquad \textit{Eq. 4}$$

Where $R_x$ represents the revenue of harvested tree *x*, $C_x$ is the direct costs associated with harvesting *tree x*, and $HC_h$ is the harvest costs incurred throughout harvest *h*. All calculations were made in Brazilian Real (R$) before being converted to US Dollars (USD$) based on the average exchange rate for 2018 (1R$ = 0.28 USD$). We calculated profits on a per hectare basis, as well as a per $m^3$.

## Results

### *Land-sharing and land-sparing with varying logging intensity*

In all concessions across all three harvest intensities, land sharing was more profitable per hectare than either form of land sparing (Figure 2). At 20 $m^3$ $ha^{-1}$, land sharing generated mean profits of \$512 ± 449 per hectare whilst block and fragmented land sparing generated mean losses of \$117 ± 220 and \$10 ± 254 per hectare, respectively, with the broad confidence intervals reflecting high variation in profitability between concessions. Land sharing was also most profitable at all harvest intensities on a volumetric (per $m^3$) basis, although land-sparing profitability per $m^3$ improved slightly with harvest intensity while land-sharing profitability fell, reducing the difference between the two strategies (Figure S3).

Profitability was highly dependent on the concession, with some generating net profits of over \$1,000 per hectare under sharing scenarios and \$500 under sparing, whereas others generated losses of up to \$200 per hectare under sharing and \$400 per hectare under sparing. In five of the six concessions where it was possible to extract up to 30 $m^3$ $ha^{-1}$, land sharing was more profitable at 20 $m^3$ $ha^{-1}$ than at 30 $m^3$ $ha^{-1}$. In the four concessions where profitability was low and harvests generated a loss in most scenarios, land sharing at 10 $m^3$ $ha^{-1}$ was the most profitable of all methods.

Under our 20 $m^3$ $ha^{-1}$ harvest scenarios, the average extent of harvest was 99.4 ± 1.5% of the concession area under land-sharing, 44.1 ± 9.1% for fragmented sparing and 49.6 ± 8.3% for block sparing. There were minimal differences in the costs per $m^3$ harvested between any of the harvest methods (Table S2).

Altering the transport costs and applying reduced stumpage fees found the profitability benefit of land-sharing to be robust to even the most drastic future changes (i.e. a 200% increase in transport costs and 100% stumpage fee reduction). For all harvest types, road construction and skidding costs exhibited a negative linear relationship with profit, but land sharing remained the most profitable harvest method in all scenarios (Figure S5). Reducing the stumpage fees increased profits in all scenarios but also had minimal effect on the relative profit benefit of land sharing over land sparing (Figure S6).

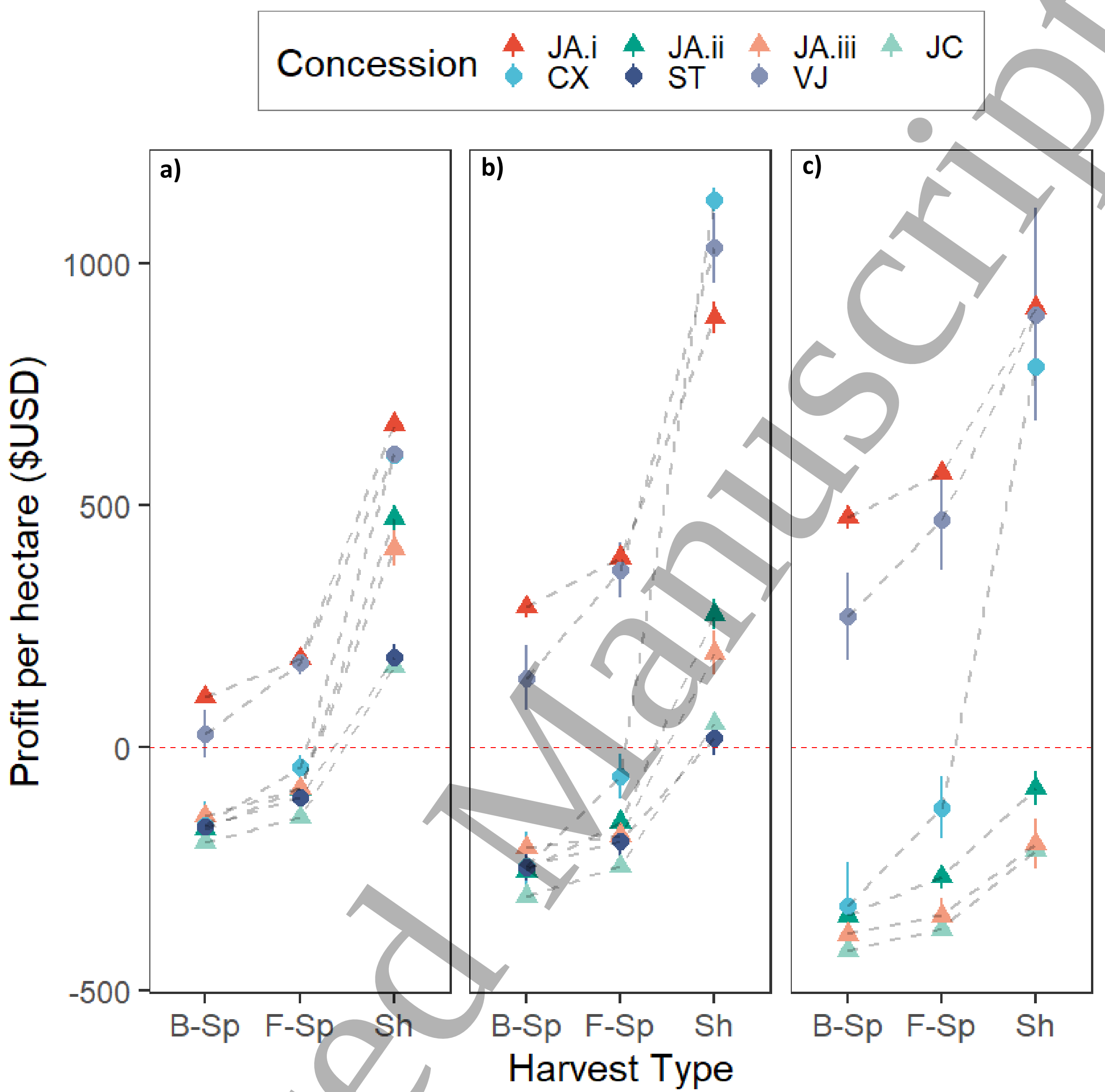


**Figure 2.** Profit per hectare ($USD) associated with block land-sparing (B-Sp), fragmented land-sparing (F-Sp), and land-sharing (Sh) timber harvest strategies in the Brazilian Amazon. Predictions are based on 100 simulated forests for each concession with an average harvest intensity of (a) 10, (b) 20 and (c) 30$m^3$ $ha^{-1}$. Points represent the mean, and lines extend one standard deviation away from the mean. Red line represents breakeven point where neither a profit nor a loss is made. Triangles represent concessions within Rondônia, circles represent concessions within Pará. Concession codes are as follows: JA.i = Jamari (Rondônia); JA.ii = Jamari (Rondônia); JA.iii = Jamari (Rondônia); JC = Jacunda (Rondônia); CX = Caxiuanã (Pará); ST = Saracá-Taquera (Pará); VJ = Jari Valley (Pará).

***Mixed Harvest strategies***

Mixed harvest strategies from complete sparing to complete sharing revealed a negative linear correlation between the proportion of land allocated to land sparing and the average profitability per hectare for six concessions, and a negative non-linear relationship in one concession (JC) (Figure 3). Complete land sharing (i.e. 100% of land allocated to sharing) was more profitable than any mixed combination of sparing and sharing strategies in all concessions, although the impact on timber revenues of increased sparing allocations varied between concessions. In one concession (CX) an even mix of sparing and sharing resulted in a 62% lower profit than full sharing but in another concession (JA.i) an even mix only resulted in a 32% lower profit. An even mix of strategies led to harvests making losses in three of the seven concessions.

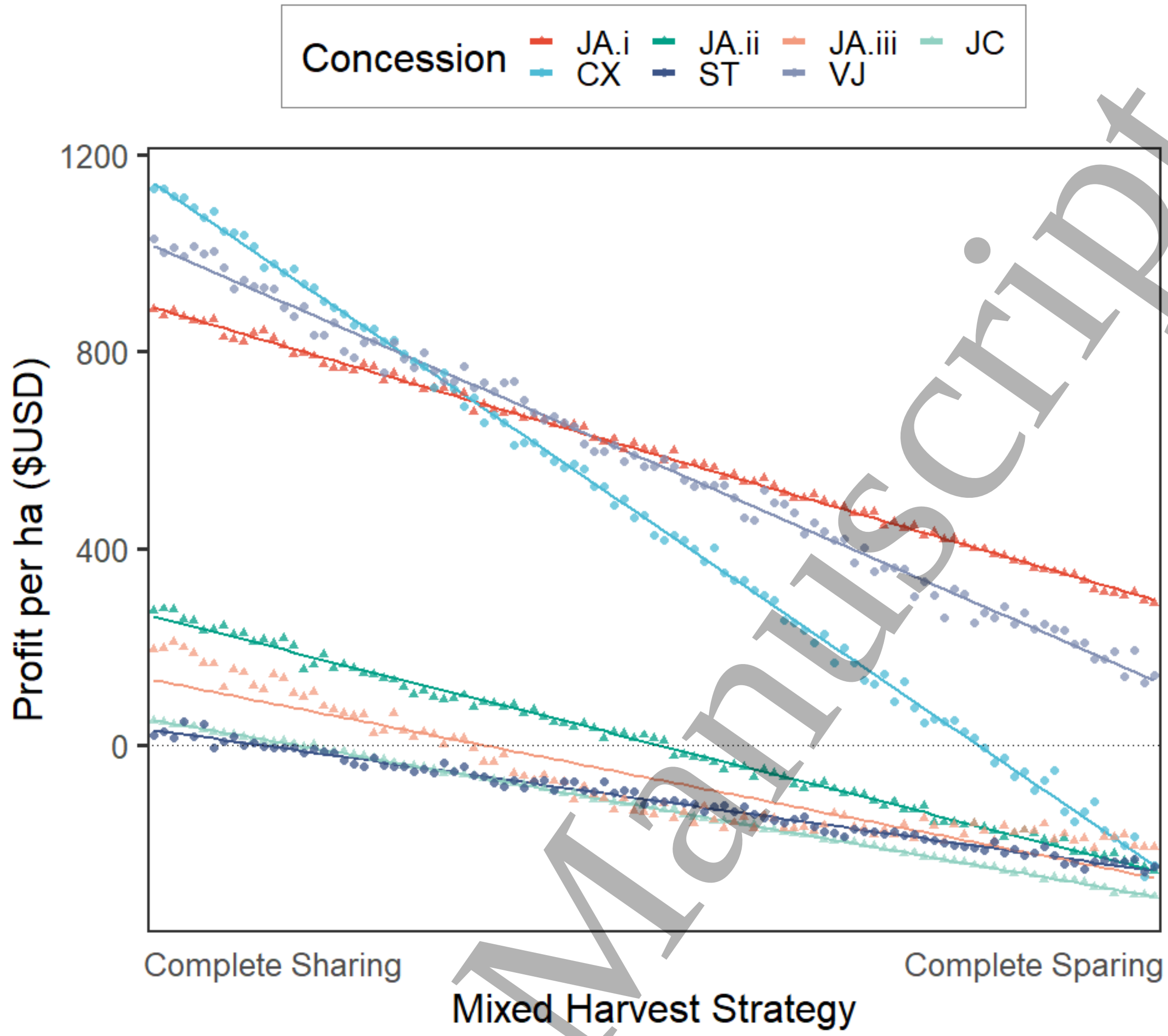


**Figure 3.** Profit per hectare ($USD) along a continuum of mixed harvest strategies at an intensity of 20 $m^3$ $ha^{-1}$, ranging from complete land sharing to complete land sparing. Points represent the mean profit of the concession at each level of strategy mix, solid line represents a linear model fit. Dotted line represents the breakeven point where neither a profit nor a loss is made. Triangles and circles represent concessions within the Amazonian states of Rondônia and Pará, respectively. Concession codes are as follows: JA.i = Jamari (Rondônia); JA.ii = Jamari (Rondônia); JA.iii = Jamari (Rondônia); JC = Jacunda (Rondônia); CX = Caxiuanã (Pará); ST = Saracá-Taquera (Pará); VJ = Jari Valley (Pará).

***Land sharing and sparing under conservation restrictions***

The relative benefit of land-sharing over land-sparing logging was highest with no conservation restrictions (e.g. \$522-630 per ha more profitable at 20 $m^3$ $ha^{-1}$). As increasingly stringent conservation restrictions were introduced, the relative profit benefit of land-sharing declined (Figure 4). Where the smallest adult trees were protected (Scenario 1), land-sharing profitability declined non-linearly at all intensities, with increasingly severe reductions in profitability at higher protection levels, whereas land-sparing profits either remained stable or decreased slightly. Nevertheless, even at the highest level of protection land sharing remained the most profitable method (e.g. \$168-231 more profitable at 20 $m^3$ $ha^{-1}$ with 60% of each species protected; Figure 4a-c).

When the largest adult trees of each species were protected (Scenario 2), increasing protection levels had a negative impact on the profitability of both land sharing and fragmented land sparing, although sharing profits suffered greater declines. At the highest levels of protection under all harvest intensities sharing remained the most profitable method, but the relative profit benefit over sparing was much lower (e.g. \$96-114 more profitable at 20 $m^3$ $ha^{-1}$ with 25% of the largest individuals protected; Figure 4d-f).

In both conservation scenarios, the percentage of species protection was positively correlated with the spatial extent of harvest for both fragmented and block land sparing. At an intensity of 20 $m^3$ $ha^{-1}$, harvests covered 44 ± 9% (fragmented) and 50 ± 8% (block) of the concession with no species protection, but under Scenario 1 harvests extended to 72 ± 11% and 77 ± 10%, respectively, of the concession area at 60% protection. At the highest restriction for 30 $m^3$ $ha^{-1}$ harvests (30% species protection), land-sparing harvests covered >84% of the concession. Similar patterns were observed under Scenario 2 (largest adults protected; Figure S4).

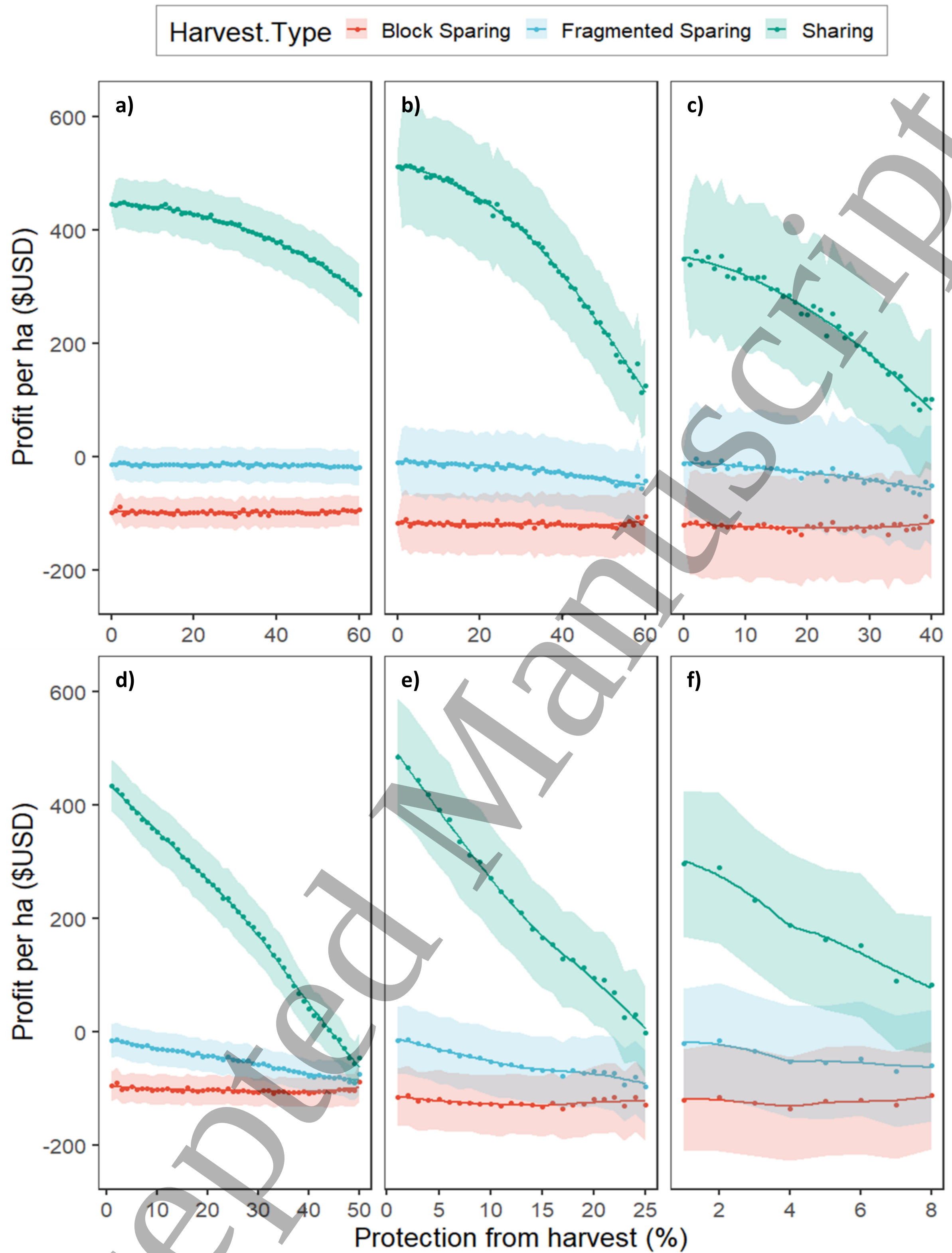


**Figure 4.** Profit per hectare($USD) of land-sparing and land-sharing logging under conservation measures. (a-c) Increasing percentage of smallest adult trees (DBH>50cm) of all species that must be protected from harvest (0-60%) at intensities of 10 (a), 20 (b) and 30 $m^3$ $ha^{-1}$ (c). (d-f) Increasing percentage of largest adult trees (DBH>50cm) of all species that must be protected from harvest (0-30%) at intensities of 10 (d), 20 (e) and 30 m3 ha-1 (f). Points represent the mean values of all concessions whilst coloured areas represent the 95% confidence interval.

## Discussion

We found land sharing to be considerably more profitable than land-sparing logging across a broad spectrum of forest structure profiles in the southwestern central and eastern Brazilian Amazon, including high basal-area closed-canopy stands and lower basal-area stands containing high densities of natural canopy gaps. Imposing conservation restrictions on harvests reduces the relative profit benefit of land sharing over land sparing, but often makes land sparing unprofitable. Our study highlights the need for economic incentives to protect primary forest patches within the logged forest matrix, reduce road penetration and associated forest degradation, and limit over-harvesting of target species. Such options would likely minimise the local ecological and biodiversity damage of selective logging in the Amazon, improving sustainability, although at larger scales may increase the rate of concession licensing and entry into old-growth forest.

Land-sharing logging across the entire concession was more profitable than land sparing, which returned a loss in four of the seven concessions. Amazonian tree communities are typically dominated by low-value species, with large high-value trees rare and sparsely distributed [35]. Logging throughout the concession at low intensities thus facilitates exploitation of rare higher-value stems, driving elevated profits. Similar timber value structures throughout the Amazon suggests the profit patterns reported here would be replicated in concessions across Amazonia. In South-east Asia, forests are dominated by dipterocarp tree species of similar value [36], likely favouring the profitability of land sparing. Furthermore, no mixed strategy of land sparing and land sharing across concessions improved profits over complete sharing, despite suggested ecological benefits of this approach [18, 19].

While the profit benefit of land-sharing declined relative to land-sparing logging under increasingly stringent conservation scenarios, it remained more profitable. Brazilian law requires a minimum of 10% of adult trees of each species to be protected [28], which our simulations show has minimal impact on the profits of either sharing or sparing. Retention of more individuals promotes longer-term profitability beyond the first harvest [37, 38], as high value stems are present in future cutting cycles. However, the increased spatial extent of land-sparing logging under conservation restrictions highlights a trade-off that could threaten the ecological benefits of land sparing from primary forest retention via reduced harvest extent and smaller road networks [17]. Stringent conservation restrictions thus push land-sparing logging towards an increasingly land sharing-type strategy. Currently, logging practices in the Brazilian Amazon are unsustainable [39, 40], and without reducing the intensity of timber extraction, increasing species retention (as simulated here), and extending recovery time between harvests, it is unclear whether land-sparing or land-sharing logging would be sustainable beyond the first harvest.

Our simulations have five caveats. Firstly, estimates are based on the revenue and costs of a logging organisation employing RIL techniques, marketing premium FSC-certified products [41] processed at their nearby sawmill, pointing to higher profits than operations using conventional logging techniques, marketing non-certified products, or lacking a sawmill. Secondly, we used species-specific prices and stumpage fees, providing more accurate revenue predictions than previous studies that categorise Amazonian species into three timber value bands [27, 42]. Price volatility between years could render low-value stems – often harvested under land sparing – unprofitable in some years. Thirdly, we modelled economic returns across a single harvest, but available timber in subsequent harvests (Brazilian law requires a minimum 30-year cycle between harvests) may only recover 50% of its original volume under optimistic 30-year scenarios [43, 44], likely negatively impacting the profitability and sustainability of future harvests under both strategies. Thus, in all but our most stringent (and often unprofitable) conservation scenarios, a single harvest rotation would likely require over a century of recovery before timber yields and profitability can recover. Fourthly, despite widespread illegal logging in the Amazon at high intensities (~40 $m^3$ $ha^{-1}$) [28, 45], we did not model harvests above the legal limit of 30 $m^3$ $ha^{-1}$ because they exceeded the average volume of profitable timber in our concessions, plus illegal operations do not engage in spatial planning or other attempts to reduce ecological damage. Finally, we were unable to account for spatial differences in harvest costs across the concession (e.g. higher harvest costs in difficult to harvest areas such as steep slopes). Under block-sparing, harvest costs could be optimised by focusing on cheaper areas of harvest.

The economic benefit of timber extraction under land-sharing in the Brazilian Amazon suggests that logging companies will preferentially use this approach, which will have key implications for Amazonian biodiversity. For Bornean birds, dung beetles, ants and Amazonian dung beetles, land sparing appears optimal [17, 20], while mixed strategies are optimal for Amazonian butterflies [19], underscoring the importance of retaining large blocks of unlogged primary forest.  While decreased timber extraction better maintains local forest structure [46] and carbon stocks [8], concession-wide estimates of carbon impacts of land-sparing and land-sharing logging suggest the least damaging practice is strongly influenced by land tenure security [21]. Further, construction of roads leads to forest cover losses of 0.6-8% within concessions, contributing up to 50% of logging carbon emissions [47], plus facilitating increased human migration, forest clearance and hunting after logging operations cease [48]. Our harvest simulations suggest that block land sparing saves ~50% of the concession as primary forest, which could be spatially optimised to protect areas with the highest conservation value, whilst meeting harvest quotas, significantly reducing road network size, and thus offering a key pathway for reducing carbon and biodiversity losses under land sparing. Land sparing therefore appears more optimal than land sharing for Amazonian biodiversity, but low profitability presents a barrier to its implementation across the Amazon.

### *Policy Implications and Conclusion*

Promoting land-sparing over land-sharing logging to limit forest degradation requires either more stringent government regulation or market-based incentive mechanisms. Governments may act to protect longer-term wood security, timber-earned revenue streams, and employment, or more broadly to deliver on climate and biodiversity goals (e.g. SDGs 13 and 15). For Brazilian logging concessions in public forests, the government already offers tax reductions for beneficial activities, including social investments [33]. Linking reductions in stumpage fees to less-disruptive harvest strategies would reduce the opportunity cost of doing so, e.g. a 25% reduction in stumpage fee would switch some land sparing operations from loss to profit making. Additionally, given that profit per hectare of current logging practices (i.e. land sharing) at 30 $m^3 ha^{-1}$ was lower than profit per hectare at 20 $m^3 ha^{-1}$ in the majority of concessions, reducing the legal cutting limits in lower basal area forests to 20 $m^3 ha^{-1}$ would protect economic returns whilst reducing unnecessary damage to forest biodiversity and carbon stocks. However, any concerted attempt to shift land management strategies (e.g., towards land sparing) must consider the social and institutional implications for all stakeholders beyond profitability and ecological conservation aims. In particular, key considerations will be the impact on timber-related job provisioning and the local community benefits of sustainable forestry in these areas.

Market-based mechanisms, including timber certification schemes, REDD+ and RIL-C (which explicitly focus on improving carbon retention via improved harvest strategies)

[21], could remove the opportunity cost of land-sparing logging through price premiums and carbon payments, especially when applying more stringent cutting limits on a per species basis. For instance, inclusion of land-sparing logging criteria within FSC-certification requirements would create an explicit link to the FSC timber price premiums of 27-57% [41]. Similarly, if land sparing reduces emissions, especially via reduced road networks, then carbon payments could be leveraged to eliminate the opportunity cost.

Our simulations demonstrate that land-sharing is more profitable than land-sparing logging in the Brazilian Amazon across a range of logging intensities and conservation-focused harvest restrictions. This suggests a conflict between economic interests and conservation of biodiversity and carbon. Stringent harvest restrictions reduce the opportunity cost of land-sparing, improve its longer-term profitability, and minimise multi-decade forest compositional decay through persistent high-grading [49], but economic incentives will be required to promote genuine shifts in logging behaviour towards land-sparing logging. While there is some scope for legal frameworks to promote this shift, market-based mechanisms are critical in promoting change. Accurately quantifying the differences in carbon emissions between the two methods will be crucial in assessing this possibility. As Brazil and other Amazonian countries continue to look towards large-scale timber concessions as a means of economic production, ensuring widespread use of optimal harvest strategies will become progressively more important in protecting the globally significant biodiversity and carbon that these forests support.

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