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Optimal strategies of Ecosystem Services provision for Amazonian production forests

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9 Optimal strategies of Ecosystem Services provision 1
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13 for Amazonian production forests 2
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Abstract

Although tropical forests harbour most of the terrestrial carbon and biological diversity on Earth they continue to be deforested or degraded at high rates. In Amazonia, the largest tropical forest on Earth, a sixth of the remaining natural forests is formally dedicated to timber extraction through selective logging. Reconciling timber extraction with the provision of other ecosystem services (ES) remains a major challenge for forest managers and policy-makers. This study applies a spatial optimisation of logging in Amazonian production forests to analyse potential trade-offs between timber extraction and recovery, carbon storage, and biodiversity conservation. Current logging regulations with unique cutting cycles result in sub-optimal ES-use efficiency. Long-term timber provision would require the adoption of a land-sharing strategy that involves extensive low-intensity logging, although high transport and road-building costs might make this approach economically unattractive. By contrast, retention of carbon and biodiversity would be enhanced by a land-sparing strategy restricting high-intensive logging to designated areas such as the outer fringes of the region. Depending on management goals and societal demands, either choice will substantially influence the future of Amazonian forests. Overall, our results highlight the need for reevaluation of current logging regulations and regional cooperation among Amazonian countries to enhance coherent and trans-boundary forest management.

Keywords Amazonia; selective logging; multicriteria optimisation; ecosystem services; timber production; carbon; biodiversity

Introduction

By storing about 30% of the Earth's terrestrial carbon [1] and half of the world's biodiversity [2], regulating hydrological cycles [3], and furnishing a wide range of timber and non-timber goods, tropical forests are critical for human welfare and climate-change mitigation. These benefits notwithstanding, tropical forests are being converted into cropland at a higher-than-ever rate (1.1 Mkm² between 2000-2012 [4]) and are facing increasing pressure from other human activities [5]. One established way to counter tropical forest loss is to establish restricted access protected areas, but this simple dichotomy (protected or not) poorly reflects the wide gradient of forest uses and their effects (e.g., [6, 7]).

In the tropics, nearly 40% of the sawn wood traded annually is harvested from natural forests [8]. Brazil is among the largest producers of tropical round wood, with 14 to 28 million m³ (25-50% of its total log production) annually harvested from Amazonian natural forests, mainly for local markets [9, 10, 11]. Selective logging is the dominant harvesting system in the region, consisting in felling only a few commercial trees (1-5 trees ha⁻¹, around 5-30 m³ha⁻¹ of timber) in the forest. Because most of the forest cover remains after the harvest, selectively logged forests still maintain most of their initial carbon stocks, biodiversity, and other conservation values [12]. Recovery of what is lost depends on logging practices, intensity, and the elapsed time before the next harvest [13, 14]. For this reason, arguments are made for the integration of selectively logged forests into forest conservation schemes [15].

Although recognition of the value of production forests in providing a diversity of ecosystem services (ES) is increasing, most conservation programs and payments for ES schemes focus on a single ES (e.g. carbon in REDD+ programs [16]). Very few studies have addressed

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3 multi-criteria decision-making process regarding the optimisation of ES provision in tropical 70
4 forests, even though some trade-offs might exist between ESs, e.g. timber production, car- 71
5 bon retention [17] or biodiversity conservation [18]. Integrating several ESs in one unique 72
6 framework is thus essential to account for the multi-functionality and complexity of forests 73
7 [19]. 74

15 Plot-level studies provide useful insights for local forest managers, but conservation- 75
16 related policies need to be informed by broader-scale assessments that account for infras- 76
17 tructure planning, location of protected areas, and logging regulations [20]. In addition, 77
18 since ES provisioning varies across space (e.g. carbon stocks [21]), logging rules should also 78
19 vary spatially to optimise ES provisioning, and complex spatial patterns are expected to 79
20 emerge when plot-level information is scaled up [22]. Nevertheless, current country-wide 80
21 logging regulations are typically based on results from local plot-level studies. For example, 81
22 minimum cutting cycles (i.e. years between logging events) are set at 20 years in Bolivia and 82
23 Peru [23], 25-35 years in Brazil [24], and 65 years in French Guiana [25]. There is thus a 83
24 need to provide policymakers with regional assessments of ES trade-offs in Amazonian pro- 84
25 duction forests, to develop spatially-explicit forest management rules that optimise multiple 85
26 ESs based on local ecological specificities. 86

44 Here we explore optimal scenarios for ES provision in Amazonian production forests in 87
45 a spatially explicit framework. We analyse the effect of different logging intensities (i.e., no 88
46 logging and logging at intensities of 10, 20, and 30 m³ha⁻¹) and cutting cycles (15, 30, and 89
47 65 years) on three ES, i.e. post-logging timber recovery, carbon storage, and biodiversity 90
48 conservation (as support of ecosystem functioning [26]). Our main research questions are: 91
49 (i) where, how much, and how often should timber harvests occur to optimise ES provision 92

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3 93 in Amazonian production forests; (ii) how do ES prioritisation and availability of production
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5 94 forest areas affect optimal logging configuration and resulting ES provision, and (iii) how
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8 95 might projected changes in high-quality timber demand affect forest management and ES
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11 96 provision?

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13 97 We explore eight management strategies (Table 1) and identify the spatial logging con-
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15 98 figuration that optimises ES provision over the first cutting cycle, given a timber extraction
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18 99 objective of $30 \text{ Mm}^3\text{yr}^{-1}$, equivalent to timber extraction rates in the region [27]. Strategies
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21 100 differ in terms of (i) ES prioritisation, (ii) total forest area allocated to selective logging, (iii)
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23 101 whether total timber stocks must fully recover (i.e., sustained timber yields objective), and
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25 102 (iv) whether a unique cutting cycle length is applied (30 years). We then compare the opti-
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28 103 mal spatial logging configurations and ES provisions associated with each strategy. Finally,
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30 104 we analyse the consequences of changing the timber extraction objective on ES provision.
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34 105 **Materials and methods**

35 106 **Study region**

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39 107 The study region is the Amazon region, located in tropical South America and straddling
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43 108 nine countries (Brazil, Bolivia, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname,
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47 109 and Venezuela). Amazonia is the most diverse and carbon-rich tropical biome on Earth
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50 110 [21, 2] with around 600 Mha of tropical rainforest of which 400 Mha is considered “intact”
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52 111 (i.e., no detectable human impacts; [28]). To date, 33% of Amazonian forests are under legal
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54 112 protection [29] (Figure 1). However, since the 1970s and the opening of the Trans-Amazonian
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57 113 highway - the first highway built deep inside the forest - 20% of the original forest extent
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3 has been replaced mainly by pastures and, more recently, soybean crops [30, 31]. Despite 114
4 the recent roads, a large portion of the forest biome is at a great distance from any road and 115
5
6 thus inaccessible to most commercial activities (Figure 1). 116
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10 Timber extraction through selective logging is the dominant forest use in the region [24]. 117
11
12 About 14% of Amazonian forests are designated for timber production [32]. Estimates of 118
13 annual sawlog extraction in these forests are around 30 Mm³ [27], but some results suggest 119
14 that timber extraction in the Brazilian Amazon has decreased during the last decade[10]. 120
15
16 This decrease is likely due to a combination of the Brazilian government's fight against 121
17 deforestation [33] and the progressive substitution of tropical timber with other cheaper 122
18 materials in construction [10]. 123
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29 **Optimisation framework** 124

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32 The optimisation procedure finds the best spatial configuration of selective logging in Ama- 125
33 zonia, which we divided into 556 1° cells (i.e., the coarsest resolution of input maps). In each 126
34 grid cell, the potential production forest (PPF) area (i.e. the area used in the optimisation 127
35 framework) is defined either as the area of accessible unprotected forests (AUFs) or as the 128
36 area of all AUFs and remote unprotected forests (RUFs) (Figure 1), depending on the man- 129
37 agement strategy (Table 1); further information is provided in section "Potential production 130
38 forest area", and Figure S3. 131
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49 To reflect the range of logging practices currently used in the region, grid cells can be 132
50 allocated to one of the following logging types: a logging intensity of 10 (Low), 20 (Medium) 133
51 or 30 (High) m³ha⁻¹, and a cutting cycle length of 15 (Short), 30 (Medium) or 65 (Long) 134
52 years, or no Logging. Medium intensity and cutting cycle length correspond to current 135
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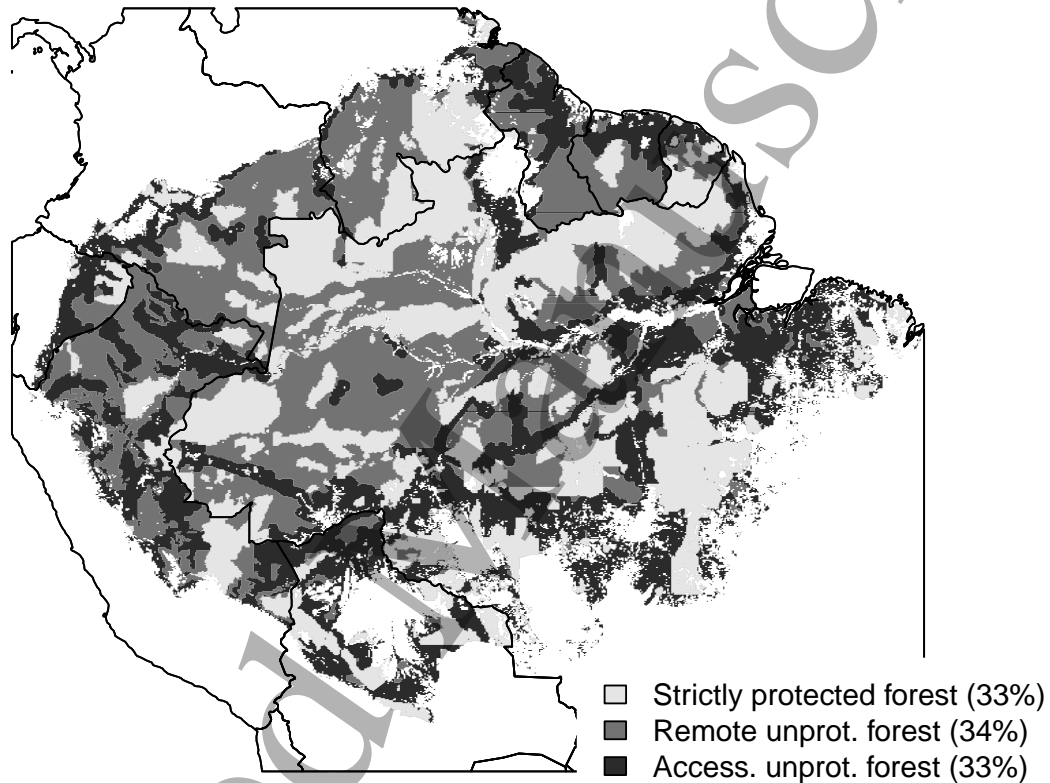


Figure 1: Availability of Amazonian forests for logging (forest cover > 90%). Strictly protected areas (light grey; does not include category VI of the IUCN) are not included in our analysis. Forests < 25 km and >25 km from any road (Accessible and Remote Unprotected Forests) are depicted in dark and medium grey, respectively. Some roads are only accessible by the river network, which results in some isolated AUFs surrounded by RUFs. Strictly protected forests cover 191 Mha, Remote Unprotected Forests 195 Mha (RUFs) and Accessible Unprotected Forests (AUFs) 190 Mha.

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3 median logging practices in Amazonia [24]. The spatial optimisation seeks the most efficient 136
4 spatial configuration of logging rules (cutting cycles and logging intensities) that maximises 137
5 an ES provision function (defined in section "ES prioritisation") under pre-defined objectives. 138
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10 The pre-defined objectives always include (1) an annual timber extraction objective (Fig- 139
11 ure 2): the optimal solution must include enough harvested areas to meet the extraction 140
12 objective; and (2) an intact-forests objective that consists of conserving intact forest land- 141
13 scapes (IFLs), defined as forests with no detectable sign of human activity [28]. IFLs are 142
14 irreplaceable for biodiversity conservation [7], especially for species that are highly sensi- 143
15 tive to forest degradation. Because Amazonian forests have high levels of endemism and 144
16 all regions are not equivalent in terms of species composition, we defined the biodiversity 145
17 conservation objective as follows: in each of the six ecoregions (according to Ter Steege *et* 146
18 *al.* [34]), namely the Guiana Shield, eastern Amazon, southeastern Amazon, central Ama- 147
19 zon, southwestern Amazon, and northwestern Amazon, at least 80% of IFLs are to remain 148
20 unlogged (equation 3). Those include forests in protected areas, inaccessible forests (>25 km 149
21 from a road or track), or forests inside grid cells allocated to the "No Logging" type. 150
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39 In some cases, an additional Sustained-Timber-Yields (STY) objective can be added, that 151
40 consists of recovering as much timber as was initially harvested (equation 4). 152
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44 The optimisation problem is defined as: 153
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46 maximise 154
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$$48 \sum_{p=1}^{556} area_p \left(\sum_{z=0}^9 ES_{p,z} \cdot x_{p,z} \right) \quad (1)$$

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3 subject to (i) a timber extraction objective P :
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$$\sum_{p=1}^{556} area_p \left(\sum_{z=0}^9 \frac{vext_z}{trot_z} \cdot x_{p,z} \right) \geq P \quad (2)$$

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12 (ii) a intact-forest-landscape objective:
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$$\forall R \in [1..6], \sum_{p \in R} (IFL_p \cdot x_{p,0}) \geq 0.8 \cdot \sum_{p \in R} IFL_p \quad (3)$$

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20 and, if included in the management strategy, (iii) a sustained-timber-yields objective:
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$$\sum_{p=1}^{556} area_p \left(\sum_{z=0}^9 (Trec_{p,z} - vext_z) \cdot x_{p,z} \right) \geq 0 \quad (4)$$

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28 where $area_p$ is the PPF area in grid cell p , either AUFs or AUFs and RUFs (Table 1),
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30 further described in section "Potential production forest area". $ES_{p,z}$ is the ES provision
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32 change when allocating cell p to logging type z , relative to the ES provision when allocating
33
34 cell p to logging type $z = 0$ (i.e. no logging): the calculation of this ES provision function
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36 is further described in paragraph "ES prioritisation". $x_{p,z} = 1$ when cell p is allocated to
37
38 logging type z , and $x_{p,z} = 0$ otherwise. $vext_z$ and $trot_z$ are respectively the logging intensity
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40 (10, 20 or 30 $m^3 ha^{-1}$) and cutting cycle length (15, 30 or 65 years) associated to logging
41
42 type z . R is the ecoregion (6 ecoregions in total) according to ter Steege *et al.* [34]. IFL_p
43
44 is the total area of intact forest landscapes in grid cell p , based on data from Potapov *et al.*
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46 [28]. $Trec_{p,z}$ is the amount of timber recovered in grid cell p after logging during the cutting
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48 cycle duration under logging type z , calculated with a previously developed volume recovery
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50 model calibrated at the Amazonian scale [35] (see paragraph "ES prioritisation").
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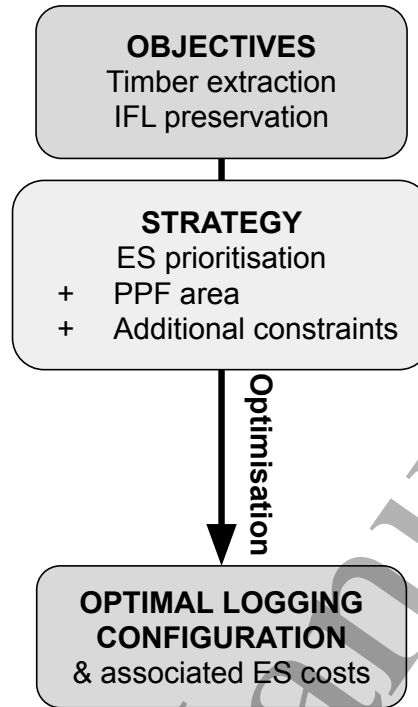


Figure 2: Spatial optimisation steps. Depending on the scenario, PPFs are either accessible unprotected forests (AUFs), or all unprotected forests, i.e. AUFs and remote unprotected forests (RUFs). IFLs are intact forest landscapes [28]. The eight strategies tested are summarised in Table 1.

The optimal spatial configuration for each strategy is found with integer linear programming using a methodology adapted from the optimisation software Marxan with Zones [36, 37], using the package *priorizr* [38] developed in R programming language [39]. Codes and data are available at <https://figshare.com/s/a60e3610337636a2b6ff>.

It should be noted that, contrary to many conservation planning studies, we did not include the connectivity of protected areas in the optimisation process. In our case, the total area of one grid cell is around 11000 km². At this scale, the additional benefit of connected grid cells is difficult to interpret, although it also has implications at large landscape scales.

178 **Strategy description**

179 We tested different strategies to meet future timber demand in Amazonia (Table 1): (1)
180 *Timber*: only timber recovery is maximised to ensure long-term timber stocks, (2) *Carbon*:
181 only carbon is maximised as a climate change mitigation strategy, (3) *Biodiversity*: only
182 biodiversity is maximised as a conservation strategy, (4) *Balanced*: timber recovery, car-
183 bon and biodiversity conservation are balanced as a multi-functionality strategy, (5) *MCC*:
184 balanced ES prioritisation under Medium (30-year) Cutting Cycles only, similar to current
185 management strategies imposing nation-wide minimum cutting cycle, (6) *STY*: balanced ES
186 prioritisation with a sustained-timber-yields (STY) objective, i.e. the volume of timber ex-
187 tracted must be recovered at the end of the first cutting cycle. In scenarios (1-6), PPFs are
188 restricted to AUFs (Table 1). Two additional scenarios also include RUFs in the PPF area:
189 (7) *Increased accessibility*: balanced ES prioritisation when all unprotected forests (AUFs
190 and RUFs) are made accessible, and (8) *STY + Increased accessibility*: balanced ES pri-
191 oritisation with a STY objective when all unprotected forests (AUFs and RUFs) are made
192 accessible. The annual timber extraction objective is first set to 30 Mm³ (Figures 3 and
193 4); the effects of changing the timber extraction objective are then tested with objectives
194 between 10-80 Mm³yr⁻¹ (Figure 5).

195 **Potential production forest area**

196 In each grid cell, we only consider unprotected forests, i.e. areas having at least 90% of forest
197 cover [4] and outside strictly protected areas (i.e. all IUCN categories except VI: "Protected
198 area with sustainable use of natural resources") [29]. Unprotected forests are further divided

	Acronym	Strategy	ES prioritisation	PPF	STY
1	Timber	Maximise timber recovery	Timber	AUF	No
2	Carbon	Climate change mitigation	Carbon	AUF	No
3	Biodiversity	Biodiversity conservation	Biodiversity	AUF	No
4	Balanced	Multi-functionality	Balanced	AUF	No
5	MCC	Only Medium (30-yr) Cutting Cycles allowed	Balanced	AUF	No
6	STY	Sustained timber yields	Balanced	AUF	Yes
7	Increased accessibility	Building roads to access remote areas	Balanced	AUF + RUF	No
8	STY + Increased accessibility	Sustained timber yields with increased accessibility	Balanced	AUF + RUF	Yes

Table 1: Strategies tested in this study. ES prioritisation refers to the weights given to ES in the optimisation process: either only one ES (timber, carbon or biodiversity) is optimised, or weights are balanced between timber recovery, carbon retention and biodiversity conservation. Potential production forests (PPFs) are areas that can be logged in a given strategy: Accessible Unprotected Forests (AUFs) are areas that have >90% forest cover, are not protected and are within 25 km of an existing road (Figure 1); Remote Unprotected Forests (RUFs) are areas with >90% forest cover outside protected areas and >25 km from a road. Two optional constraints can be added: STY (Sustained Timber Yields) requires that the total timber stocks are recovered in all logged grid cells whereas the 30-year cycle constraint allows only 30-year cutting cycles (*MCC* strategy).

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3 into two groups, depending on their distance to any road, here defined as any motorable track
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5 registered in OpenStreetMap [40]. Areas within 25 km of an existing road are referred to
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7 as Accessible Unprotected Forests (AUFs); areas >25 km from an existing road are referred
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9 to as Remote Unprotected Forests (RUFs). In Peru, where an official map of permanent
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11 production forests was available online [41], we added these permanent production forests to
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13 AUFs.
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18 Depending on the scenario (Table 1), PPF area is then calculated for each grid cell as
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20 either the area of AUFs (scenarios 1-6) or AUFs and RUFs (scenarios 7-8). Because only 50-
21
22 80% of production forest area is considered suitable for logging due to steep slopes, riparian
23
24 buffers and previous heavy degradation [42, 43], the PPF area is multiplied by a coefficient
25
26 $\pi = 58\%$. This value corresponds to the mean ratio between the area actually logged and
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28 the total area of forest concessions in French Guiana [35], and is similar to other pan-tropical
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30 data [44].
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36 ES prioritisation

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39 The spatially explicit ES provision function is estimated as the relative difference between
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41 the ES provision (i.e., timber volumes, carbon sequestration, and potential species richness)
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43 when a grid cell p is allocated to one logging type z and the ES provision when the same
44
45 grid cell is not logged (logging type $z = 0$):
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$$51 \quad ES_{p,z} = \alpha_T \cdot \frac{\Delta T_{p,z}}{T_{\bullet,p}} + \alpha_C \cdot \frac{\Delta C_{p,z}}{C_{\bullet,0}} + \alpha_B \cdot \frac{\Delta B_{p,z}}{B_{\bullet,0}} \quad (5)$$

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55 α_T , α_C and α_B are the relative weights of timber, carbon and biodiversity respectively.
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When a unique ES (timber, carbon or biodiversity) is prioritised in a given strategy, its weight is set to 1 and the others are set to 0. When ES prioritisation is balanced, $\alpha_T = \alpha_C = \alpha_B = \frac{1}{3}$. To analyse the effect of ES prioritisation on final ES provision, we ran 66 simulations with all combinations of weights from 0 to 1, with 0.1 steps. Results are presented in the Supplementary material (Figure S4).

$\Delta T_{p,z}$, $\Delta C_{p,z}$ and $\Delta B_{p,z}$ are respectively the net timber volume change (in m^3ha^{-1}), the net carbon stock change (in $\text{Mg C}\cdot\text{ha}^{-1}$), and the potential richness loss (mammals and amphibians) in grid cell p under logging type z (after one cutting cycle). Additional details are provided in equations 6, 7 and 8 respectively (see below).

$T_{\bullet,0}$, $C_{\bullet,0}$, and $B_{\bullet,0}$ are respectively the mean timber volume [35], mean carbon stocks [21] and mean potential richness of mammals and amphibians [45] in unlogged forests ($z = 0$) over all grid cells.

$\Delta T_{p,z}$ is calculated as:

$$\Delta T_{p,z} = -\text{vect}_z + \text{Trec}_{p,z} \quad (6)$$

where vect_z is the logging intensity associated to logging type z and $\text{Trec}_{p,z}$ is the timber recovery in grid cell p under logging type z , calculated with a previously developed volume recovery model calibrated at the Amazonian scale [35], with all parameters set to their maximum likelihood value.

$\Delta C_{p,z}$ is calculated as:

$$\Delta C_{p,z} = -\text{Cemi}_{p,z} + \text{Crec}_{p,z} \quad (7)$$

where $\text{Cemi}_{p,z}$ are the total carbon emissions caused by logging (yarding/skidding, road opening and incidental damage [46]; see supplementary section A) associated to logging type

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3 238 z in grid cell p and $Crec_{p,z}$ is the carbon recovery in grid cell p under logging type z (over
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6 239 one cutting cycle), calculated with a previously developed carbon recovery model calibrated
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8 240 at the Amazonian scale [47], with all parameters set to their maximum likelihood value.

9
10 241 $\Delta B_{p,z}$ is calculated as:

$$15 \quad \Delta B_{p,z} = (Rm_p \cdot \beta m + Ra_p \cdot \beta a) \cdot vert_z \quad (8)$$

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19 242 where Rm_p and Ra_p are the pre-logging potential richness of mammals and amphibians
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21 243 respectively [45], $\beta m = -1.44$ and $\beta a = -1.53$ are the estimated slopes of post-logging species
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23 244 loss in the Neotropics for mammals and amphibians respectively, according to Burivalova et
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26 245 al. [18]. $vert_z$ is the logging intensity in logging type z .

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28 246 Mammals and amphibians were chosen because of data availability (potential richness
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30 247 maps and effect of selective logging on each taxon); moreover, they both play key roles in
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33 248 ecosystem functioning [48, 49, 50, 51], and thus on ES provision. We used global maps of
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36 249 mammals and amphibians potential richness derived from IUCN species range maps [45],
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38 250 which can fairly represent patterns of conservation priority [52].

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40 251 We hypothesize that amphibians and mammals potential richness do not recover after
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43 252 logging (no effect of cutting cycle length), because logging roads make forests more accessible
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45 253 for other human activities (e.g. hunting [53]), thus having a long-term effect on sensitive taxa
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48 254 such as mammals and amphibians [54]. However, post-logging recovery has been observed
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50 255 in some cases, e.g. in bat communities [55]: we thus analyse the consequences of different
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53 256 biodiversity recovery rates on optimal logging configuration in the supplementary section B.

Results

Optimal logging configuration under a 30 Mm³yr⁻¹ timber extraction objective

Our predictions when timber recovery is optimised (i.e. *Timber* strategy) result in exploitation of 88% of all PPFs over one cutting cycle, of which 7% are under high-intensity short-cycle logging, 3% under low-intensity short-cycle logging and 78% under low-intensity long-cycle logging (Figure 3a). In contrast, maximising carbon and biodiversity retention results in the preservation of 85% of PPFs, and logging 15% of PPFs under the highest intensity (30 m³ha⁻¹) and shortest cutting cycle (15 years) allowed (Figure 3b-c). Logged areas are distributed around outer fringes of Amazonia: southeastern Amazonia for both carbon and biodiversity, northern Amazonia for carbon and the southwestern border for biodiversity. These areas correspond to the lowest values on above-ground carbon and potential richness maps, explaining why they are allocated to intensive logging when those ESs are optimised.

Balancing timber, carbon and biodiversity (i.e. *Balanced* strategy) results in preservation of 74% of PPFs, logging 13% of PPFs under high-intensity (30 m³ha⁻¹) short-cycle (15 years) logging and 13% under low-intensity (10 m³ha⁻¹) long-cycle (65 years) logging (Figure 3d). Similar to the *Carbon* and *Biodiversity* strategies, heavily logged areas are concentrated on the peripheries of the Basin, especially on its southeastern border and low-intensity logging is concentrated in the south and northwest whereas central, western and northeastern Amazonia remain mostly unlogged. Allowing only 30-year cutting cycles (*MCC* strategy) results in the preservation of a smaller share of production forests (48%) while 16% are logged under high

intensity ($30 \text{ m}^3\text{ha}^{-1}$) and 36% under low intensity ($10 \text{ m}^3\text{ha}^{-1}$; Figure 3e).

Adding a full-timber-recovery constraint (STY; Figure 3f) results in allocating a higher proportion of forests to low-intensity long-cycle logging (29% versus 13% in the *Balanced* strategy) and preserving fewer areas (60% versus 70% in the *Balanced* strategy).

Increasing forest accessibility through road building (Figure 3g) results in a spatial configuration similar to the *Balanced* strategy. The total area under high-intensity ($30 \text{ m}^3\text{ha}^{-1}$) short-cycle (15 years) logging is slightly lower than in the *Balanced* strategy (13 Mha instead of 14 Mha) and the total area under low-intensity ($10 \text{ m}^3\text{ha}^{-1}$) long-cycle (65 years) logging is higher (24 Mha instead of 14 Mha). Adding a STY constraint (*STY + Increased accessibility* strategy) increases the proportion of low-intensity long-cycle logging (15% versus 12% in the *Increased accessibility* strategy) and decreases the proportion of preserved areas (79% versus 82% in the *Increased accessibility* strategy) (Figure 3h).

Effect of strategy choice on ES provision

The *Timber* strategy results in the best final timber stocks (+2.3% of initial timber stocks, Figure 4a), the lowest carbon stocks (-4% of initial carbon stocks, Figure 4b) and the least biodiversity retention (-6.4% of initial value, Figure 4c). The *Carbon*, *Biodiversity*, *Balanced* and *Increased accessibility* strategies result in timber losses (-2.1%, -2.1%, -1.1% and -0.3%, respectively), but low carbon emissions (-1.4%, -1.6%, and -1.7%, and -1.3%, respectively) and low biodiversity losses (-2.3%, -1.9%, -2.5%, and -2.2%, respectively). The strategies with a STY constraint (*STY* and *STY + Increased accessibility*) result in no change in timber stocks (Figure 4a), at the cost of higher carbon and biodiversity losses than the strategies without the STY constraint (the *Balanced* and *Increased accessibility* strategy, respectively;

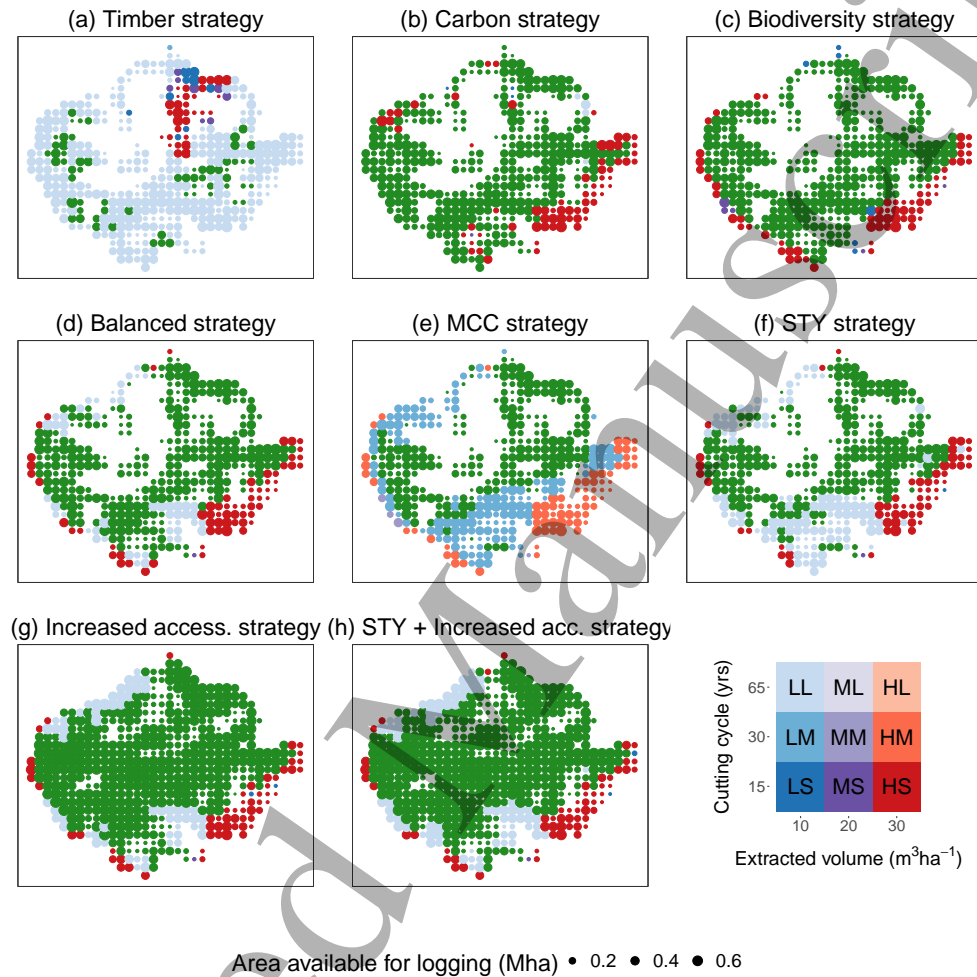


Figure 3: Results of spatial optimisation with the eight strategies defined in Table 1 with a natural forest timber extraction objective of $30 \text{ Mm}^3\text{yr}^{-1}$. Green areas are not logged, white areas are not PPFs. The size of each dot is proportional to the PPF area. Logging type colour (blue - purple - red) represents the logging intensity (Light: 10, Medium: 20 and High: $30 \text{ m}^3\text{ha}^{-1}$). Logging type transparency represents the cutting cycle length (Short: 15, Medium: 30, Long: 65 years): light colours correspond to longer cycles. For example, in the *Balanced* strategy (d), most PPFs are not logged (green), except some areas in the margin of the Basin that are intensively logged (red; $30 \text{ m}^3\text{ha}^{-1}$ every 15 years) in east and southwest Amazonia, and extensively logged (light blue; $10 \text{ m}^3\text{ha}^{-1}$ every 65 years) in south and northwest Amazonia.

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3 300 Figure 4b-c). In contrast, the *MCC* strategy performs very poorly at provision of all three
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6 301 ESs. Indeed, this strategy results in the highest reduction of timber stocks (-2.1%) and the
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8 302 second highest reduction of carbon stocks (-3.3%) and biodiversity (-4.4%).
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12 303 **Changing the timber extraction objective**

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15 304 Our model framework allowed us to test the ability of the eight forest management strategies
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18 305 to satisfy timber demands that range from 10 to 80 Mm³yr⁻¹. Increasing timber extraction
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21 306 results in an increase of area harvested (except for the *Timber* strategy; Figure 5a), and a
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23 307 reduction of ES provision (Figure 5d-f). For the *Timber* strategy, the total area logged is
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25 308 already at its maximum value (around 80 Mha) even with low timber extraction objectives
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28 309 (Figure 5a). For this strategy, increasing timber extraction from 20 to 80 Mm³yr⁻¹ would
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30 310 result in increasing mean logging intensity by 60% (from 10 to 16 m³ha⁻¹) and decreasing
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32 311 mean cutting cycle length by 15 years (from 60 to 45 years) (Figure 5b-c).
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35 312 The *Carbon* and *Biodiversity* strategies show similar patterns: both rely upon high-
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37 313 intensity (30 m³ha⁻¹) short-cycle (15 years) logging, independently from the timber extrac-
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39 314 tion objective (Figure 5b-c). Increasing timber extraction in both strategies results in a linear
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42 315 increase in logged areas (Figure 5a).
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44 316 When ES prioritisation is balanced (*Balanced* and *Increased accessibility* strategies), tim-
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46 317 ber extraction is mostly achieved through low-intensity long-cycle logging when the timber
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48 318 extraction objective is low (Figure 5b-c). However, increasing timber extraction under both
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51 319 strategies generates a shift from low-intensity long-cycle logging to high-intensity short-cycle
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54 320 logging (Figure 5b-c; Figure S5), and extended total area logged.
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57 321 Adding the STY constraint to the *Balanced* and *Increased accessibility* strategies (respec-
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tively the *STY* and *STY + Increased accessibility* strategies) does not drastically change simulations when extraction objectives are low ($< 20 \text{ Mm}^3\text{yr}^{-1}$). At higher extraction objectives, mean logging intensity plateaus at approximately $15 \text{ m}^3\text{ha}^{-1}$ and the mean cutting cycle stabilises at 50 years, resulting in a sharp increase in the total area logged (Figure 5a). The *STY* constraint can only meet $50 \text{ Mm}^3\text{yr}^{-1}$ in AUFs (i.e. in the *STY* strategy) and $60 \text{ Mm}^3\text{yr}^{-1}$ when including RUFs (i.e. in the *STY + Increased accessibility* strategy).

Finally, the *MCC* strategy (i.e. balanced ES prioritisation with cutting cycles of 30 years) results in low-intensity logging when the total extraction remains lower than $20 \text{ Mm}^3\text{yr}^{-1}$ (Figure 5b). Increasing timber extraction results in a sharp increase in both the total area logged and the logging intensity (Figure 5a-b). When the timber extraction objective reaches $80 \text{ Mm}^3\text{yr}^{-1}$, the total area logged is close to its maximum value (around 80 Mha; Figure 5a) and all areas logged are under high-intensity logging ($30 \text{ Mm}^3\text{yr}^{-1}$; Figure 5b). In terms of ES provision, the *MCC* strategy performs poorly compared to others, especially at high timber-extraction objective (Figure 5d-f).

Discussion

Our results show that regional optimisation of ES provision results in a strong spatial structuring of logging. Intermediate logging cycles (30 years) and intensities ($20 \text{ m}^3\text{ha}^{-1}$) are virtually never chosen, and imposing some standardisation (e.g. 30-year cutting cycles in the *MCC* strategy) results in sub-optimal ES provision. This spatial heterogeneity in our results highlights the need to account for regional variations in ES provision when designing forest management, instead of applying uniform logging regulations.

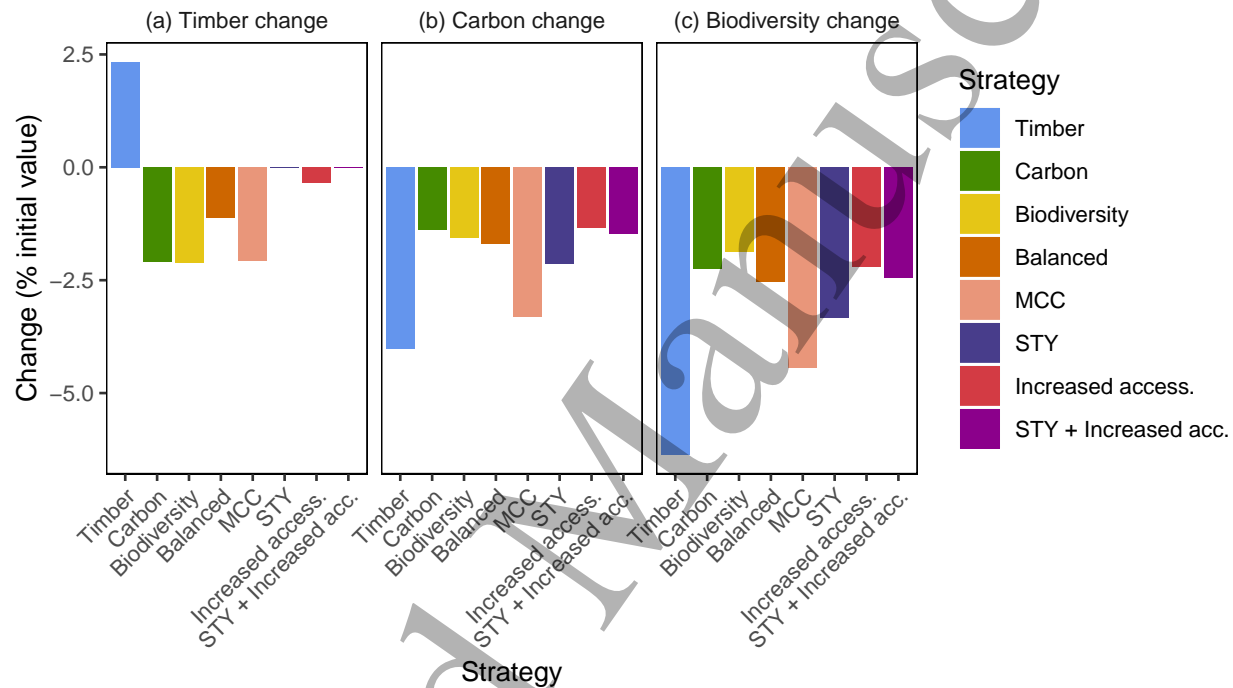


Figure 4: Impact of the eight management strategies (described in Table 1) in terms of total ES provision (% of the initial ES value) with the timber extraction objective of $30 \text{ Mm}^3\text{yr}^{-1}$. (a) Changes in regional timber stocks; (b) changes in regional carbon stocks; and, (c) changes in regional biodiversity. A positive value indicates an increase in total ES provision; a negative value indicates a loss in total ES provision. Changes in ES provision are standardised by the initial value of a given ES (i.e. initial timber, carbon stocks, and mammals and amphibians potential richness as a proxy of biodiversity) over all areas with forest cover $>90\%$ (see Figure S3: "All forests").

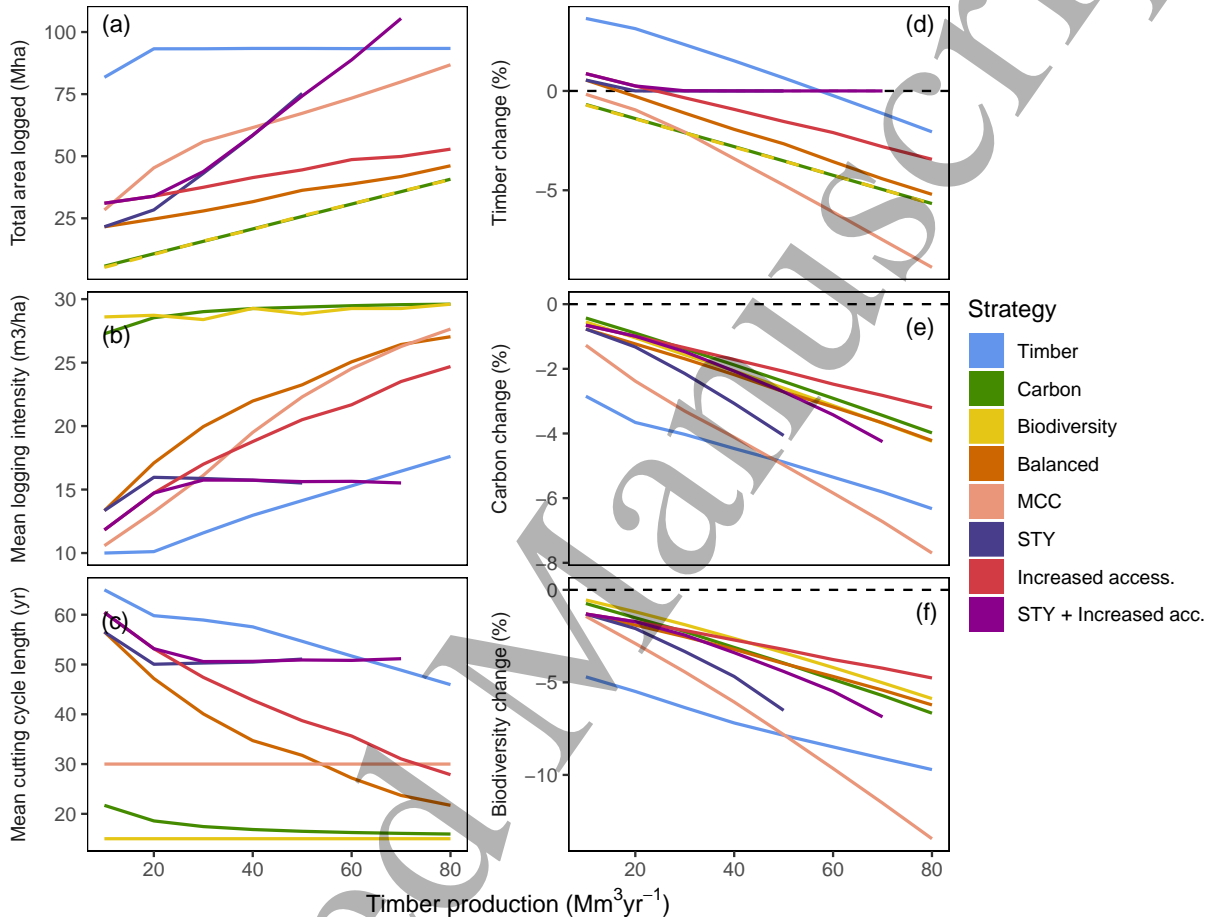


Figure 5: Characterisation of different strategies for timber extraction with different timber extraction objectives. (a) Total area logged (Mha). (b) Mean logging intensity in logged areas (m³ha⁻¹). (c) Mean cutting cycle length (yr). (d) Changes in timber stocks (% of the initial value). (e) Carbon emissions (% of the initial value) (f) Changes in biodiversity value (% of the initial value). The eight strategies' characteristics are summarised in Table 1. *STY* and *STY + Increased accessibility* strategies cannot sustainably provide more than 50 and 60 Mm³ of annual timber extraction respectively. In plots (d-f), values are calculated over all areas outside of protected areas. Additional maps with distribution of logging types (intensity, cutting cycle) are provided in the supplementary material (Figure S5).

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3 343 The joint optimisation of three ESs in our framework revealed the inability to find an ideal
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6 344 solution that would optimise both timber stocks recovery and forest conservation (carbon and
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8 345 biodiversity). It therefore seems crucial to reassess either the objectives (i.e. combining a
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10 346 sustainable production with forest conservation) or the strategy (i.e. conventional selective
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13 347 logging) of timber production in Amazonian forests.
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17 348 **Regional differences in Amazonian forests and consequences for ES** 18 19 20 349 **provision** 21 22

23 350 The spatial configuration of optimal logging (Figure 3) is closely linked to major regional
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26 351 differences in the functioning of Amazonian forests. Forests of the Guiana Shield (northeast-
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28 352 ern Amazonia) grow on nutrient-poor soils and suffer few natural disturbances [56], which
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30 353 selected for low turnover rates and slow-growing species [57]. Guiana shield forests thus har-
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33 354 bour large amounts of carbon [21] and support rich vertebrate communities [58] due to their
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35 355 long-term persistence [59] and are therefore not selected for logging when biodiversity and
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38 356 carbon are optimised (Figure 3a-b). Forests of the Guiana Shield have also been shown to
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40 357 play a crucial role in the Amazonian hydrological cycle [60, 61], enhancing the importance of
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43 358 their conservation in future management strategies. Similarly, northern and central Amazo-
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45 359 nian forests encompass high diversity of vertebrates [45] and carbon [21], and are thus rarely
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48 360 selected for logging when biodiversity and carbon storage are prioritised (Figure 3a-b). If
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50 361 conservation is the main objective of Amazonian forest management, the consolidation of
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52 362 the protected area network in central and northeastern Amazonian forests will provide high
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55 363 benefits for conservation and climate change mitigation, especially if this promotes higher
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connectivity between existing protected areas [62].

Southeastern forests have, in turn, relatively lower biodiversity and carbon stocks. They are thus often allocated to high-intensity short-cycle logging when carbon and biodiversity are optimised (Figure 3a-b). However, due to the region's dense road network that increased forest degradation through logging, fragmentation and/or wildfire [63, 64], timber extraction potential in southeastern forests may have been overestimated, even in closed-canopy forests [65]. Southeastern forests are also predicted to experience longer and more severe droughts shortly [66]. These droughts, in combination with fires induced by increased temperatures and decreased humidity in logged forests [67], can have negative impacts on future timber provision [14], carbon stocks and biodiversity [63].

Land-use strategies, trade-offs and implications for policy-making

Current logging regulations (e.g. 35-year maximum cutting cycle in the Brazilian Amazon) were thought to be a compromise between producing enough timber to make financial benefits and letting the forest recover long enough to make logging sustainable [68]. Several studies have shown that these logging rules are not sufficient to recover pre-logging forest characteristics [69, 70, 14]. Moreover, our results show that current regulations (e.g. imposing fixed and nation-wide cutting cycles, similar to the *MCC* strategy), increase the loss of all ESs and lead to sub-optimal management (Figure 4). The standard strategy often promoted for the maintenance of timber stocks in tropical forests is to change national regulations so that cutting cycles are longer and logging intensities are lighter, but these recommendations may result in a significant increase in total harvested forest areas to compensate for the reduction in timber extracted per ha and per year.

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386 Our results reveal that the main trade-off among ecosystem services considered in this
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387 study is between a long-term provision of timber, and the conservation of carbon stocks and
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388 biodiversity (Figure S4). These results fit into the broader "land sharing vs land sparing"
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389 debate, and whether timber extraction should concentrate on a few intensely-logged areas
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390 (land sparing), or be carried at low intensity over the entire landscape (land sharing). Land-
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391 sparing logging was shown to create heterogeneous landscapes that favour higher levels of
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392 beta-diversity and maintenance of biodiversity at landscape scale [6, 71]. It has been ar-
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393 gued that under strong forest governance, land-sharing logging could optimise both carbon
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394 and biodiversity retention [72]. More recently, a simulation exploring different management
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395 strategies in East Kalimantan forests found that the optimal forest conservation strategy
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396 consisted in mixing both approaches: intensifying timber production through the conversion
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397 of degraded forests into plantations, and implementing reduced-impact logging in current
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398 logging concessions and some natural forests [73]. Our findings also show that a land-sparing
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399 approach (e.g. the *Carbon* and *Biodiversity* strategies) not only minimises biodiversity loss
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400 (Figure 3b, Figure 5f), but also reduces carbon emissions (Figure 3a, Figure 5e). How-
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401 ever, these land-sparing strategies result in low timber recovery compared to a land-sharing
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402 strategy (e.g. the *Timber* strategy, Figure 4a).

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403 There is therefore no win-win strategy to sustain current timber demand and ESs provision
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404 in production forests. Further, the current application of intermediate logging rules increases
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405 ESs losses (Figure 5d-f). The fate of Amazonian production forests hence depends on political
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406 choices and future societal demand for ESs. If maintaining long-term timber supplies from
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407 natural production forests is the goal [74], then low-intensity logging should be preferred and
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408 applied across most of the Amazon, notably in the western part of the Basin (Figure 3a).

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3 It is important to note, however, that we did not analyse the net profitability, which could 409
4 disadvantage a land-sharing approach because of high transport and road-building costs. 410
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6 This strategy might thus not be adopted by forest owners that generally manage forests to 411
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8 maximise financial benefits. 412
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12 In contrast, if society demands the preservation of carbon and biodiversity (e.g. carbon- 413
14 based policies like REDD+ [75]), policies should focus on conserving intact inland forests 414
15 while allowing high-intensity logging on the fringes of the Amazon Basin. High-intensity 415
16 logging will probably result in a sharp decrease in timber resources in over-harvested areas. If 416
17 no action is taken to improve post-logging timber recovery, loggers might resort to harvesting 417
18 new forest areas after the first cutting cycle, thus increasing carbon and biodiversity costs. 418
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20 Alternative pathways include active forest restoration with intensive silviculture and mixed- 419
21 species timber plantations [76] to stimulate recovery in over-harvested forests. However, the 420
22 additional costs associated with such operations can be discouraging, especially in a context 421
23 of land tenure insecurity [77]. Enhancing timber recovery will, therefore, require adapted 422
24 policies and financial incentives, e.g. through payments for ecosystem services [78]. 423
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39 Increasing the PPF area (in the *Increased accessibility* strategies, Table 1) provides more 424
40 options for optimising logging spatial configuration, and hence tends to increase ES provision 425
41 overall: the *Increased accessibility* and *STY + Increased accessibility* strategies have higher 426
42 ES values than the *Balanced* and *STY* strategies, respectively (Figure 5d-f). Nevertheless, 427
43 insofar as logging roads render forests vulnerable to fire [67], hunting, wood-fuel harvest- 428
44 ing and illegal logging [79], uncontrolled forest degradation in new production forests could 429
45 increase the environmental costs of the *Increased accessibility* strategy. 430
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431 **How to further improve ES provision in production forests?**

432 Timber production, carbon sequestration and biodiversity are not the only ESs provided by
433 Amazonian production forests. Other key ESs include water cycling [80] and limiting soil
434 erosion [81]. The spatial and temporal variation of these ESs in Amazonian logged forests
435 has, to our knowledge, not yet been studied, and we have therefore not included them in our
436 optimisation framework.

437 Standardising logging rules (e.g. applying a unique 30-year cutting cycle in the *MCC*
438 strategy) resulted in the lowest ES provision in our results: improving forest management
439 will thus require some adaptation to local ecological specificities, e.g. forest types, recovery
440 rates or local patterns of biodiversity. Because of the coarse resolution of our analysis, results
441 might not be adapted to the definition of selective logging rules at the concession level. The
442 overall patterns observed in Figure 3 should be conserved at finer scales, but there might
443 be some intra-cell heterogeneity of optimal logging distribution. Applying such detailed
444 regulations will require highly-trained technicians to define, licence and implement forest
445 management plans.

446 We did not explore the potential of improved logging techniques, generally known as
447 Reduced-Impact Logging (RIL), to enhance simultaneously conservation values and tim-
448 ber recovery. A compelling body of evidence shows that RIL practices could provide large
449 improvements in terms of timber recovery, carbon emissions and biodiversity protection
450 [82, 83, 84, 85], and many authors thus argue that they should be an essential point in
451 forest management strategies [72, 73]. Additionally, silvicultural treatments such as liana-
452 cutting, thinning and girdling, or enrichment planting, can also significantly increase timber

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3 recovery with reasonable financial costs [86]. Despite this evidence, RIL techniques and other 453
4 silvicultural treatments remained poorly implemented in the field [87]. We thus decided to 454
5 base our study on currently dominant logging practices, keeping in mind that ES provision 455
6 would be improved if RIL was more widely implemented. 456
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13 One key point to bear in mind is that our simulations are restricted to the first cutting 457
14 cycle. This is particularly important for STY strategy, as even if our predictions ensure a 458
15 sustainable timber production over the first cutting cycle, we cannot rule out decreases af- 459
16 terwards. There is almost no data on multi-cycle logging in Amazonia, and most permanent 460
17 forest plots have only been logged once [88], although most production forests may have 461
18 undergone multiple illegal re-entries [89]. Gathering more information on the effect of mul- 462
19 tiple cutting cycles on forest dynamics is of utmost importance to glimpse at the future of 463
20 production forests. 464
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32 Another limitation is the small number of existing studies on the effect of selective log- 465
33 ging on biodiversity, resulting in a high uncertainty on actual species richness loss rates [18]. 466
34 Moreover, the use of species richness as a proxy of biodiversity overlooks species character- 467
35 istics and spatial species turnover [90]. Accounting for range size [91], IUCN conservation 468
36 status [92], or habitat specialisation [93], could help better depict the biodiversity cost of 469
37 logging. However, to our knowledge, no studies have quantified the effect of logging on such 470
38 biodiversity measures. More studies on the biodiversity impact of logging would thus be 471
39 key to optimise conservation in Amazonian production forests. Nevertheless, in the case 472
40 of habitat specialisation, the focus on forest specialists is expected to increase the effect of 473
41 logging in the densely forested central Amazon and decrease its effect on the basin margins 474
42 where landscapes are more open and forest specialist species are less common [94]. Thus, an 475
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3 476 analysis focused on forest specialists should accentuate the pattern observed in Figure 3c.
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6 477 Finally, even though our findings provide an interesting insight on potential trade-offs
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8 478 that future forest managers and decision-makers will face, a large part (20-60%) of logging is
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10 479 illegal in the Amazon [95, 96]. Changing logging rules to maintain the environmental value of
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12 480 production forests can be jeopardised by a lack of control over their application. Improving
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14 481 Amazonian forests' governance will be key to maintain ecosystem services through informed
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16 482 management.
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40 491 ticipated in the discussions related to this paper, and especially the Instituto Boliviano de
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42 492 Investigación Forestal.
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50 493 **Data availability**

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54 494 The data that support the findings of this study are openly available at [https://figshare.](https://figshare.com/s/a60e3610337636a2b6ff)
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56 495 [com/s/a60e3610337636a2b6ff](https://figshare.com/s/a60e3610337636a2b6ff). This link will be changed to a DOI once the paper is ac-
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8 **Author contributions** 9

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11 CP and BH designed the study, CP performed simulations and wrote the first draft, CP, ER,
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14 FEP, TAPW and BH wrote the paper, all other authors contributed data, commented on
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17 and approved the manuscript.
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