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# **Prospective carbon balance of the wood sector in a tropical forest territory using a temporally-explicit model**

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## 22 **Highlights**

- 23 • Temporally-explicit large scale carbon balance model guides wood sector strategies.
- 24 • RIL allows increasing logging intensity (x 1.5) without additional carbon emissions.
- 25 • Plantation reduces pressure on forests without effect on long- term carbon balance.
- 26 • Converting forest to timber plantation leads to a short-term carbon emission peak.
- 27 • Adding plantations improves timber carbon balance compared to selective logging only.

## 28 **Abstract**

29 Selective logging in tropical forests is often perceived as a source of forest degradation and carbon  
30 emissions. Improved practices, such as reduced-impact logging (RIL), and alternative timber  
31 production strategies (*e.g.* plantations) can drastically change the overall carbon impact of the  
32 wood production sector. Assessing the carbon balance of timber production is crucial but highly  
33 dependent on methodological approaches, especially regarding system boundaries and  
34 temporality. We developed a temporally-explicit and territory scale model of carbon balance  
35 calibrated with long-term local data using Bayesian inference. The model accounts for carbon  
36 fluxes from selective logging in natural forest, timber plantation, first transformation and avoided  
37 emissions through energy substitution. We used it to compare prospective scenarios of  
38 development for the wood sector in French Guiana. Results show that intensification of practices,  
39 through increased logging intensity conducted with RIL and establishment of timber plantations,

are promising development strategies to reduce the carbon emissions of the French-Guianese wood sector, as well as the area needed for wood production and hence the pressure on natural forests. By reducing logging damage by nearly 50%, RIL allows increasing logging intensity in natural forest from 20 m<sup>3</sup> ha<sup>-1</sup> to 30 m<sup>3</sup> ha<sup>-1</sup> without affecting the carbon balance. The use of logging byproducts as fuelwood also improved the carbon balance of selective logging, when substituted to fossil fuel. Allocating less than 30 000 ha to plantation would allow producing 200 000 m<sup>3</sup> of timber annually, while the same production in natural forest would imply logging more than 400 000 ha over 60 years. Timber plantation should be preferentially established on non-forested lands, as converting natural forests to plantation leads to high carbon emission peak over the first three decades.

We recommend a mixed-strategy combining selective logging in natural forests and plantations as a way to improve long-term carbon balance while reducing short-term emissions. This strategy can reduce the pressure on natural forests while mitigating the risks of changing practices and allowing a diversified source of timber for a diversity of uses. It requires adaptation of the wood sector and development of technical guidelines. Research and monitoring efforts are also needed to assess the impacts of changing practices on other ecosystem services, especially biodiversity conservation.

## **Keywords**

Bayesian modelling, French Guiana, Land-sparing strategy, Reduced-impact logging, Selective logging, Timber plantation

# 1 Introduction

Tropical forests play a major role in climate change mitigation. They store  $271 \pm 16$  Pg of carbon as biomass (Grace et al., 2014), and account for a gross carbon sink of  $2.7 \pm 0.7$  Pg year<sup>-1</sup> (2000-2007), which represents about 70% of the gross sink of all forests worldwide (Pan et al., 2011). It is therefore important to understand the effects of human activities on the carbon stocks and fluxes of tropical forests. Deforestation and degradation of these forests represent a carbon emission of  $2.01 \pm$  Pg year<sup>-1</sup> (Grace et al., 2014). Selective logging - *i.e.* the harvest of a few trees per ha - is an important activity in tropical forests. It is often perceived as a source of degradation (Lewis et al., 2015), in part because of the loss of biomass associated with extracted trees, logging damage and logging infrastructure. Conversely, some consider selective logging as a way to increase the economic value of tropical forests in order to prevent deforestation (Mohren, 2019), while retaining most of the biodiversity and ecosystem functioning and service provision of intact forests (Burivalova et al., 2020; Edwards et al., 2014b), a sort of “conservation through use” (Putz et al., 2012).

More than 400 million ha of tropical forests are classified as production forests (Blaser et al., 2011). Estimates of total annual emissions from selective logging in the tropics range from 800 to nearly 2000 Tg CO<sub>2</sub> (Ellis et al., 2019). Pearson et al. (2014) showed that the carbon emissions from selective logging were equivalent to 12% of the emissions from deforestation, as an average over the nine tropical countries they studied. Given the global importance and increased public interest in carbon emissions, it is of utmost importance for decision-makers to identify which changes in prevailing practices can help improve the overall carbon balance of the wood sector.

81 At the country and territory scale, different strategies have been proposed for decreasing carbon  
82 emissions from selective logging while maintaining wood production. These mitigation strategies  
83 fall under the scope of the land-sparing *versus* land-sharing debate, initially developed for food  
84 production (Green et al., 2005) and later extended to the wood sector (Edwards et al., 2014a;  
85 Runting et al., 2019). The land-sparing strategy is based on a spatial separation of production and  
86 conservation functions of the land allowed by increased productivity, as opposed to the land-  
87 sharing strategy combining several functions in the same area. Evidence shows that a land-sparing  
88 strategy consisting of increasing logging intensity in some areas while keeping other areas free  
89 from logging can have positive effects on both carbon balance and biodiversity conservation  
90 (Edwards et al., 2014a; Griscom et al., 2018; Piponiot et al., 2019). Timber plantations further  
91 segregate production and conservation functions. They have a low value for biodiversity  
92 conservation (Bremer and Farley, 2010 ; Barlow et al., 2007) but their intensive wood production  
93 can be an alternative strategy to selective logging in natural forest (Buongiorno and Zhu, 2014).  
94 They are increasingly considered as a climate mitigation strategy through the storage of carbon in  
95 live trees and wood products (Minnen et al., 2008; Sanquetta et al., 2018). However, they have  
96 significantly lower stock of carbon than natural forests (Liao et al., 2010). The type of land  
97 converted to plantation therefore matters and plantation establishment after deforestation often  
98 results in overall carbon emissions (Guillaume et al., 2018).

99 Beyond the land-sharing *versus* land-sparing debate, improved logging practices in natural forests  
100 can have positive impacts on climate change mitigation, other ecosystems services and  
101 biodiversity conservation (Griscom et al., 2017; Griscom and Cortez, 2013; Putz et al., 2008;  
102 Runting et al., 2019). Reduced impact logging (RIL) can improve the overall carbon balance by  
103 reducing the amount of damage while maintaining wood production, and hence avoiding leakage

104 of the negative impacts of logging (Griscom and Cortez, 2013). RIL is defined as ‘intensively  
105 planned and carefully controlled timber harvesting conducted by trained workers in ways that  
106 minimize the deleterious impacts of logging’ (FAO, 2004) and consists in a set of practices  
107 encompassing planned logging activities, improved harvesting operations (*e.g.* directional felling)  
108 and post-harvesting operations (*e.g.* rehabilitation of skidding trails) (Putz et al., 2008; Sist, 2000).  
109 A subset of RIL practices, grouped under the name of Reduced-Impact Logging for Climate Change  
110 Mitigation (RIL-C) (Ellis et al., 2019 ; Griscom et al., 2014), especially aim to reduce logging  
111 emissions. They are particularly promising as Ellis et al. (2019) has shown that they could lead to  
112 60% reduction in logging emissions. In some places, intensification of logging (*i.e.* increased  
113 volume of extracted wood) also results in reduced emissions per volume of extracted wood,  
114 probably because of a more efficient use of logging infrastructure and a reduction of damage per  
115 volume unit (Ellis et al., 2019). By reducing the two greater sources of tree death, namely damage  
116 and logging infrastructure (Pearson et al., 2014), both RIL and increased intensity logging can  
117 reduce the amount of dead biomass and the resulting emissions, leading to a shorter time for  
118 recovery of lost biomass (West et al., 2014). Although rarely adopted by the wood sector (Ruslandi  
119 et al., 2017c), silvicultural treatments, such as thinning to improve growth of commercial species,  
120 enrichment planting and liana cutting may also improve recovery of biomass and carbon stock  
121 (Cerullo and Edwards, 2019; Gourlet-Fleury et al., 2013; Ruslandi et al., 2017a).

122 Monitoring the carbon emissions of logging and forestry practices is important to assess their  
123 effectiveness in reducing carbon emissions of the wood sector and inform forest policies for  
124 mitigation of climate change. However, while deforestation is relatively easy to monitor through  
125 remote sensing, degradation - as it does not lead to a total loss of forest cover - is much more  
126 difficult to assess (Grace et al., 2014; Pearson et al., 2014). Remote sensing approaches using high

127 resolution satellite imagery have allowed large scale monitoring of selective logging impacts  
128 (Asner et al., 2002). Such approaches are however limited as they can only detect canopy damage.  
129 Methods based on field measurement of logging damage can produce a finer assessment of logging  
130 emission at the smaller scale of the logging concession. Griscom et al. (2014) and Feldpausch et al.  
131 (2005) have proposed such a method accounting for emission due to timber extraction, logging  
132 damage and logging infrastructure, which has since been widely used (Ellis et al., 2019). Carbon  
133 emissions are expressed relatively to the amount of wood produced (using the Total Emission  
134 Factor (Griscom et al., 2014; Pearson et al., 2014 ; Zalman et al., 2019) and the Carbon Impact  
135 factor (Ellis et al., 2019; Goodman et al., 2019; Umunay et al., 2019)), which is particularly  
136 interesting to compare the relative importance of these different sources of emissions and the  
137 efficiency of different logging practices for climate change mitigation (see the recent special issue  
138 on RIL-C (Ellis and Putz, 2019)). However, both remote sensing and previously cited field-based  
139 approaches use a committed emissions approach, meaning that they only account for fluxes at the  
140 time of logging (Fearnside, 1997), whereas carbon fluxes continue long after logging operations.  
141 For example, decomposition of logging damage left on site occurs over several decades (Hérault et  
142 al., 2010a). Committed emission approaches also fail to account for long-term carbon recovery,  
143 which is the recovery of carbon within the selectively logged plot resulting from increased growth  
144 of remaining trees due to increased canopy openness and changes in competition levels (Hérault  
145 et al., 2010b). However, carbon recovery may happen within a few decades, and can therefore be  
146 achieved within a cutting cycle, *i.e.* the time period between two harvests (typically 20 to 35 years  
147 but up to 65 years in the case of French Guiana) (ONF, 2016; Piponiot et al., 2016). Some carbon  
148 balance models only consider biogenic carbon in forests, overlooking the downstream part of the  
149 wood sector. Harvested wood products can however store significant amounts of carbon over a

150 long period of time (IPCC, 2006), and using wood as a substitute for a more carbon demanding  
151 material or source of energy can lead to avoided emissions (Bellassen and Luyssaert, 2014).  
152 Another group of carbon emissions assessment methods are based on a life cycle accounting  
153 approach (Alice-Guier et al., 2019; Numazawa et al., 2017; Olguin et al., 2018 ; Piponiot et al.,  
154 2016a). Such approaches consider larger system boundaries as they include forest regrowth (*i.e.*  
155 forest re-establishment on areas fully cleared during logging, such as roads and wood storage  
156 decks), wood decomposition in the forest and the fate of wood products. They are also temporally  
157 explicit. They assess the different carbon fluxes either by using previously published models  
158 (Alice-Guier et al., 2019; Numazawa et al., 2017) or models calibrated with local field data (Olguin  
159 et al., 2018; Piponiot et al., 2016a). Such studies often show a more carbon neutral impact of the  
160 wood sector than studies with narrower system boundaries and committed emissions (Alice-Guier  
161 et al., 2019). They can allow a wide scale assessment of the carbon balance of the wood sector,  
162 from the region to the whole country (Alice-Guier et al., 2019), and can be used in a predictive  
163 manner to compare outcomes of prospective scenarios (Olguin et al., 2018; Piponiot et al., 2016a).

164 Building on the carbon life cycle approach, our study advances a model of carbon balance for the  
165 wood sector. This model uses a carbon accounting approach and relies on local permanent forest  
166 monitoring plots to calibrate statistical models for the different fluxes using a Bayesian approach.  
167 Its novelty is that it is temporally explicit and can be used on a large scale (scale of the whole  
168 territory), that it has wide system boundaries and that it includes both selective logging and  
169 timber plantation. We emphasise its usefulness in the context of French Guiana as a prospective  
170 tool for assessing strategies of development of the wood sector. French Guiana (4°13'N,  
171 52°59'0'W) is a French oversea territory located in the Guiana shield, in the North-East of  
172 Amazonia, with an equatorial climate (Guitet et al., 2015). Its striking specificity is its very high

cover of tropical wet forests (97.3% percent of the land is covered by natural forests (FAO, 2020)). Most forests are managed by the ONF, the French National Forest Service. The 2.4 Mha of forests forming the Permanent Forest Estate are designated as production or conservation forests (Piponiot et al., 2016a) and account for about 30% of forest cover of the territory. Current wood production is obtained exclusively by low intensity selective logging with long cutting cycles (65 years) (ONF, 2016). The annual production ranges from 65 000 to 80 000 m<sup>3</sup> of timber per year (Piponiot et al., 2016a) and is mostly used locally for construction. A rapidly growing human population (2.6% increase per annum, source *INSEE* national population census 2010-2015) leads to a greatly increasing demand for wood. The local strategic plan for the forest and wood sector (Collectivité Territoriale de Guyane et al., 2019) states the aim to increase the annual timber production to 200 000 m<sup>3</sup> by 2030, and to diversify practices with the development of timber plantation and the use of wood biomass as a source of energy.

The objectives of our study are (1) to develop a temporally explicit model of carbon balance taking into account biogenic carbon fluxes in natural forests and plantation, and the downstream activities of the wood sector including first transformation in the sawmill, (2) to apply this model at the plot scale to identify practices with the more positive impact on carbon balance, and (3) to apply it to past and future practices at the scale of the whole territory of French Guiana to compare the carbon balance of different prospective scenarios of timber production.

## 2 Materials and Methods

### 2.1 Model overview

193 A detailed glossary of all variables and all parameters is given in Table A.1 and Table A.2,  
194 respectively.

195 To model the carbon balance of timber production, we developed a model based on a previous  
196 version that aimed to assess retrospective carbon balance (Piponiot et al., 2016a). The model  
197 calculates annual fluxes from aboveground biomass (AGB) at the scale of each natural forest or  
198 plantation plot and integrates them in time and across plots. The model is temporally-explicit,  
199 meaning that carbon fluxes are accounted for in the year when they actually occur. The new  
200 version includes a retrospective component to model the carbon balance due to historical logging,  
201 and a prospective component for future balance based on prospective scenarios. The system  
202 boundaries of the model range from the forest to the first transformation in the sawmill and  
203 combustion in the biomass plant. It therefore includes all biogenic fluxes (forest regrowth and  
204 recovery, tree growth in plantation and wood decay on site) and the logistic activities (emission  
205 from machines and fuel consumption for staff and wood transport, for tree felling and for logging  
206 infrastructure). It excludes second transformation and export. Our model accounts for  
207 aboveground biomass only, and excludes belowground biomass and soil carbon. To be able to  
208 include new fluxes needed for the prospective part, we developed new submodels to account for  
209 timber production in plantations, use of RIL techniques, and use of byproducts as fuelwood. We  
210 accounted for logistic activities, and improved some of the existing submodels. We also added the  
211 possibility to account for avoided emissions by substitution of fuelwood to fossil fuel, to assess the  
212 interest of using logging and plantation byproducts for energy and reduce emissions from fossil  
213 fuel.

214 The overall model is presented in Fig. 1. The different carbon fluxes of the models (noted  $C$ ) are  
 215 briefly presented in this section, which refers to the sections where the submodels are presented  
 216 in detail. All these carbon fluxes are summed to get the net balance over time. Carbon emissions  
 217 from logistic activities ( $C^{logisticsNF}$  and  $C^{logisticsP}$ ), all sawmill fluxes ( $C^{decaysawnS}$ ,  $C^{wastes}$  and  
 218  $C^{CopS}$ ), wood burning and operating of biomass plants ( $C^{burntBP}$  and  $C^{opBP}$ ), and wood decay on  
 219 site ( $C^{decayFWN}$  and  $C^{decayCWN}$ ) are considered positive, and carbon storage from forest recovery  
 220 ( $C^{recovNF}$ ) and regrowth in natural forest ( $C^{regrowthNF}$ ), tree growth in plantation ( $C^{growth}$ ), and  
 221 avoided emission in biomass plant ( $C^{avoidBP}$ ) are negative. In natural forest, selective logging  
 222 produces timber (section 2.6.1), and results in logging damage in the plot (section 2.6.2) and  
 223 deforestation for logging infrastructure (logging roads, main skid trails and logging decks)  
 224 (section 2.6.3). After logging, carbon is stored back through forest recovery within the plot  
 225 (section 2.6.4), and forest regrowth occurs on areas deforested for logging infrastructure (only on  
 226 main skid trails and logging decks) (section 2.6.5). The main objective of plantations is to produce  
 227 timber, fuelwood being a byproduct. Plantations are established either on non-forested land or by  
 228 clearing natural forests already logged in the past (section 2.5.1). Even if it is questionable in most  
 229 contexts, the latter option is the more realistic in the context of very high forest cover and the  
 230 resulting low availability of non-forested land in French Guiana. Our model therefore incorporates  
 231 the emissions from the deforestation of natural forests to establish plantations, as not doing so  
 232 would wrongly improve the overall carbon balance of the sector. This deforestation produces  
 233 timber and fuelwood and leaves wood to decompose on site. Once established, plantations store  
 234 carbon through tree growth. Successive thinning operations in the plantations produce fuelwood  
 235 and the final harvest produces both timber and fuelwood (section 2.5.2). After the first harvest,  
 236 plantations are re-established on the same plot, without incurring additional deforestation. For

237 both logging in natural forest and plantation harvesting, produced timber is processed in the  
238 sawmill (section 2.8). Our model accounts for carbon fluxes up to the first transformation.  
239 Byproducts used as fuelwood are burnt in the biomass plant, which generates direct emissions  
240 through combustion and leads to avoided emissions by substitution to another source of energy  
241 (section 2.9). Our model accounts for avoided emissions from fuelwood substitution to fossil fuel  
242 (heavy fuel and diesel), as this source of energy is currently predominant in French Guiana  
243 (Explicit and Alter, 2012). It also allows for avoided emissions to be excluded, as a more  
244 conservative scenario reflecting the likely shift to greener energy in the future. These two  
245 possibilities therefore reflect two extreme cases in between which the future reality is likely to be  
246 situated. All the remaining tree parts are left to decay on site (section 2.10). The code is written in  
247 the R environment (R Core Team, 2018) and available online  
248 ([https://github.com/EcoFoG/C\\_balance\\_forest\\_FG](https://github.com/EcoFoG/C_balance_forest_FG)).

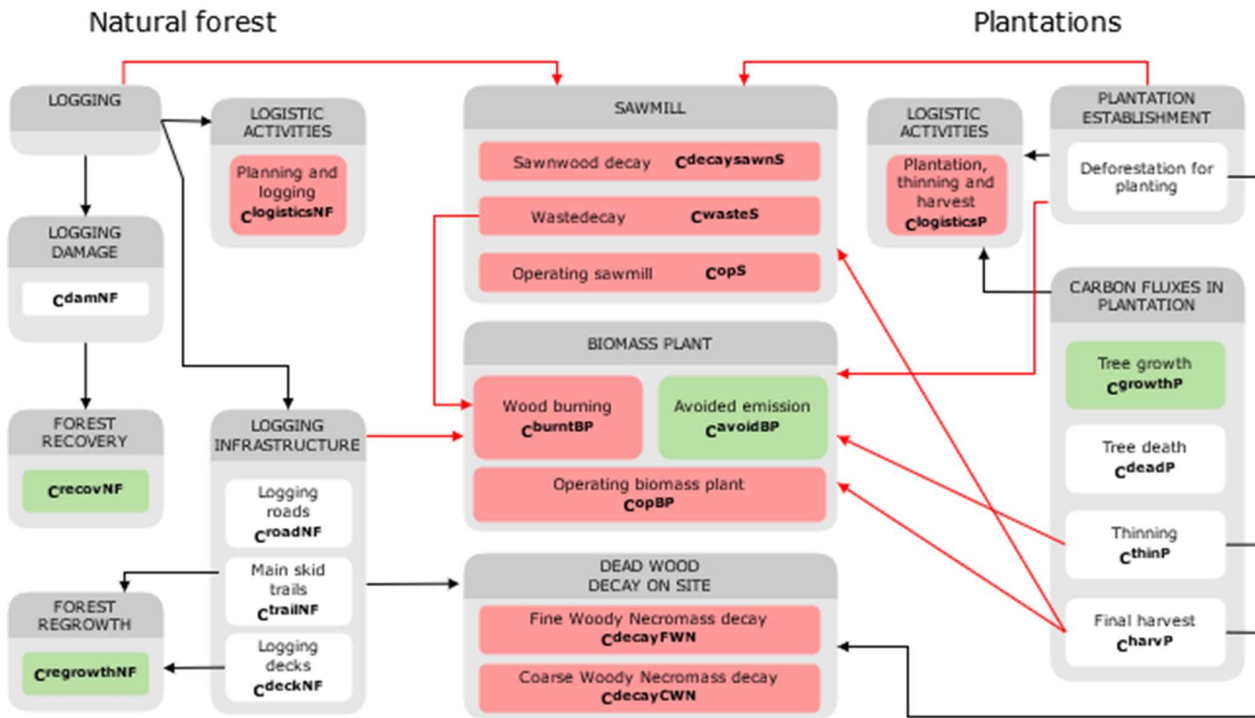


Figure 1: Overview of the carbon balance model and all submodels. Red boxes and arrows are for carbon emissions, green ones for carbon storage. The net carbon balance is the sum of all colour fluxes. White boxes and black arrows do not directly lead to emissions or storage. All grey boxes refer to a section of the description of the model. Carbon fluxes ( $C$ ) are referred to in these sections.

## 2.2 Data for model calibration and input

We calibrated all submodels using local or regional data (French Guiana or Amazonia), with the exception of the sawnwood decay submodel obtained from the literature (IPCC, 2003). We used data from two networks of permanent forest plots, in which all trees with a  $DBH \geq 10$  cm are mapped, botanically identified and periodically measured. We used data from 12 sites of the Guyafor network (Cirad et al., 2020), which covers the northern part of French Guiana (between 1 and 16 plots per site, all undisturbed, ranging from 4 to 6.25 ha). One of these sites, Arbocel, is a

261 secondary forest undergoing natural succession after having been clearcut in 1976 (Chave et al.,  
 262 2020). We also used data from 13 sites (94 plots, selectively logged, ranging from 0.25 to 6.25 ha)  
 263 of the Amazonian part of the TmFO network (Sist et al., 2015). For all these plots, AGB was  
 264 calculated with the *BIOMASS* package (Réjou-Méchain et al., 2017) in R (R Core Team, 2018), using  
 265 the allometric equation and the bioclimatic predictor to estimate tree height proposed by Chave et  
 266 al. (2014). In addition, the effects of RIL were estimated from post-logging monitoring of damage  
 267 conducted by the ONF (unpublished) on 6 conventionally logged and 8 RIL sites situated in the  
 268 Permanent Forest Estate in French Guiana. The productivity of plantations was obtained from a 30  
 269 year-old experimental plantation established in Sinnamary, French Guiana, considering the 7  
 270 species that performed the best (*Sterculia pruriens*, *Simarouba amara*, *Diploptropis purpurea*,  
 271 *Qualea rosea*, *Eperua falcata*, *Dicorynia guianensis* and *Vochysia tomentosa*) (Nicolini and Morel,  
 272 2016).

273 For the retrospective part of the model, location and intensity of selective logging conducted  
 274 between 1974 and 2018 were obtained from ONF statistics (ONF, unpublished). For the  
 275 prospective part, plots to log or to deforest for plantation were drawn among the list of plots  
 276 situated in the Permanent Forest Estate. Environmental parameters specific to each plot were  
 277 used: initial AGB in natural forest prior to logging or conversion to plantation (Fayad et al., 2016),  
 278 mean annual precipitation and precipitation seasonality from WorldClim (Fick and Hijmans,  
 279 2017), and soil bulk density from the Harmonized global soil database (Fischer et al., 2008).

280 We considered that the carbon content of AGB ( $C_{content}$ ) is 0.47 (Réjou-Méchain et al., 2017) and  
 281 that the water content of green wood ( $H$ ) is 45% (expert knowledge ONF). The dry wood density  
 282 of timber ( $WD_{timbNF}$ ) and fuelwood from natural forest were taken as 0.609 and 0.604

( $WD_{fuelNF}$ ), which are respectively the mean wood density of the three main commercial species weighted by their relative contribution to annual timber volume production (Piponiot et al., 2016a), and an estimated mean across all species (expert knowledge ONF). The dry wood density of wood from plantation ( $WD_P$ ) is taken on a plot basis for the species considered for the plantation productivity model from 0.356 to 0.753, median 0.588. Wood densities at 12% humidity (Ollivier et al., 2007) were converted to 0% humidity (Vieilledent et al., 2018).

### 2.3 *Propagating model uncertainties using a Bayesian framework*

All submodels were written under the Bayesian paradigm and inferred using an adaptive form of the Hamiltonian Monte Carlo sampling (Carpenter et al., 2017) with the *rstan* package (Stan Development Team, 2018). The Bayesian modelling approach has two main advantages. First, prior knowledge of the processes under study can be combined with new empirical data in a consistent modelling framework. Second, it allows for rigorous propagation of uncertainties from each submodel to the overall model. This enabled us to provide credibility intervals resulting from the cumulative uncertainties. To do so, we ran a high number of simulations (2000 when the model is run at the plot scale and 500 for the scenarios). We ensured that the number of simulations was sufficient to guarantee stability of the results, by running the model several times with the chosen number of simulations and checking that the results did not change. As all submodels were calibrated by Bayesian inference, we obtained a high number of values for all model parameters, called posteriors. These posteriors are presented in Table A.2. For the simulation step, we randomly drew 2000 (for the plot scale) or 500 (for the scenario scale) parameter values from the posteriors. These parameters defined the distributions of the variables predicted by the submodels, in which we randomly drew a value per simulation. In doing so, we

305 propagated the uncertainties due to both the data and the model fit. This was done per plot for the  
306 submodels fitted at the plot scale (carbon fluxes in plantation, logging damage, logging  
307 infrastructure, recovery, regrowth, decay), and for the whole simulation for submodels relevant at  
308 the territory scale (sawmill). We then calculated summary statistics (median and credibility  
309 intervals) over all simulations.

310 We conducted a sensitivity analysis on the main submodels to assess their relative contributions  
311 to the overall model uncertainty. To do so, we made each submodel deterministic, in turn, by  
312 setting their parameters at their maximum likelihood, and taking the mode of the posterior  
313 distribution of results. The uncertainty of the other submodels was retained. The stronger the  
314 difference in variability of the results compared with the fully stochastic simulations, the higher  
315 was the uncertainty due to the considered submodel.

#### 316 2.4 *Running the carbon balance model*

317 The carbon balance model was run at two scales. First, we ran it at the scale of a single 1 ha plot  
318 with median environmental conditions to explore the effect of each practice taken individually.  
319 Then, we ran the model at the scale of French Guiana to explore different prospective scenarios of  
320 timber production developed together with stakeholders from the wood sector (Table 1) during a  
321 scenario-planning workshop (Table A.3). We purposely chose very contrasting scenarios to be  
322 able to identify interesting practices for the development of the wood sector, but our model can  
323 also be used to test more nuanced scenarios. For all scenarios, the prospective period extended  
324 from 2019 to 2088. We included historical selective logging (1974-2018) because these past  
325 activities will still induce carbon fluxes in the future. For this retrospective part, all timber comes  
326 from logging in natural forest. For the prospective part, each scenario set an annual objective of

327 timber production from natural forest and from plantation. When the modelled production of  
328 timber from plantation is lower than the scenario's objective, the amount of timber logged in  
329 natural forests is adjusted to meet the overall objective of timber production. The scenario  
330 *Business as usual* corresponds to current selective logging practices in natural forest and is the  
331 only one for which the target annual timber production is 80 000 m<sup>3</sup> year<sup>-1</sup>. For all the other  
332 scenarios, this volume is set to 200 000 m<sup>3</sup> year<sup>-1</sup> to reflect the future objective set by the strategic  
333 plan for the forest and wood sector (Collectivité Territoriale de Guyane et al., 2019). The scenario  
334 *Intensification* tests increased intensity of logging implemented together with RIL in natural forest.  
335 The scenario *Natural forest + plantation* aims at producing wood both from natural forest and  
336 plantation. The scenario *Plantation* produces wood solely from plantation, although logging in  
337 natural forest is carried out during the plantation establishment phase and for years when the  
338 overall targeted volume is not met. For this scenario, all the plantations are established on natural  
339 forest after deforestation. The scenario *Plantation no deforestation* is a variation of *Plantation* for  
340 which there is no deforestation to establish the plantation, *i.e.* they are established on bare land.  
341 The scenario *Plantation risk* is a variation of *Plantation* for which the plantation productivity is  
342 less than expected, and the plantation duration thus has to be increased. For each scenario at the  
343 scale of the plot and at the scale of the whole territory, the model was run both with and without  
344 accounting for avoided emissions resulting from the substitution of fuelwood, to be able to  
345 compare these two cases.

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349

350 Table 1: Prospective scenarios

	Timber from plantation (m3 year <sup>-1</sup> ) *	Timber from natural forest (m3 year <sup>-1</sup> ) *	Logging intensity (m3 ha <sup>-1</sup> )	Logging type	Fuelwood	Plantation duration (exp./obs.)	Plantation productivity	Deforestation to plant
Business as usual	0	80 000	20	Conv.	No	NA	NA	NA
Intensification	0	200 000	30	RIL	Yes	NA	NA	NA
Nat. for. + plant.	120 000	80 000	20	Conv.	Yes	30/30	exp.	yes
Plantation	200 000	0	20	Conv.	Yes	30/30	exp.	yes
Plant. no defor.	200 000	0	20	Conv.	Yes	30/30	exp.	no
Plantation risk	200 000	0	20	Conv.	Yes	30/35	2/3 x exp.	yes

351       *\* The annual production of timber, both for plantation and natural forest, is the targetted*  
352       *one. If the production from plantation is less than expected, logging in natural forest is*  
353       *increased to compensate even if the targetted volume is null (especially during the*  
354       *establishment phase of the plantation when most of the wood comes from natural forest).*  
355       *Nat. For. stands for Natural forest, plant. for plantation, defor. for deforestation, Conv. for*  
356       *conventional logging, exp. for expected and obs. for observed*

357   2.5   *Plantation*

358   2.5.1   *Plantation establishment*

359   In this section, we present how the model selects the plots for establishing the plantations, and the  
360   calculation of  $ACS^{ONF}$ , the aboveground carbon stock of the plot prior to the first plantation, and  
361   the area actually planted  $Area^{plantP}$ .

362   To calculate the annual area of plantation needed to meet the objective of timber production of the  
363   scenarios, we used the submodel of carbon fluxes in plantations presented in section 2.5.2 over a  
364   high number of simulations to get the mean expected volume of timber per ha. Note that this  
365   volume can differ from the mean volume that will actually be obtained if the observed productivity

is altered (for scenario *Plantation risk*). For scenarios establishing the plantations on forested land, forest plots that have previously been logged are deforested to establish the plantations. The aboveground biomass of these plots is then harvested for timber and fuelwood, and a portion is left to decay on site (see sections 2.8, 2.9 and 2.10). This occurs only for the first cycle of plantations, as plantations are immediately replanted in the same plot after the first harvest. Plots that have been logged earlier (1974-1983, then 1984-1993) are deforested preferentially. Within these age categories, we have chosen to draw plots randomly as there is currently no spatial planning of plantation in French Guiana. A random draw associated with a high number of simulations allowed us to take into account the spatial variability of initial conditions. For scenarios establishing the plantations on non-forested land, we assumed that there is no vegetation on the land, hence an initial AGB of zero.

The area of plot  $p$  with suitable topography for plantation  $Area_{p,s}^{plantP}$  (ha) is

$$Area_p^{plantP} = \frac{0.5}{0.543} \times Area_p^{loggedP} \quad (1)$$

where  $Area_p^{loggedP}$  (ha) is the area that had been logged, because the proportion of a total plot that can be logged ( $R_{logNF}$ ) has a median value of 0.543 (see section 2.6.1), and the proportion of a plot that can be planted is 0.5 (median value, expert knowledge ONF). For each year  $t < P_{duration}$  and each simulation  $s$  plots are drawn randomly without replacement until the needed annual area of plantation is met. The area needed in a given year is adjusted to reach the needed area cumulatively over the years.

### 2.5.2 Carbon fluxes in plantation

386 This section presents how  $C^{thinP}$ ,  $C^{har}$  and  $C^{deadP}$ , the carbon fluxes resulting from trees that  
 387 are thinned, harvested or died respectively, and  $C^{growth}$ , the carbon flux resulting from tree  
 388 growth, in a given year were obtained (Fig. 2-a). We followed a two-step approach.

389 In the first step, we calculated the amount of carbon accumulated over the whole plantation cycle,  
 390 in different compartment (Fig. A.1).  $ACS^{endP}$  is the aboveground carbon stock accumulated in  
 391 trees that reached the end of the plantation cycle,  $ACS^{lostP}$  is the aboveground carbon stock lost  
 392 from trees that died before the end of the plantation cycle, either because they died naturally or  
 393 were thinned, and  $ACS^{thinP}$  is the amount of aboveground carbon in trees that were thinned.

394 The amount of biomass accumulated at year  $t$  after plantation in trees that reached the end of the  
 395 plantation  $AGB_{p,s,t}^P$  (Mg ha<sup>-1</sup>) is modelled with a lognormal distribution, as follows:

$$396 \quad AGB_t^P \sim Lognormal(\ln(\theta_p \times t), \sigma_p^2) \quad (2)$$

397 with  $\theta_p$  the median annual accumulation of AGB, and  $\sigma_p^2$  the variance of  $\log(AGB)$ .

398 The aboveground carbon stock of a plantation  $p$  for simulation  $s$  at time of harvest  $ACS_{p,s}^{endP}$  (Mg  
 399 ha<sup>-1</sup> of C) is:

$$400 \quad ACS_{p,s}^{endP} = AGB_{p,s,t=P_{duration}}^P \times C_{content} \quad (3)$$

401 where  $P_{duration}$  is the plantation duration (also called rotation length, *i.e.* time from plantation to  
 402 harvest).

403 The plantation productivity can be altered by applying a reduction factor  $R_{reducP} < 1$  (taken as  
 404 2/3 for scenario *Plantation risk*) to  $ACS_{p,s}^{endP}$ .

405  $ACS^{lostP}$  and  $ACS^{thinP}$  cannot be assessed directly, because of the lack of repeated tree inventories  
 406 in plantation, so we obtained them by using two proportions:  $R_{thinEndP}$  and  $R_{thinLostP}$ .

407  $R_{thinEndP}$  is the proportion of ACS in thinned trees ( $ACS^{thinP}$ ) relative to the ASC at the end of the  
 408 plantation cycle ( $ACS^{endP}$ ), and was assumed to be a constant for all plantations  $p$  and simulations  
 409  $s$ :

$$410 \quad ACS_{p,s}^{thinP} = ACS_{p,s}^{endP} \times R_{thinEndP} \quad (4)$$

411 We obtained  $R_{thinEndP}$  from plantation production tables that report the volume of wood  
 412 harvested at the end of the plantation and the total volume of wood harvested during thinning  
 413 events (Dupuy and Mille, 1991).

414  $R_{thinLostP}$  is the proportion of  $ACS^{thinP}$  relative to the ACS lost (by natural death or thinning) after  
 415 the year of first thinning event  $t_{firstP}$ , and is thus a measure of thinning efficiency:

$$416 \quad R_{thinLostP} = \frac{ACS_{p,s}^{thinP}}{ACS_{p,s}^{lostP} - (ACS_{p,s}^{lostP} \times t_{firstP} / P_{duration})} \quad (5)$$

417 To get  $R_{thinLostP}$ , we assumed that it depends on the number of thinning events  $N_{thinP}$  (set to 3  
 418 from expert knowledge) and the duration of the plantation. Thinning every year ( $N_{thinP} =$   
 419  $P_{duration}$ ) would lead to  $R_{thinLostP} = 1$ , meaning that thinning would take all natural mortality. We  
 420 thus get  $R_{thinLostP}$  as follows:

$$421 \quad R_{thinLostP} = \left( \frac{N_{thinP}}{P_{duration}} \right)^{\gamma_P} \quad (6)$$

422 where  $\gamma_P$  is a parameter of elasticity chosen as follows: if  $\gamma_P = 1$ , only the mortality of the year  
 423 would be taken by the thinning. Lower values of  $\gamma_P$  correspond to more efficient thinning practices  
 424 that allow harvesting of trees that would have died in subsequent years, thus minimising the

amount of dead wood. We took as small value of  $\gamma_P$  (0.1) because we anticipated that thinning practices will efficiently reduce natural tree mortality.

$ACS_{p,s}^{lostP}$  is obtained from equations (4) and (5):

$$ACS_{p,s}^{lostP} = \frac{ACS_{p,s}^{endP} \times R_{thinEndP}}{(1 - \frac{t_{firstP}}{P_{duration}}) \times R_{thinLostP}} \quad (7)$$

In the second step, these quantities of carbon calculated over the whole plantation cycle are used to calculate the carbon fluxes at any year of a plantation (Fig. A.2).

We assumed that the amount of carbon in thinned trees is equally distributed among thinning events, hence, we have  $C_{p,s,t}^{thinP}$  the amount of carbon in thinned trees at year  $t$  after plantation (Mg ha<sup>-1</sup> of C):

$$C_{p,s,t}^{thinP} = \begin{cases} \frac{ACS_{p,s}^{thinP}}{N_{thinP}} = \frac{ACS_{p,s}^{endP} \times R_{thinEndP}}{N_{thinP}} & \text{for } t \text{ a thinning years} \\ 0 & \text{for } t \text{ any other other years} \end{cases} \quad (8)$$

where  $N_{thinP}$  is the number of thinning events conducted at regular time intervals.

If no thinning occurred,  $ACS_{p,s}^{lostP}$  would be entirely due to natural tree mortality. We assumed that the amount of carbon lost in dead trees would be equally distributed across years. The annual amount of carbon in dead tree  $C_{p,s,t}^{natdeadP}$  (Mg ha<sup>-1</sup> of C) would therefore be:

$$C_{p,s,t}^{natdeadP} = \frac{ACS_{p,s}^{lostP}}{P_{duration}} \text{ for } t \text{ any year} \quad (9)$$

As thinning aims at anticipating the mortality of the following years, it changes the annual amount of carbon in dead trees of the following  $j + 1$  years, with

$$j_{p,s} = \lfloor \frac{C_{p,s,t}^{thinP}}{C_{p,s,t}^{natdeadP}} \rfloor \quad \text{where } t \text{ is any thinning year} \quad (10)$$

The actual annual amount of carbon in dead trees  $C_{p,s,t}^{deadP}$  (Mg ha<sup>-1</sup> of C) is then, with  $t_{thin}$  a given year of thinning and  $t$  any year before the next thinning:

$$C_{p,s,t}^{deadP} = \begin{cases} 0 & \text{for } t_{thin} < t \leq t_{thin} + j_{p,s} \\ C_{p,s,t}^{natdeadP} \times (1 - (\frac{C_{p,s,t}^{thinP}}{C_{p,s,t}^{natdeadP}} - j_{p,s})) & \text{for } t = t_{thin} + j_{p,s} + 1 \\ C_{p,s,t}^{natdeadP} & \text{for } t > t_{thin} + j_{p,s} + 1 \end{cases} \quad (11)$$

where  $j_{p,s}$  is obtained with equation (10).

The annual amount of carbon in trees that are harvested  $C_{p,s,t}^{harvpP}$  (Mg ha<sup>-1</sup> of C) is:

$$C_{p,s,t}^{harvpP} = \begin{cases} ACS_{p,s}^{endP} & \text{for } t \text{ the harvest year} \\ 0 & \text{for } t \text{ any other year} \end{cases} \quad (12)$$

The annual amount of carbon stored by tree growth  $C_{p,s,t}^{growthP}$  (Mg ha<sup>-1</sup> of C) is:

$$C_{p,s,t}^{growthP} = \frac{ACS_{p,s}^{endP} + ACS_{p,s}^{lostP}}{P_{duration}} \quad \text{for } t \text{ any year} \quad (13)$$

## 2.6 Natural forest

### 2.6.1 Logging

Plots of natural forest on which selective logging is conducted are randomly drawn, for the same reason as randomly drawing plots to establish plantation, from all the unlogged plots of the Permanent Forest Estate. Plots are drawn until the total timber objective (from natural forests and plantations together) is met. A plot that has been logged once cannot be logged again during the same simulation, because cutting cycles are long in French Guiana (65 years) and because the submodels are not fitted for a second logging cycle due to the absence of data. The area logged

459  $Area^{loggedNF}$  is calculated for each plot and each simulation, from the proportion of the total area  
 460 with a topography suitable for logging ( $R_{logNF}$ ).

### 461 2.6.2 Logging damage

462 In this section, we present how we modelled  $C^{damNF}$ , the amount of carbon in wood resulting from  
 463 logging damage. As for the other submodels, logging damage is modelled using data from  
 464 permanent forest plots. We chose this method over the use of published data based on post-  
 465 logging measurements following the method from Griscom et al. (2014) and Feldpausch et al.  
 466 (2005) to be able to assess and propagate model uncertainties. Logging damage includes trees that  
 467 have been damaged by logging and secondary skid trails and died within five years, and unused  
 468 parts of logged trees. To calculate the amount of carbon in wood resulting from logging damage  
 469 for plot  $p$ , simulation  $s$ , for year of logging  $t$ ,  $C_{p,s,t}^{damNF}$  (Mg ha<sup>-1</sup> of C), we modelled the proportion of  
 470 carbon in damage relative to the carbon in non-logged biomass ( $\frac{C_{p,s,t}^{damNF}}{ACS_p^{0N} - ACS_{p,t}^{extNF}}$ ) with a beta  
 471 distribution as a function of proportion of carbon in biomass that was logged relative to pre-  
 472 logging biomass ( $\frac{AC_{p,t}^{extNF}}{AC_p^{0NF}}$ ). We used the following model (Fig. 2-b):

$$473 \quad \frac{C_{p,s,t}^{damNF}}{ACS_p^{0N} - ACS_{p,t}^{extNF}} \sim Beta(\alpha_{Dam}, \beta_{Dam}) \quad (14)$$

474 with  $\alpha_{Dam} > 0$  and  $\beta_{Dam} > 0$  the shape parameters,  $ACS_p^{0NF}$  (Mg ha<sup>-1</sup> of C) the pre-logging  
 475 aboveground carbon stock (ACS), and  $ACS_{p,t}^{extNF}$  (Mg ha<sup>-1</sup> of C) the ACS of extracted timber. The  
 476 mean and variance of the distribution are:

$$\begin{aligned}
E\left(\frac{C_{p,s,t}^{damNF}}{ACS_p^{0NF} - ACS_{p,t}^{extNF}}\right) &= \frac{\alpha_{Dam}}{\alpha_{Dam} + \beta_{Dam}} = \left(\frac{ACS_{p,t}^{extNF}}{ACS_p^{0NF}}\right)^{\gamma_{damNF}} \\
Var\left(\frac{C_{p,s,t}^{damNF}}{ACS_p^{0NF} - ACS_{p,t}^{extNF}}\right) &= \frac{1}{\phi_{damNF} + 1} \times \left(1 - \left(\frac{ACS_{p,t}^{extNF}}{ACS_p^{0NF}}\right)^{\gamma_{damNF}}\right) \times \left(\frac{ACS_{p,t}^{extNF}}{ACS_p^{0NF}}\right)^{\gamma_{damNF}}
\end{aligned} \tag{15}$$

with  $\gamma_{damNF} \geq 0$  and  $\phi_{damNF} \geq 0$ . We chose a power function model with a positive exponent to have an increasing relationship that can be concave, convex or linear.

When RIL is implemented, we apply a reduction coefficient  $R_{RilNF}$  to  $C_{p,s,t}^{damNF}$ :

$$C_{p,s,t}^{damRilNF} = C_{p,s,t}^{damNF} \times (1 - R_{RilNF}) \tag{16}$$

$R_{RilNF}$  was modelled with a Beta distribution, using data of post-logging monitoring (ONF, unpublished) (Table A.2).

### 2.6.3 Logging infrastructure

We present here the method used to obtain  $C^{roadNF}$ ,  $C^{trailNF}$  and  $C^{deckNF}$ , the amounts of carbon contained in trees cut for creation of logging roads, main skid trails and wood storage decks, respectively. Logging roads are defined as the access to an area on which at least 3000 m<sup>3</sup> of wood (timber + fuelwood) is harvested. Main skid trails are defined as the access to an area of at least 5 ha but on which less than 3000 m<sup>3</sup> of wood is harvested. Other access are secondary skids trails and are accounted for in the *Damage* submodel.

We first modelled  $L_{p,s}^{accessNF}$ , the length of all access (logging road + main skid trails, m ha<sup>-1</sup>) in plot  $p$ , with a uniform distribution as followed:

$$L_{p,s}^{accessNF} \sim U(28,33) \tag{17}$$

From this, we got the length of roads and the length of skid trails using  $R_{p,s}^{roadNF}$ , the proportion of  $L_{p,s}^{accessNF}$  represented by road. It follows a beta distribution and depends on the volume of timber

496 (i.e. the logging intensity  $LogInt_p^{NF}$ ) and of fuelwood ( $Vol_{p,s}^{fuelNF}$ ) per ha of plot  $p$  (see section 2.9.1  
 497 for how to get this volume).

$$498 \quad R_{p,s}^{roadNF} \sim \text{Beta}(\alpha_{Road}, \beta_{Road}) \quad (18)$$

499 with  $\alpha_{Road} > 0$  and  $\beta_{Road} > 0$  the shape parameters. The mean and variance of the distribution  
 500 are:

$$501 \quad \begin{aligned} E(R_{p,s}^{roadNF}) &= \frac{\alpha_{Road}}{\alpha_{Road} + \beta_{Road}} = \frac{1}{1 + \exp(-(\eta_{RoadNF} + \lambda_{RoadNF} \times \ln(LogInt_p^{NF} + Vol_{p,s}^{fuelNF})))} \\ Var(R_{p,s}^{roadNF}) &= \frac{(1 - E(R_{p,s}^{roadNF})) \times E(R_{p,s}^{roadNF})}{\phi_{RoadNF} + 1} \end{aligned} \quad (19)$$

502 We then modelled the mean width of roads and trails using normal distributions, as follows. The  
 503 mean width of a road  $W_{p,s}^{roadNF}$  (m) is

$$504 \quad W_{p,s}^{roadNF} \sim \mathcal{N}(\alpha_{WroadNF} + \beta_{WroadNF} \times (LogInt_p^{NF} + Vol_{p,s}^{fuelNF}); \sigma_{WroadNF}^2) \quad (20)$$

505 and the mean width of a main trail  $W_{p,s}^{trailNF}$  (m) is

$$506 \quad W_{p,s}^{trailNF} \sim \mathcal{N}(5.0000383, 0.0019279^2) \quad (21)$$

507  $R^{roadNF}$ ,  $L^{accessNF}$ ,  $W^{roadNF}$  and  $W^{trailNF}$  were modelled using data obtained with the road and  
 508 trail simulator used by the ONF to design access, applied on five sites. From this, we were able to  
 509 calculate the amount of carbon in trees cut for logging roads made for plot  $p$  of simulation  $s$   
 510  $C_{p,s}^{roadNF}$  (Mg ha<sup>-1</sup> of C)

$$511 \quad C_{p,s}^{roadNF} = \frac{ACS_p^{0NF} \times R_{p,s}^{roadNF} \times L_{p,s}^{accessNF} \times W_{p,s}^{roadNF}}{10000} \quad (22)$$

512 and the amount of carbon in trees cut for main skid trails  $C_{p,s}^{trailNF}$  (Mg ha<sup>-1</sup> of C)

$$C_{p,s}^{trailNF} = \frac{ACS_p^{0NF} \times (1 - R_{p,s}^{roadNF}) \times L_{p,s}^{accessNF} \times W_{p,s}^{trailNF} \times R_{50NF}}{10000} \quad (23)$$

where  $R_{50NF}$  is the proportion of  $ACS^0$  in trees with DBH < 50cm (Piponiot et al., 2016a), as we consider that main skid trails avoid big trees.

The amount of carbon in trees cut for storage decks made for plot  $p$  of simulation  $s$   $C_{p,s}^{deckNF}$  (Mg ha<sup>-1</sup> of C) is obtained modelled with a lognormal distribution, as follows (Piponiot et al., 2016a):

$$\frac{C_{p,s}^{deckNF}}{ACS_p^{0NF}} \sim \text{Lognormal}(-6.12, 0.58^2) \quad (24)$$

#### 2.6.4 Forest recovery

The amount of carbon accumulated through recovery within plot  $p$  for simulation  $s$  by year  $t_1$  after logging year  $t$   $C_{p,s,t1}^{recovNF}$  (Mg ha<sup>-1</sup> of C) is obtained with the following hierarchical model, as follows (Fig. 2-c):

$$\begin{aligned} \ln(C_{p,s,t1}^{recovNF}) &\sim \mathcal{N}(\ln(\alpha_{p,s}^{recovmaxNF} \times (1 - \exp(-\beta_{recovNF} \times ((t_1 - t) / \theta_{p,s}^{recovNF})^{\gamma_{recovNF}}))), \sigma_{recovNF}^2) \\ \alpha_{p,s}^{recovmaxNF} &\sim \mathcal{N}_{t0}(ACS_p^{0NF} - ACS_{p,s}^{postNF}, \sigma_{recovmaxNF}^2) \text{ normal distrib. truncated at 0} \\ \theta_{p,s}^{recovNF} &\sim \mathcal{N}_{t0}(\theta_{recov0NF} + \sum_{l=1}^5 (\lambda_l \times V_{p,s,l}), \sigma_{recov\theta NF}^2) \text{ normal distrib. truncated at 0} \end{aligned} \quad (25)$$

with  $ACS_{p,s}^{postNF}$  (Mg ha<sup>-1</sup> of C) the ACS immediately after logging,  $\alpha_{p,s}^{recovmaxNF}$  the maximum recovered at the asymptote,  $\beta_{recovNF}$  the recovery rate,  $\theta_{recov0NF}$  and  $\gamma_{recovNF}$  shape parameters, and  $V_{p,s,l}$  the five environmental covariates of plot  $p$  for simulation  $s$ :  $loss^{NF}$  is the disturbance intensity caused by logging (*i.e.* the loss of ACS through timber and damage, relatively to the pre-logging ACS),  $acs^{0NF}$  (Mg ha<sup>-1</sup> of C) the pre-logging ACS,  $prec^{NF}$  the mean annual precipitation,  $seas^{NF}$  the precipitation seasonality and  $bd^{NF}$  the soil bulk density. All covariates were standardised with data used to calibrate this submodel (Piponiot et al., 2016; Sist et al., 2015).

### 531 2.6.5 Forest regrowth

532 The amount of carbon accumulated through forest regrowth on main skid trails and logging decks  
 533 (not on logging roads that stay open) for plot  $p$  for simulation  $s$  by year  $t_1$  after logging year  $t$   
 534  $C_{p,s,t_1}^{regrowthNF}$  (Mg ha<sup>-1</sup> of C) is obtained with the following hierarchical model, (Fig. 2-d):

$$535 \begin{aligned} \ln(C_{p,s,t_1}^{regrowthNF}) &\sim \mathcal{N}(\ln(\alpha_{p,s}^{regrowthNF} \times (1 - \exp(-\theta_{regrowthN} \times (t_1 - t)))), \sigma_{regrowthNF}^2) \\ \alpha_{p,s}^{regrowthNF} &\sim \mathcal{N}(ACS_p^{0NF}, \sigma_{regrowthmaxNF}^2) \end{aligned} \quad (26)$$

536 Data used to calibrate this model came from a site that has been mechanically logged (Chave et al.,  
 537 2020), which is therefore similar to trails and decks and reduces the risk of overestimating  
 538 regrowth rate.

### 539 2.7 Logistic activities

540 In this section, we calculate  $C^{logisticsNF}$  and  $C^{logisticsP}$ , the emissions from logistic activities in  
 541 natural forest and plantations, respectively. These emissions are accounted for using data from  
 542 expert knowledge (ONF and researchers working on experimental plantation) and Guitet et al.  
 543 (2011). These activities encompass all work done by forest staff in logged natural forests and  
 544 plantation and include petrol consumption and emissions generated by vehicle and machinery  
 545 manufacturing (embodied energy). Biogenic carbon fluxes are not accounted for among these  
 546 activities, as they are accounted for by the other submodels. All emissions occur in the year when  
 547 activities are conducted.

548 In plantation,  $C^{logisticsP}$  is due to deforesting for plantation establishment that leads to emissions  
 549 from staff transport to plan and supervise the activities (0.03 kg ha<sup>-1</sup> of C), and from the activity of  
 550 tree felling: staff transport and chainsaws (2.55 kg of C per Mg of green wood). Staff transport,

wood shredding and subsoiling to prepare the plantation emits 35.04 kg ha<sup>-1</sup> of C. Planting trees emits 39.33 kg ha<sup>-1</sup> of C, solely due to staff transport as no machinery is used for planting. Staff transport and wood shredding for the first thinning emit 9.41 kg ha<sup>-1</sup> of C. Staff transport and tree felling for other thinning events and final harvest emits 2.55 kg of C per Mg green of wood.

In natural forest,  $C^{logisticsNF}$  is due to planning the logging (staff transport for pre-logging diagnostics and inventory), which emits 0.03 kg ha<sup>-1</sup> of C, road building, including planning and supervision, which leads to emissions of 0.53 kg m<sup>-1</sup> of C, and logging activity, including staff transport, which emits 2.55 kg of C per Mg of green wood (timber and fuelwood).

For both natural forest and plantation, the loading and transport of timber and fuelwood lead to the emissions of 0.72 kg of C per Mg of green wood, plus 0.02 kg of C per Mg of green wood and km, which contributes to  $C^{logisticsNF}$  and  $C^{logisticsP}$ . Transport distances from plantation to both sawmill and biomass plant are set to 100 km. For natural forest, these distances are set to 150 km. The sawmill and biomass plant are considered to be in the same place.

## 2.8 Sawmill

### 2.8.1 Origin and fate of the carbon in the sawmill

The timber arriving to the sawmill comes from plantation ( $C^{timbP}$ ) and from natural forest ( $C^{timbNF}$ ).

In plantation, the amount of carbon in timber for plot  $p$ , simulation  $s$  and year  $t$   $C_{p,s;t}^{timbP}$  (Mg of C) come from deforestation for the establishment or harvest, and is calculated as follows:

$$C_{p,s,t}^{timbP} = \begin{cases} R_{timbdeforP} \times ACS_p^{0NF} \times Area_{p,s}^{plantP} & \text{for } t \text{ an establishment year} \\ R_{timbharvP} \times C_{p,s,t}^{harvP} \times Area_{p,s}^{plant} & \text{for } t \text{ a harvest year} \\ 0 & \text{for } t \text{ any other year} \end{cases} \quad (27)$$

where  $ACS_p^{0NF}$  (Mg ha<sup>-1</sup> of C) is the ACS of the forest plot before deforestation for plantation establishment ( $ACS_p^{0NF} = 0$  when there is no deforestation), and  $R_{timbdeforP}$  and  $R_{timbharvP}$  are the proportion of wood that is used as timber from the initially deforested area and extracted during the final harvest, respectively.

For logging in natural forest, the amount of carbon in timber for plot  $p$  and simulation  $s$   $C_{p,s}^{timbN}$  (Mg of C) is:

$$C_{p,s}^{timbNF} = LogInt^{NF} \times WD_{timbNF} \times C_{content} \times Area_{p,s}^{loggedNF} \quad (28)$$

This timber arriving to the sawmill then becomes either sawnwood (containing an amount of carbon  $C_{p,s,t}^{sawnS}$ , Mg of C), offcuts and sawdust used in the biomass plant to produce energy ( $C_{p,s,t}^{fuels}$ , Mg of C), or true waste ( $C_{p,s,t}^{wasteS}$ , Mg of C) being fine sawdust. These quantities are calculated as follows:

$$\begin{aligned} C_{p,s,t}^{sawnS} &= E_S \times C_{p,s,t}^{timb} \\ C_{p,s,t}^{fuels} &= (1 - E_S) \times (1 - R_{wasteS}) \times C_{p,s,t}^{timb} \\ C_{p,s,t}^{wasteS} &= (1 - E_S) \times R_{wasteS} \times C_{p,s,t}^{timb} \end{aligned} \quad (29)$$

where  $E_S$  is the sawmill efficiency (the default value is taken at 0.3 through discussion during the scenario-planning workshop (Table A.3) to reflect the current low sawmill efficiency in French Guiana, but can be modified), and  $R_{wasteS}$  the proportion of waste that cannot be used as fuelwood. The substitution of wood to another material is not taken into account because of the lack of good local estimates of displacement factors (Sathre and O'Connor, 2010).

## 588 2.8.2 Carbon fluxes from the sawmill

589 Emissions from the sawmill are due to the decay of sawnwood ( $C^{decaysawnS}$ ), to the operating of  
590 the sawmill ( $C^{op}$ ), and to immediate decomposition of true waste and hence immediate emission  
591 of their carbon ( $C^{wasteS}$ ).

592 To calculate  $C^{decaysawnS}$ , we take the half-life of sawnwood  $t_{0.5S}$  as the default value from the IPCC  
593 for both for wood from natural forest and plantation, in the absence of more specific data (IPCC,  
594 2003). The cumulative emissions due to sawnwood decay from plot  $p$ , simulation  $s$  at year  $t_1$  after  
595 sawing year  $t$   $C_{p,s,t_1}^{decaysawnS}$  (Mg of C) are:

$$596 \quad C_{p,s,t_1}^{decaysawnS} = C_{p,s,t}^{sawnS} \times (1 - \exp(-\lambda_{decays} \times (t_1 - t))) \text{ with } \lambda_{decays} = \frac{\ln(2)}{t_{0.5S}} \quad (30)$$

597 The emissions due to the operating of the sawmill for wood from plot  $p$ , simulation  $s$  in the year of  
598 sawing  $t$   $C_{p,s,t}^{opS}$  (Mg of C) are:

$$599 \quad C_{p,s,t}^{opS} = \frac{C_{p,s,t}^{sawnS}}{WD_{timbNF} \times C_{content}} \times Conso_s \times \frac{C_{fossil}}{1000} \quad (31)$$

600 where  $Conso_s$  is the energy consumption of the sawmill (kW.h m<sup>-3</sup>), and  $C_{fossil}$  are the emissions  
601 for the production of electricity from fossil fuel in French Guiana (kg kW.h<sup>-1</sup> of C) (Explicit and  
602 Alter, 2012).

## 603 2.9 Biomass plant

### 604 2.9.1 Origin of carbon arriving to the biomass plant

605 The wood used as fuelwood comes from plantation ( $Fuel^P$ ) and from natural forest ( $Fuel^{NF}$ .  
 606 Offcuts and sawdust from the sawmill burnt in the biomass plant are accounted for in these  
 607 quantities. All emissions occur in the year of arrival of fuelwood to the biomass plant.  
 608 In plantation, the quantity of fuelwood from plot  $p$ , simulation  $s$  at year  $t$   $Fuel_{p,s,t}^P$  (Mg of green  
 609 wood) is due to deforestation for the establishment, all thinning happening at least ten years after  
 610 plantation, and harvest, Fig. 2-a), and is calculated as follows:

$$611 \quad Fuel_{p,s,t}^P = \begin{cases} \frac{R_{fueldeforP} \times ACS_p^{ONF} + C_{p,s,t}^{fuelS}}{C_{content} \times (1 - H)} \times Area_{p,s}^{plantP} & \text{for } t \text{ the establishment year} \\ \frac{R_{fuelthin} \times C_{p,s,t}^{thinP}}{C_{content} \times (1 - H)} \times Area_{p,s}^{plantP} & \text{for } t \text{ a thinning year } \geq 10 \text{ years} \\ \frac{R_{fuelharvp} \times C_{p,s,t}^{harvp} + C_{p,s,t}^{fuelS}}{C_{content} \times (1 - H)} \times Area_{p,s}^{plantP} & \text{for } t \text{ the harvest year} \\ 0 & \text{for } t \text{ any other year} \end{cases} \quad (32)$$

612 where  $R_{fueldeforP}$ ,  $R_{fuelthin}$ , and  $R_{fuelharvp}$  are the proportion of carbon that can be used as  
 613 fuelwood (respectively from deforested, thinned and harvested wood),  $C_{p,s,t}^{fuelS}$  is the sawdust used  
 614 as fuelwood (from equation (29)), and  $H$  the water content of green wood.

615 For logging in natural forest, the quantity of fuelwood from damage and deforestation for  
 616 infrastructure, for plot  $p$ , simulation  $s$  at  $t$  the year of logging  $Fuel_{p,s,t}^{NF}$  (Mg of green wood), is:

$$617 \quad Fuel_{p,s,t}^{NF} = \begin{cases} \frac{C_{p,s,t}^{damNF} \times R_{fueldamconvNF} + C_{p,s,t}^{fuelinfraNF} + C_{p,s,t}^{fuelS}}{C_{content} * (1 - H)} \times Area_p^{loggedNF} & \text{for conventional logging} \\ \frac{C_{p,s,t}^{damRILNF} \times R_{fueldamRilNF} + C_{infrafuel} + C_{p,s,t}^{fuelS}}{C_{content} * (1 - H)} \times Area_p^{loggedNF} & \text{for RIL} \end{cases} \quad (33)$$

618 where  $R_{fueldamconvNF}$  and  $R_{fueldamRilNF}$  are the proportions of carbon from damage that can be  
 619 used as fuelwood for conventional logging, respectively RIL (when the scenario does not use  
 620 logging byproducts for fuelwood, these proportions are null),  $C_{fuelinfraNF}$ , a constant (null when

there is no use of logging byproducts as fuelwood), is the carbon contained in wood destroyed for logging infrastructure that can be used as fuelwood,  $C_{p,s,t}^{fuelS}$  is the sawdust used as fuelwood (from equation (29)), and  $H$  the water content of green wood. To obtain  $R_{fuelDamconvNF}$  and  $R_{fuelDamRilNF}$ , we inferred beta distributions using the damage model to get the current proportion of a collection of 20 Mg of green fuelwood collected for a logging intensity of 20 m<sup>3</sup> ha<sup>-1</sup> (expert knowledge ONF). These distributions have a mean of 0.22 and 0.45, and a variance of 0.001 and 0.009 for  $R_{fuelDamconvNF}$  and  $R_{fuelDamRilNF}$  respectively.

For some tests at the plot scale, the efficiency of fuelwood collection in natural forest can be altered by applying a modifying factor to  $R_{fuelDamconvNF}$ .

### 2.9.2 Carbon fluxes from the biomass plant

Emissions from the biomass plant are due to the combustion ( $C^{burntBP}$ ), the avoided emissions ( $C^{avoidBP}$ ), and the emissions due to the operating of the biomass plant ( $C^{opBM}$ ). All these emissions occur in the same year that the wood arrives at the biomass plant.

During combustion, all the carbon contained in a quantity of fuelwood  $Fuel_{p,s,t}$  from plot  $p$ , simulation  $s$  at year  $t$  is emitted, so  $C_{p,s,t}^{burntBP}$  (Mg of C) is:

$$C_{p,s,t}^{burntBP} = Fuel_{p,s,t} \times C_{content} \times (1 - H) \quad (34)$$

The avoided emissions correspond to the emissions for the production of the same amount of energy from fossil fuel,  $C_{p,s,t}^{avoidBP}$  so (Mg of C) is:

$$C_{p,s,t}^{avoidBP} = PCI_H \times Fuel_{p,s,t} \times E_{BP} \times \frac{C_{fossil}}{1000} \quad (35)$$

640 where  $PCI_H$  is the lower heating value of green wood at a water content  $H$  (kW.h Mg<sup>-1</sup>), obtained  
641 from the lower heating value of dry wood taken at 18.8 MJ kg<sup>-1</sup> for the wood from natural forest  
642 (average for the 50 most common species in northern French Guiana, Pinta et al. (2011)), and  
643 taken on a plot basis among the wood density of the 7 species considered for the plantation.  $E_{BP}$  is  
644 the efficiency of the biomass plant (the default value, taken at 0.22 through discussion during the  
645 scenario-planning workshop (Table A.3), can be modified).

646 For  $C_{p,s,t}^{opBM}$  (Mg of C), we only consider wood chipping and the construction of the storage  
647 platform:

$$648 \quad C_{p,s,t}^{opBM} = Fuel_{p,s,t} \times Conso_{BP} \quad (36)$$

## 649 *2.10 Dead wood decay on site*

### 650 *2.10.1 Origin of the carbon left to decay on site*

651 In this section, we present the calculation of the amount of carbon contained in wood that is left to  
652 decay on site in natural forest  $C^{decayPNF}$  and plantations  $C^{decayP}$ , in the year when the  
653 decomposition starts - *i.e.* the year when the trees die.

654 In plantation,  $C_{p,s,t}^{decayP}$  for plot  $p$ , simulation  $s$  and year  $t$  comes both from the deforestation for  
655 plantation establishment and from the plantation itself.  $C_{p,s,t}^{decayP}$  is:

$$656 \quad C_{p,s,t}^{decayP} = \begin{cases} ACS_p^{0N} \times Area_{p,s}^{plant} \times (1 - R_{timbdeforP} - R_{fueldeforP}) & \text{for } t \text{ the establishment year} \\ (C_{p,s,t}^{deadP} + C_{p,s,t}^{thinP}) \times Area_{p,s}^{plantP} & \text{for } t \text{ a thinning year } < 10 \text{ years} \\ (C_{p,s,t}^{deadP} + C_{p,s,t}^{thinP} \times (1 - R_{fuelthinP})) \times Area_{p,s}^{plantP} & \text{for } t \text{ a thinning year } \geq 10 \text{ years} \\ (C_{p,s,t}^{deadP} + C_{p,s,t}^{harvP} \times (1 - R_{timbharv} - R_{fuelharvP})) \times Area_{p,s}^{plantP} & \text{for } t \text{ the harvest year} \\ C_{p,s,t}^{deadP} \times Area_{p,s}^{plantP} & \text{for } t \text{ any other year} \end{cases} \quad (37)$$

657 In natural forest,  $C_{p,s,t}^{decayNF}$  is contained in the part of dead wood resulting from damage and  
 658 infrastructure that is not used as fuelwood. Here  $t$  is the year of logging.  $C_{p,s,t}^{decayNF}$  is:

$$659 \quad C_{p,s,t}^{decayNF} = (C_{p,s,t}^{damNF} \times (1 - R_{fueldamNF}) + (C_{p,s,t}^{roadNF} + C_{p,s,t}^{trailNF} + C_{p,s,t}^{deckNF} - C_{p,s,t}^{fuelinfraNF}) \times Area_{p,s,t}^{loggedNF} \quad (38)$$

### 660 2.10.2 Carbon fluxes from wood decay on site

661 To get the carbon emissions due to decay, we use the same model as Piponiot et al. (2016a): we  
 662 consider different decay rates for the fine woody necromass  $FWN$  (leaves, twigs and branches  
 663 with diameter  $<10\text{cm}$ ) and the coarse woody necromass  $CWN$  (logs and branches with diameter  $\geq$   
 664  $10\text{cm}$ ).

665 In plantation, before 10 years after the plantation, all dead wood is  $FWN$ . After 10 years, the  
 666 proportion of  $CWN$  is  $R_{CWN}^P$ . At harvest, all the wood left on site is shredded so all is  $FWN$ . In  
 667 natural forest and for the deforestation conducted to establish plantation, the proportion of  $CWN$   
 668  $R_{CWN}^{NF}$  is modelled using the individual scale model of Chambers et al. (2004) and Chambers et al.  
 669 (2000) with data from 11 sites of Guyafor (Cirad et al., 2020), taken from Piponiot et al. (2016a).

670 The carbon contained in the coarse woody necromass starting to decay at year  $t$  for plot  $p$ ,  
 671 simulation  $s$   $C_{p,s,t}^{initCWN}$  (Mg of C) is therefore

$$672 \quad C_{p,s,t}^{initCWN} = \begin{cases} 0 & \text{in plantation for } t < 10 \text{ years} \\ R_{CWN}^P \times C_{p,s,t}^{decayP} & \text{in plantation for } t \geq 10 \text{ years} \\ 0 & \text{for } t \text{ the harvest year in plantation} \\ R_{CWN}^{NF} \times C_{p,s,t}^{decayNF} & \text{in natural forest} \end{cases} \quad (39)$$

673 and the carbon contained in the fine woody necromass  $C_{p,s,t}^{initFWN}$  (Mg of C) is

$$C_{p,s,t}^{initFWN} = \begin{cases} C_{p,s,t}^{decayP} & \text{in plantation for } t < 10 \text{ years} \\ (1 - R_{CWN}^P) \times C_{p,s,t}^{decayP} & \text{in plantation for } t \geq 10 \text{ years} \\ C_{p,s,t}^{decayP} & \text{for } t \text{ the harvest year in plantation} \\ (1 - R_{CWN}^{NF}) \times C_{p,s,t}^{decayNF} & \text{in natural forest} \end{cases} \quad (40)$$

From these two quantities, we then calculate the cumulative amount of carbon from decay of FWN  $C_{p,s,t_1}^{decayFWN}$  (Mg of C) for plot  $p$  (plantation or natural forest), simulation  $s$ , emitted by year  $t_1$  as follows, from Chambers et al. (2000) in Piponiot et al. (2016a):

$$C_{p,s,t_1}^{decayFWN} = C_{p,s,t}^{initFWN} \times (1 - \exp(-\lambda_{FWN} \times (t_1 - t))) \quad (41)$$

where  $C_{p,s,t}^{initFWN}$  is the quantity of carbon (Mg of C) in FWN starting to decay at year  $t$ , and  $\lambda_{FWN}$  is the decay rate of FWN.

The cumulative amount of carbon by decay of CWN  $C_{p,s,t_1}^{decayCWN}$  (Mg of C), for plot  $p$  (plantation or natural forest), simulation  $s$ , emitted by year  $t_1$  is obtained from the model developed by Piponiot et al. (2016a), based on the individual scale model of Hérault et al. (2010a):

$$C_{p,s,t_1}^{decayCWN} = C_{p,s,t}^{initCWN} \times (1 - R_{CWN1} \times \exp(-\lambda_{CWN1} \times (t_1 - t)) - (1 - R_{CWN1}) \times \exp(-\lambda_{CWN2} \times (t_1 - t))) \quad (42)$$

where  $C_{p,s,t}^{initCWN}$  is the quantity of carbon in CWN starting to decay at year  $t$  (Mg of C),  $\lambda_{CWN1}$  and  $\lambda_{CWN2}$  are the two decay rates for CWN, and  $R_{CWN1}$  is the fraction of CWN decaying at rate  $\lambda_{CWN1}$ .

## 2.11 Carbon Impact Factor and Total Emission Factor

To compared the results from our model with those resulting from the method of Griscom et al. (2014), we calculated the committed emissions from the shoot and root parts of trees killed by logging (tree logged, logging damage and logging infrastructure) on a 1 ha plot with median

environmental conditions, and expressed them as the Total Emission Factor  $TEF$  ( $\text{Mg m}^{-3}$  of C) and as the Carbon Impact Factor  $CIF$  (unitless) calculated as follow:

$$TEF = \frac{(ACS^{extNF} + C^{damNF} + C^{roadNF} + C^{trailNF} + C^{deckNF}) \times (1 + 0.235)}{LogInt^{NF}} \quad (43)$$

where 0.235 is the root:shoot biomass ratio taken from Mokany et al. (2006), to be consistent with studies using  $TEF$  and  $CIF$  (but see Qi et al. (2019)).

$$CIF = \frac{(C^{damNF} + C^{roadNF} + C^{trailNF} + C^{deckNF})}{ACS^{extNF}} \quad (44)$$

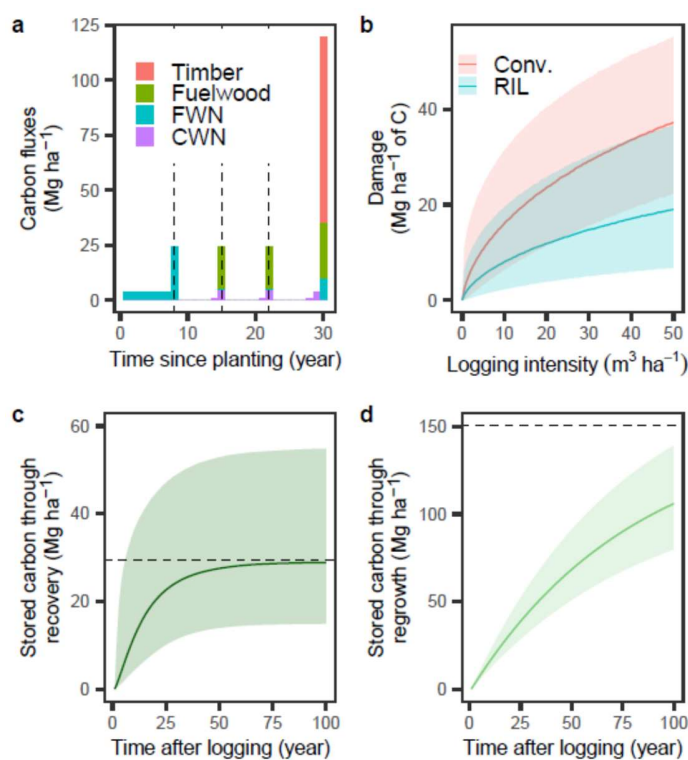
### 3 Results

Unless stated otherwise, all results reported are median values, with 95% credibility intervals given in brackets.

#### 3.1 Main submodels

With conventional logging, the volume of damage was considerably higher than the volume of timber: at a logging intensity of  $20 \text{ m}^3 \text{ ha}^{-1}$ , damage represented  $82.97 \text{ m}^3 \text{ ha}^{-1}$  [40.82, 141.55] (*i.e*  $23.76 \text{ Mg ha}^{-1}$  of C [11.69, 40.54]) (Please note: for damage, recovery and regrowth, values are given for a plot with median environmental conditions). With RIL, damage was reduced by 46.7% [11.8%, 84.2%]: at a logging intensity of  $20 \text{ m}^3 \text{ ha}^{-1}$ , damage represented  $41.54 \text{ m}^3 \text{ ha}^{-1}$  [13.55, 90.25] (*i.e*  $11.90 \text{ Mg ha}^{-1}$  of C [3.88, 25.85]) (Fig. 2-b). Carbon recovery within logged plots of natural forest was fast during the first three decades, and then slowed down. Recovery of 90% of the carbon lost through logging (extracted timber and damage) at  $20 \text{ m}^3 \text{ ha}^{-1}$  was attained after a median of 40 years (Fig. 2-c). Carbon accumulation through forest regrowth on main skid trails

710 and logging decks took longer: accumulation of 90% of the pre-deforestation carbon amount took  
711 a median of 190 years (Fig. 2-d). Carbon accumulation in plantations was 3.87 Mg ha<sup>-1</sup> year<sup>-1</sup> of C  
712 [2.61, 5.75], which, for a plantation species with median wood density, corresponded to 14.01 m<sup>3</sup>  
713 ha<sup>-1</sup> year<sup>-1</sup> [9.45, 20.81].



714

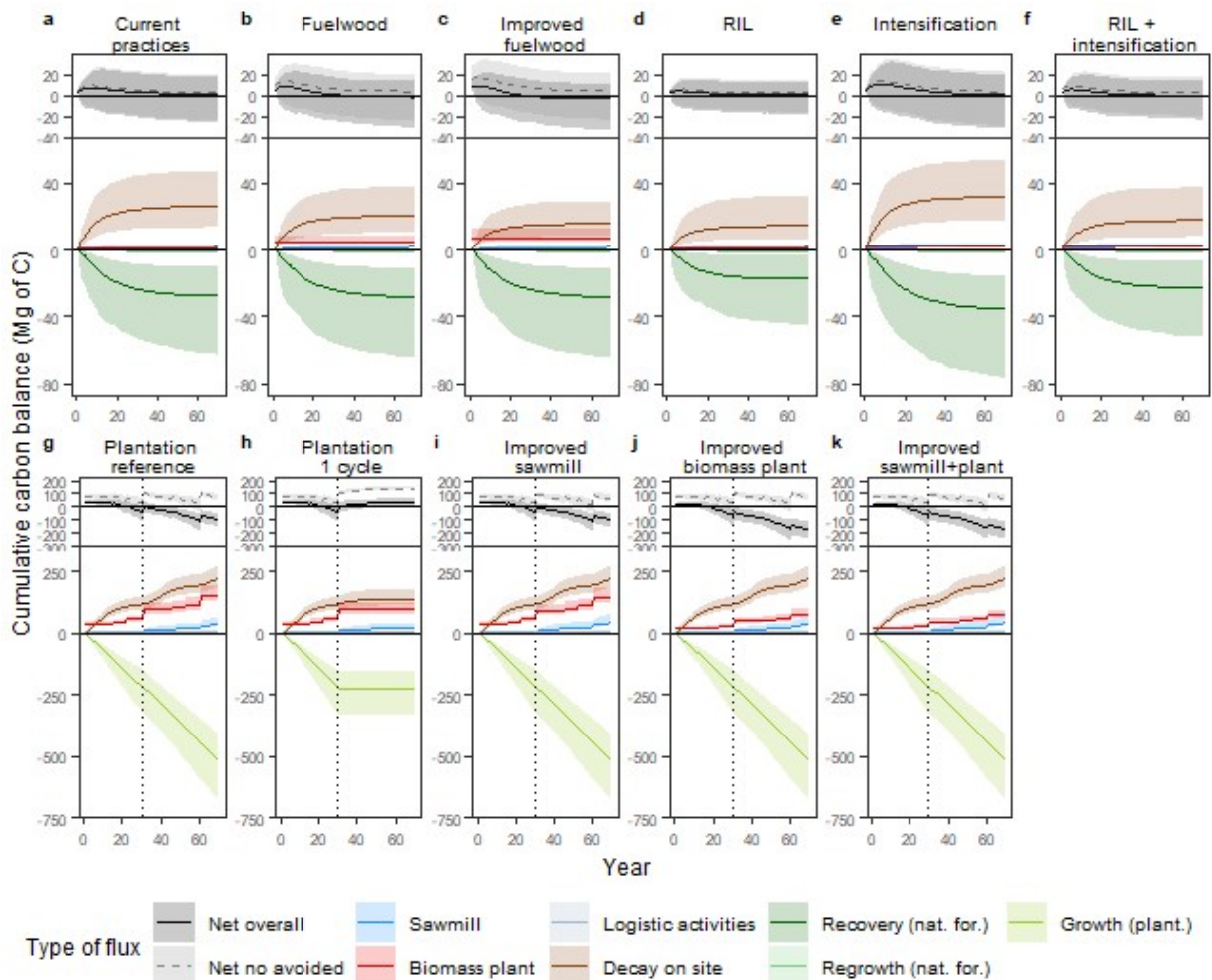
715 *Figure 2: Main submodels: (a) Plantation, (b) logging damage, (c) carbon recovery in the logging*  
716 *plot after logging at 20 m<sup>3</sup> ha<sup>-1</sup>, and (d) forest regrowth on cleared skid trails and logging decks.*  
717 *Logging damage, carbon recovery and forest regrowth are run for a 1 ha plot with median*  
718 *environmental conditions. Plantation is run with a 1 ha plot taking median value of productivity.*  
719 *Solid line is the median value and shaded areas the 95% credibility intervals. Dashed lines are the*  
720 *carbon accumulation potential for the recovery model (i.e amount of carbon lost through logging)*

721 *and the forest regrowth model (i.e initial amount of carbon), For the plantation model, dashed lines*  
722 *mark thinning events. FWN and CWN stand for Fine Woody Necromass and Coarse Woody*  
723 *Necromass, respectively.*

### 724 3.2 Plot scale

725 For logging in natural forests, forest recovery and decay of dead wood on site were responsible for  
726 the two main carbon fluxes (Fig. 3 a-f). The best practices at the plot scale were RIL over the short  
727 term and improved fuelwood collection over the long term. Using logging byproducts as fuelwood  
728 led to a net carbon storage after a median of 35 years, and was attained faster with improved  
729 fuelwood collection (27 year). This is explained by avoided emissions through the use of fuelwood  
730 that led to a lower increase in biomass plant emissions relative to the decrease of decay on site,  
731 compared to the case without fuelwood collection. Improved fuelwood collection gave a net  
732 balance of -3.4 Mg of C [-33.8, 10.6] after 70 years. RIL reduced emissions compared to current  
733 practices over the short term (3.5 Mg of C [-14, 14.4] at 10 years *versus* 7.1 Mg of C [-14.6, 23.7]),  
734 but not much over the long term (0.4 Mg of C [-18.4, 11.3] at 70 years *versus* 0.8 Mg of C [-26.7,  
735 16.8] for current practices). Logging intensification allowed producing 1.5 times more timber than  
736 current practices without changing the carbon balance over the long term (0.7 Mg of C [-32, 19.1]  
737 at 70 years for intensification with conventional logging and -0.1 Mg of C [-23.4, 14] with RIL).  
738 Over the short term, intensification even produced fewer emissions when conducted with RIL (5  
739 Mg of C [-14.5, 19.1] at 10 years), but not with conventional logging (10.6 Mg of C [-16.2, 30.1]. The  
740 median Total Emission Factor was between 1.1 and 1.99 Mg m<sup>-3</sup> of C of extracted timber and the  
741 Carbon Impact Factor between 2.11 and 4.63 (Table A.4). Both these factors showed that RIL and  
742 higher logging intensity reduced emissions (Table A.4).

743 For plantations, carbon accumulation in growing trees, and emissions by decay of dead wood on  
744 site and from the biomass plant are the most important fluxes (Fig. 3 g-k). The best practices for  
745 the carbon balance of plantations were to use a deforested plot for several plantation cycles, and  
746 to improve biomass plant efficiency. Not replanting after the first harvest, for instance in the case  
747 of conversion of plantation to another land use, had a negative impact on the carbon balance over  
748 the long term (38 Mg of C [1.5, 62.4] at 70 years without replanting *versus* -93.5 Mg of C [-149.6, -  
749 50.2] for the reference plantation practice that included replanting). In this case, the carbon  
750 emissions due to deforestation to establish the plantation were no longer compensated by the  
751 growth of planted trees, which led to net carbon emissions after the first harvest. Improving the  
752 sawmill efficiency had a limited impact (-95 Mg of C [-152.7, -48.7] at 70 years for a sawmill  
753 efficiency of 0.4 compared to the efficiency of 0.3 for plantation reference), whereas improving  
754 biomass plant efficiency was more beneficial (-168.4 Mg of C [-243, -113.1] at 70 years for a  
755 biomass plant efficiency of 0.32 compared to the plantation reference with an efficiency of 0.22),  
756 because of higher avoided emission from substitution of fuelwood to fossil fuel.



757

758 *Figure 3: Cumulative carbon fluxes for 1ha plots with median environmental conditions (a-f: logging*  
 759 *in natural forest, g-k: plantation). a-Current practices: 20m<sup>3</sup> ha<sup>-1</sup>, no fuelwood from logging, no RIL.*  
 760 *b-Fuelwood: 20m<sup>3</sup> ha<sup>-1</sup>, fuelwood from logging, no RIL. c-Improved fuelwood: 20m<sup>3</sup> ha<sup>-1</sup>, improved*  
 761 *(x2) fuelwood from logging, no RIL. d-RIL: 20m<sup>3</sup> ha<sup>-1</sup>, no fuelwood from logging, RIL. e-*  
 762 *Intensification: 30m<sup>3</sup> ha<sup>-1</sup>, no fuelwood from logging, no RIL. f-RIL + intensification: 30m<sup>3</sup> ha<sup>-1</sup>, no*  
 763 *fuelwood from logging, RIL. g-Plantation reference: default modelling of plantation trajectories, h-*  
 764 *Plantation 1 cycle: plantation with no replanting after first harvest, i-Improved sawmill: plantation*  
 765 *with improved sawmill efficiency (0.4 instead of 0.3), j-Improved biomass plant: plantation with*

766 improved biomass plant efficiency (0.32 instead of 0.22), k-Improved sawmill+plant: plantation with  
767 improved sawmill and biomass plant efficiency. Solid line is the median value and shaded areas the  
768 95% credibility intervals over 2000 simulations. Avoided emissions are accounted for, except for the  
769 flux Net no avoided. Note that in some cases (e.g. Current practices), net overall and net overall  
770 without avoided emissions are largely overlapping.

### 771 3.3 Scenarios

772 Cumulative and annual total carbon fluxes for each scenario are presented in Fig. 4 and detailed  
773 fluxes in Fig. A.3-8.

774 The scenario *Business as usual* is the reference scenario targeting an annual production of timber  
775 of 80 000 m<sup>3</sup>. It had the lowest emissions over the short term (0.64 Tg of C [0.5, 0.77] at the peak  
776 in 2041), but was also the only one with net emissions in 2088 (0.43 Tg of C [0.2, 0.66]) when  
777 accounting for avoided emissions (Fig. 4).

778 All the other scenarios, targeting an annual production of timber of 200 000 m<sup>3</sup>, led to a net  
779 carbon storage over the long term when accounting for avoided emissions, as an important part of  
780 the damage was used as fuelwood and led to avoided emissions instead of decaying on site. The  
781 ranking of these scenarios differed depending on whether the long-term balance or the short-term  
782 emissions were considered (Fig. 4-a). Over the short term, the scenario *Plantation* was the worse  
783 regarding emission levels at the peak (1.76 Tg of C [1.58, 1.95] in 2042, as opposed to 1.55 Tg of C  
784 [1.4, 1.79] in 2042 for *Natural forest + plantation*, and 0.76 Tg of C [0.66, 0.87] in 2028 for  
785 *Intensification*). This highest peak in the scenarios involving plantation was due to the high annual  
786 emissions in the establishment phase of the plantation, before the first harvest (Fig. 4-b). Soon  
787 after this, the annual flux became negative as plantation trees started to grow. These high

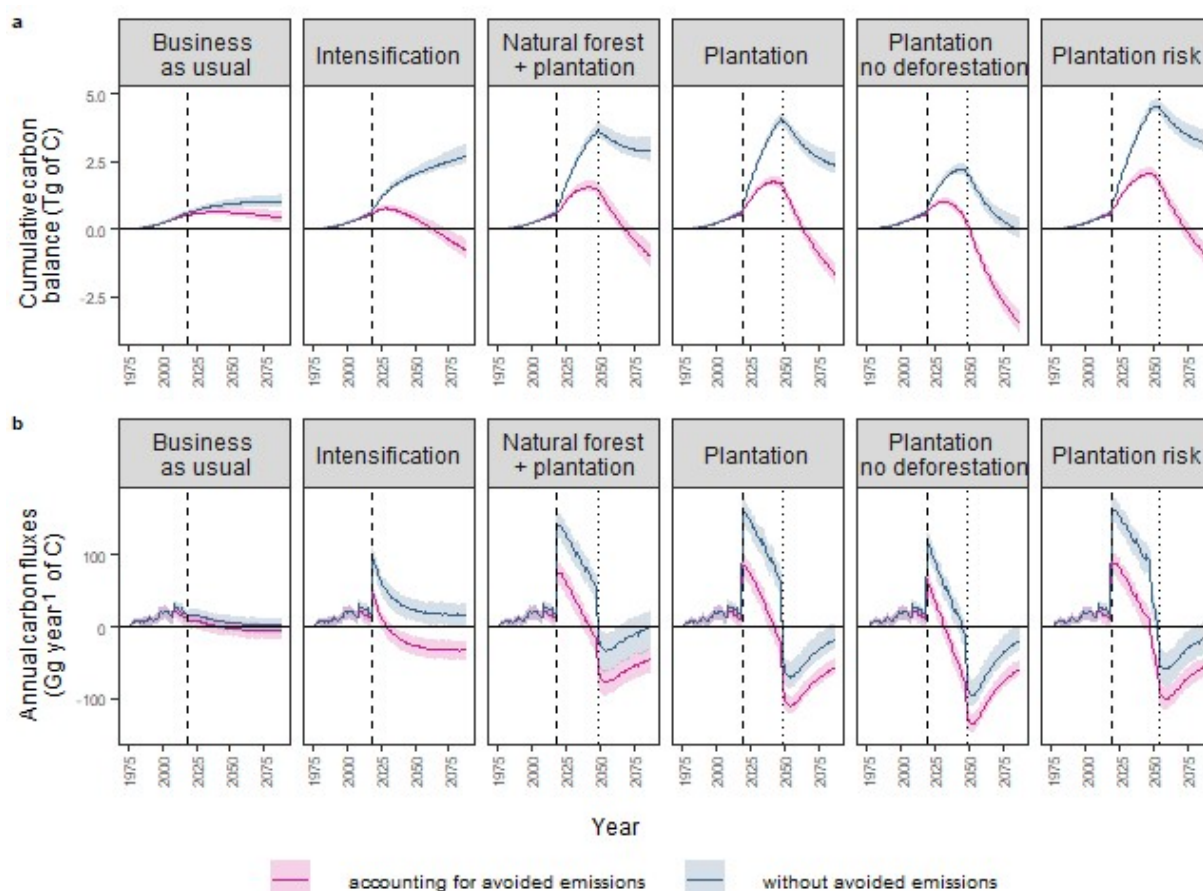
emissions observed for the net overall flux in the establishment phase of plantation were less pronounced when there was no deforestation for planting (scenario *Plantation no deforestation*). For this scenario, the peak was attained earlier (in 2032) and was less important (1.01 Tg of C [0.89, 1.16]) than for the other scenarios with plantation. This is due to the fact that the plantations started storing carbon from the moment they were established (Fig. A.7), since establishment did not involve carbon emitting deforestation. Over the long term, wood production only from plantations without deforestation (scenario *Plantation no deforestation*) had the best carbon balance (*i.e.* the more negative emissions: -3.52 Tg of C [-3.84, -3.04] in 2088), better than the scenario plantation with deforestation (*Plantation*) (-1.7 Tg of C [-2.01, -1.26]), and than the scenario combining production in *Natural forest + plantation* (-1.03 Tg of C [-1.38, -0.52]). When the plantations productivity was less than expected (scenario *Plantation risk*), the carbon balance worsened, both over the long term (-0.93 Tg of C [-1.24, -0.47] in 2088) and in the shorter term (2.08 Tg of C [1.9, 2.32] in 2048).

When avoided emissions from energy production derived from biomass instead of fossil fuel were not accounted for, the ranking of scenarios according to their carbon balance was drastically changed. The scenarios based on plantation (except *Plantation no deforestation*) became the worse in the short and the long term, even more so when plantations were less productive than expected (scenario *Plantation risk*): 2.87 Tg of C [2.52, 3.38] in 2088 for *Natural forest + plantation*, 2.35 Tg of C [2.04, 2.81] for *Plantation* and 3.19 Tg of C [2.87, 3.67] for *Plantation risk*, compared to 2.72 Tg of C [2.41, 3.16] for *Intensification*. This was explained by a greater amount of fuelwood produced during the establishment phase of plantation, compared to natural forest (Fig. 5-b), as fuelwood is the only flux for which the model accounts for avoided emissions. The scenario *Plantation no deforestation* was the only one for which a net storage was achieved (in 2087) even

811 when avoided emissions were not accounted for, because no fuelwood was produced when  
812 plantations were established.

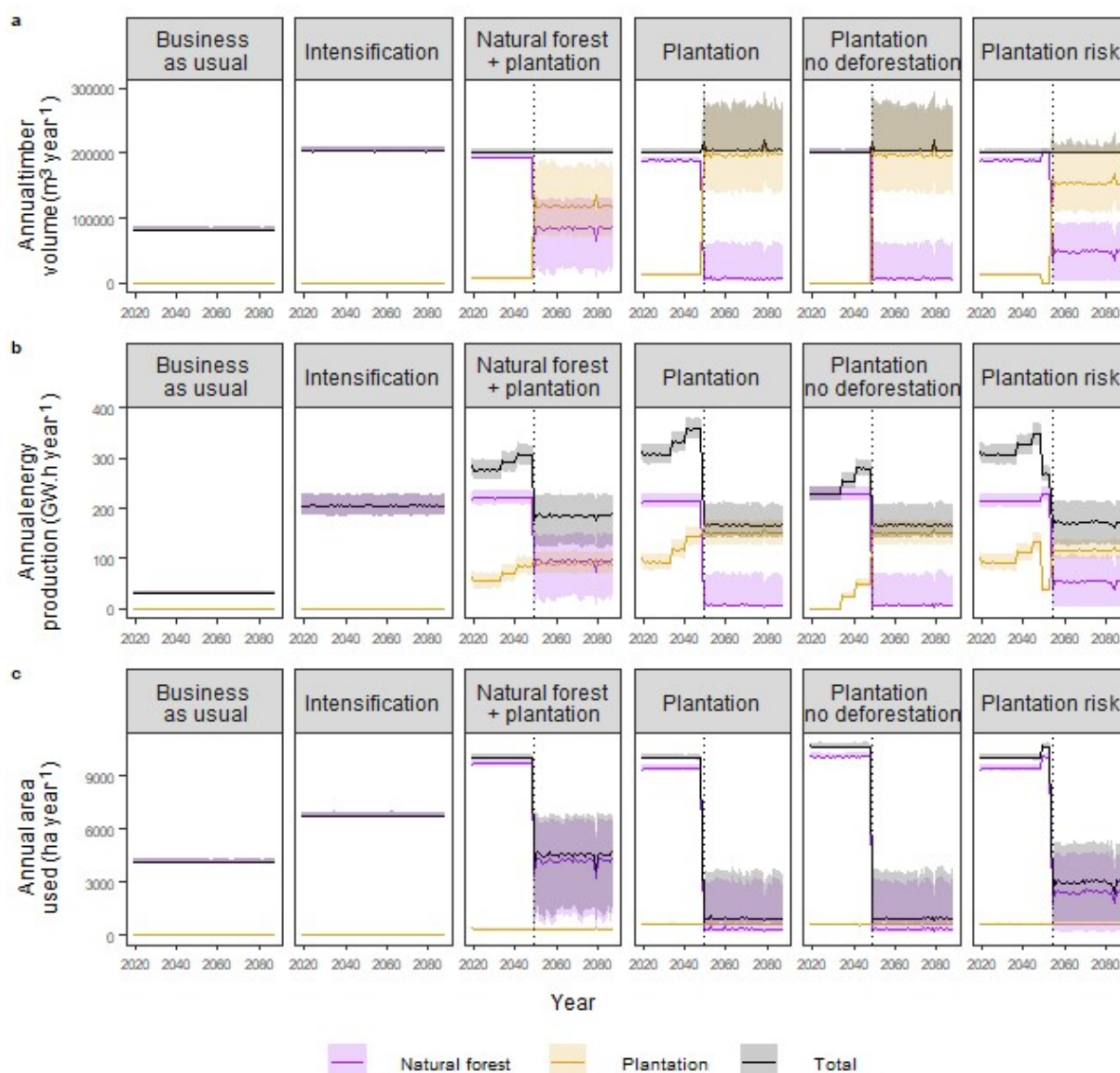
813 In terms of pressure on land, *i.e.* the area of land logged and planted in each scenario (Fig. 5-c), the  
814 scenarios *Plantation* and *Plantation no deforestation* were the least severe as 917 ha year<sup>-1</sup> [658,  
815 3627] (respectively 923 ha year<sup>-1</sup> [656, 3608]) were affected annually in the productive phase of  
816 plantation, which was about 7 times less than the area logged in the scenario *Intensification* (6762  
817 ha year<sup>-1</sup> [6671, 6967]). If plantations were less productive than expected, then the reduced  
818 provision of wood from plantations was partially compensated by an increase in the area of  
819 natural forest logged (3026 ha year<sup>-1</sup> [736, 5195] affected in total for the scenario *Plantation risk*),  
820 which was still about 2 times less than the area affected with *Intensification*.

821 For energy production, all five scenarios were equivalent once plantations became productive  
822 (Fig. 5-b). During the establishment phase of plantations, a higher amount of energy was produced  
823 from use of wood during deforestation for planting, except for the scenario without deforestation.



824

825 Figure 4: (a) Cumulative carbon balance and (b) annual carbon fluxes for each scenario. Solid line is  
 826 the median value and shaded areas the 95% credibility intervals over 500 simulations. The dashed  
 827 line marks the start of the prospective period, and dotted one the time when the first plantations are  
 828 harvested.

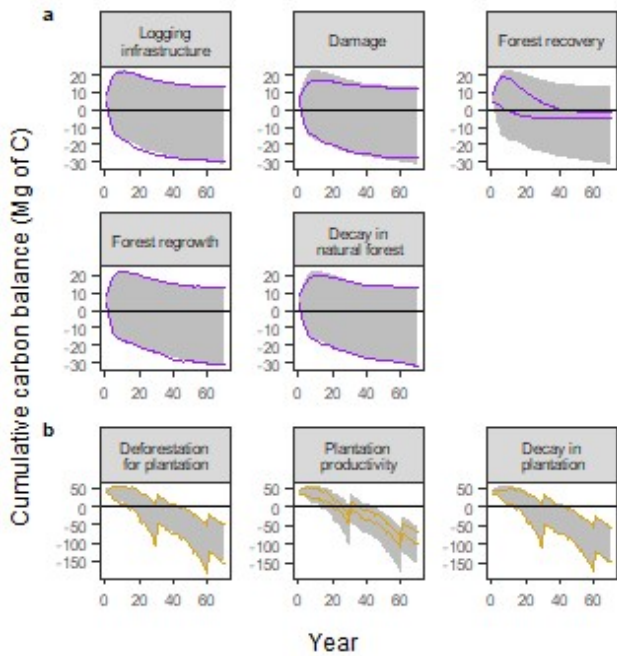


829

830 *Figure 5: (a) Annual timber volume, (b) annual energy production and (c) area used annually*  
 831 *(logged or planted) for each scenario. Solid line is the median value and shaded areas the 95%*  
 832 *credibility intervals over 500 simulations.*

### 833 3.4 Sensitivity analysis

834 The highest sources of uncertainty of the overall model were by far the forest recovery submodel  
835 in natural forest and the productivity in plantation (Fig. 6). This is because both submodels have a  
836 high variability (Fig. 2-c for recovery and section 3.1 for productivity in plantation) and have a  
837 high contribution to the net fluxes. Recovery is indeed one of the two most important fluxes in  
838 natural forests (Fig. 3 a-f). Plantation productivity is at the basis of the calculation of  $C^{thinP}$ ,  
839  $C^{deadP}$ ,  $C^{harvP}$  and  $C^{growt}$ , which are used to calculate all fluxes (section 2.5).



841 *Figure 6: Contribution of the uncertainty of the main submodels ((a) in natural forests and (b) in*  
842 *plantation) to the overall model. This sensitivity analysis was conducted on 1 ha plots with median*  
843 *environmental conditions. The colour envelopes represent 95% credibility intervals when the*  
844 *considered submodel is made deterministic, and the grey shaded areas are the 95% credibility*  
845 *intervals of the overall model when all its uncertainty is taken. The bigger the difference between*  
846 *these two areas is, the more the submodel uncertainty contributed to the overall uncertainty.*

## 847    **4     Discussion**

### 848    *4.1    Model validity and limitations*

849    The model that we developed allows the assessment of the carbon balance of wood production at  
850    a territory scale. It can be used both retrospectively (using local logging records) for carbon  
851    accounting, and as a prospective tool to compare scenarios of development of the wood sector.

852    The model is temporally-explicit insofar as the submodels consider carbon fluxes as a function of  
853    time, as opposed to considering them as committed emissions. Our results showed that the fluxes  
854    with highest contribution were biogenic fluxes taking place over several decades, therefore  
855    considering the temporality of fluxes improved model outputs (Iordan et al., 2018; Newell and  
856    Vos, 2012) and allowed comparison scenarios using different temporal scales of analysis. We did  
857    not use a discounting rate for delayed emissions, but this could further improve scenario  
858    comparison. Rigorous submodels of biogenic carbon fluxes were calibrated with local data and  
859    explicitly considered local environmental factors, in line with tier 3 recommendations from IPCC  
860    (IPCC, 2006). Inferring these models in a Bayesian framework enabled us to propagate the  
861    uncertainty from each submodel to the overall model. The overall approach taken by our model is  
862    valid beyond the context of French Guiana and can easily be adapted to other contexts.

863    The statistical submodels were calibrated with data from permanent forest plots, which differs  
864    from the most commonly used method of assessment of logging emissions based on post-logging  
865    field measurements of wood destroyed (Griscom et al., 2014 ; Feldpausch et al., 2005). However,  
866    results of our model, when expressed using the same indicators (TEF and CIF), were in the same  
867    range as the ones obtained by the method of Griscom et al. (2014) and Feldpausch et al. (2005)  
868    (Table A.4). The same trends were also observed: logging damage represented an important part

869 of total emissions (Fig. 3 a-f, Pearson et al. (2014), Umunay et al. (2019), Zalman et al. (2019)),  
870 Improved practices (RIL) decreased carbon emissions (Fig. 3 a-f, Ellis et al. (2019), Umunay et al.  
871 (2019), Zalman et al. (2019)). Increased logging intensity decreases emissions per volume of wood  
872 produced (Fig. 3 a-f) (Griscom et al., 2014; Umunay et al., 2019).

873 An important feature of our model is the way we accounted for avoided emissions. Regarding the  
874 avoided emissions resulting from the substitution of fuelwood, we considered two possibilities  
875 representing the two extremes of a continuum on which the future reality is likely to be:  
876 accounting for a substitution to fossil fuel, or not accounting for any avoided emissions. The first  
877 approach is relevant in the current context in French Guiana where most of energy is produced  
878 from fossil fuel and hydropower. As the only dam in French Guiana is already functioning at full  
879 capacity, the increasing demand in the immediate future is therefore expected to be met by fossil  
880 fuel, and local guidelines recommend considering avoided emissions by substitution to fossil fuel  
881 only (Explicit and Alter, 2012). However, under EU climate policies, the relative contribution of  
882 renewable energies in the energy mix is expected to change (Lesperance et al., 2018). Our second  
883 approach, which does not account for avoided emissions from substitution of energy sources, is  
884 very close to what would happen should the energy mix be exclusively solar and wind power. The  
885 emissions due to energy production from fossil fuel are indeed much higher than those of solar or  
886 wind power (883 g eqCO<sub>2</sub> kW.h<sup>-1</sup> vs 55 and 7 g eqCO<sub>2</sub> kW.h<sup>-1</sup>, respectively (Explicit and Alter,  
887 2012)). As for the substitution of wood to another material, we decided to not take it into account  
888 (but our model allows us to do so), although they can have a positive effect on overall carbon  
889 balance (Butarbutar et al., 2016). The reasons for this choice were the difficulty to estimate the  
890 proportion of wood used in substitution from another material in a prospective way, and the

891 difficulty to get good estimates of displacement factors relevant for the local context (Sathre and  
892 O'Connor, 2010).

893 Some of the limitations of our model result from a lack of data and therefore highlight the need for  
894 further research, as outlined in the following points. (i) Among the six carbon pools that IPCC  
895 guidelines recommend to consider (IPCC, 2006), our model accounts for aboveground biomass,  
896 deadwood and harvested wood, but not for belowground biomass, soil organic matter and litter. A  
897 large scale study in Brazilian Amazonia showed no effect of selective logging on soil carbon and  
898 litter (Berenguer et al., 2014). Regarding the conversion of natural forest to plantation, there is no  
899 consensus on the effect on soil carbon, with some studies reporting an increase whereas others  
900 report a decrease (Eclesia et al., 2012). The age of the plantation is also an important determinant  
901 of the amount of soil carbon (Eclesia et al., 2012). As for the belowground biomass compartment,  
902 data are lacking and root/shoot allometries are often used (Griscom et al., 2014; Mokany et al.,  
903 2006). However, if these ratios have been shown to be dependent on the aboveground biomass  
904 (Mokany et al., 2006), there is no information on their dynamics after selective logging or forest  
905 conversion to plantation, impeding their use for our time-explicit model. (ii) Our model does not  
906 consider post-logging silvicultural treatments in natural forests, such as thinning to improve  
907 growth of commercial species, enrichment planting and liana cutting. One of the reasons is that  
908 such practices are not among the possible changes in practices foreseen by the local strategic plan  
909 for the forest and wood sector (Collectivité Territoriale de Guyane et al., 2019). But more  
910 importantly, such practices are rarely implemented and data on their effects on carbon dynamics  
911 are lacking. The rare studies conducted on this topic however report a positive effect of  
912 enrichment planting and liberation from liana on biomass accumulation and growth of future crop  
913 trees (Ruslandi et al., 2017b ; Mills et al., 2019 ; Villegas et al., 2009). (iii) Our submodel of carbon

914 recovery in natural forest was fitted in the context of a first logging cycle, which was sufficient for  
915 our objective considering the long cutting cycles implemented in French Guiana (65 years). For  
916 other countries in Amazonia with shorter cutting cycles, calibrating models for the second logging  
917 cycle would be interesting. However, most long-term logged forest monitoring concerns only the  
918 first logging cycle (Sist et al., 2015). (iv) Data on plantation productivity are still lacking in French  
919 Guiana (Nicolini and Morel, 2016) and we have been unable to find published data on the  
920 numerous plantations conducted in the neighbouring countries of the Guiana shield. (v) Finally,  
921 our model does not account for the changes in forest and plantation productivity and capacity to  
922 recover after logging that are expected with climate changes (Aubry-Kientz et al., 2019; Sullivan et  
923 al., 2020).

924 Sensitivity analyses (Fig 3.5) showed that the main sources of uncertainty in the overall model  
925 come from forest recovery in natural forest and plantation productivity. These uncertainties result  
926 in part from data limitations (the absence of monitoring after more than three decades after  
927 logging (Sist et al., 2015) and scarcity of data on plantations, but may also result from the large  
928 stochasticity in the biological process of productivity (Norden et al., 2015) and their sensitivity to  
929 climatic events such as drought (Vidal et al., 2016).

#### 930 4.2 *Intensifying practices to preserve larger areas: a land-sparing strategy*

931 As our model runs at the scale of the whole territory, it informs on the best prospective strategies  
932 for the wood sector to achieve its targeted future timber production while being sustainable. A  
933 broad scale approach is indeed more appropriate to assess the ability of practices to maintain  
934 multiple ecosystem services (Putz and Thompson, 2020). A key finding of our study was that  
935 intensification of practices can allow producing more wood without proportionally increasing the

936 pressure on land (i.e. the area of land dedicated to wood production, be it in natural forest or in  
937 plantation) or even reducing it (Fig 3.4). This allows for wider areas of natural forests to be left  
938 untouched for biodiversity conservation (Edwards et al., 2014a; Putz and Thompson, 2020). This  
939 intensification can be achieved by higher logging intensities in natural forest and/or by producing  
940 wood in plantation. Regarding the carbon balance, even in the extreme case for which avoided  
941 emissions from energy substitution were not taken into account, these strategies were at best  
942 much better (scenario *Plantation no deforestation*) or equivalent to a proportional increase in  
943 emissions (all other scenarios but *Plantation risk*) when compared to *Business as usual* over the  
944 long term (Fig 3.3). This supports a land-sparing approach of timber production, which is in line  
945 with studies using spatial optimisation to explicitly test different wood production strategies in  
946 the context of the land-sparing *versus* land-sharing debate. At the scale of Amazonia, Pioniot et al.  
947 (2019) found that logging at high intensity on limited areas and leaving large areas of forest  
948 untouched was the best strategy to maximize both carbon storage and biodiversity conservation.  
949 In Indonesia, Runting et al. (2019) showed that the optimal timber production strategy for  
950 mammal conservation was towards the land-sparing end of the continuum, by mixing areas of  
951 logging with RIL practices, plantation and protected areas.

952 In line with results from Runting et al. (2019), our results show that logging intensification in  
953 natural forest (i.e. harvesting a higher volume per ha) needs to be conducted together with the  
954 implementation of RIL practices. At the plot scale (Fig. 3 a-f), increasing the intensity of logging  
955 without RIL increased the amount of logging damage (Fig. 2). As a result, a plot undergoing a  
956 higher logging intensity takes longer to recover the carbon lost through logging (Fig. 3 a and e), as  
957 previously found in the Brazilian Amazonia (Numazawa et al., 2017). Intensification without RIL is  
958 hence detrimental for the short-term carbon balance (Fig. 3 a and e). RIL drastically limits the

amount of damage to the remnant tree stand (14.8 Mg ha<sup>-1</sup> of C [5.1, 30.5] for 30m<sup>3</sup> ha<sup>-1</sup> with RIL, versus 29.3 [15.8, 46.8] Mg ha<sup>-1</sup> of C without RIL) (Fig. 2), as found by numerous studies supporting RIL implementation (see Boltz et al. (2003) for a review). In addition, intensification leads to a substantial reduction of the area of logging roads and trails. For instance, at a logging intensity of 20m<sup>3</sup> ha<sup>-1</sup>, the area of logging roads and main skid trails is 12m<sup>2</sup> m<sup>-3</sup>, whereas it is 9m<sup>2</sup> m<sup>-3</sup> for a logging intensity of 30m<sup>3</sup> ha<sup>-1</sup> (calculated for one plot, without RIL and without fuelwood collection). Besides the reduction of carbon emissions from trees cut for roads and trails, this has broader environmental impacts as logging roads can have negative impacts on soil, wildlife and tree communities (Kleinschroth and Healey, 2017). This can also represent an important economic incentive, considering the cost of logging road infrastructure (in French Guiana, between 40 and 120 k€ km<sup>-1</sup>, 47 to 140 k\$ km<sup>-1</sup>, for creation only, not including maintenance cost, depending on the type of road; source ONF unpublished). The impact of logging intensification on other environmental services such as timber provisioning needs however to be considered carefully. Even if the growth of trees of commercial species may benefit from logging gaps (Hérault et al., 2010b), high intensity logging removes most of the high diameter individuals of these species. As a result, at the plot scale, the recovery of the commercial volume of wood lost through logging takes longer when logging intensity is higher (Piponiot et al., 2018).

Timber plantations are a step further towards a land-sparing strategy. The scenario with the best carbon balance is by far the one consisting of establishing plantations on non-forested land to meet all timber needs (scenario *Plantation no deforestation*) (Fig. 4). This scenario is the only one leading to a net storage in 2088 when avoided emissions are not considered. To produce 200 000 m<sup>3</sup> of timber per year, this scenario requires plantation establishment of a median value of 923 ha per year over 30 years. After this time, the land is replanted after harvest. An area of 27 690 ha

982 dedicated to plantation would therefore cover all timber needs. Producing timber exclusively from  
983 natural forest on the other hand would require logging 6762 ha per year at 30 m<sup>3</sup> ha<sup>-1</sup>, which  
984 represents 405 720 ha over 60 years, the length of two plantation rotations. As a reference,  
985 current areas of plantation in French Guiana are limited to the experimental plantations  
986 conducted in the 1960's and 1970's (FAO, 2020), and the area of natural forests needed to produce  
987 the current 65 000 to 80 000 m<sup>3</sup> of timber per year at a logging intensity of 20 m<sup>3</sup> ha<sup>-1</sup> is between  
988 3000 and 4250 ha (Piponiot et al., 2016a).

989 Finding non-forested land to establish plantations can however be an issue. In French Guiana,  
990 97.3% of land is covered by forest (FAO, 2020). Natural non-forested land such as savannah are  
991 already subject to high anthropic pressures despite their ecological value (Stier et al., 2020). There  
992 is therefore a low availability of non-forested land. A rapidly growing human population increases  
993 the need for non-forested land, especially for food production. Timber plantations will therefore  
994 be in competition with agricultural demands on non-forested land and with the conservation of  
995 natural forest. The Permanent Forest Estate, which would be the more suitable area for plantation  
996 as it is located close to most human activity areas, benefits from a protection status allowing  
997 selective logging but forbidding land conversion (Piponiot et al., 2016a). The availability of land  
998 where plantation can be established might therefore become increasingly problematic. Because of  
999 this context specific situation, and although deforestation to establish plantation is increasingly  
1000 criticised and may be prohibited in a non distant future, we modelled the carbon balance of  
1001 scenarios for which plantation are established on natural forests. One of these scenarios  
1002 (*Plantation*) would lead to the best carbon balance over the long term (Fig. 4). These scenarios  
1003 however have the worst carbon balance over the short term (next 30 years), with the highest  
1004 carbon emissions at peak (Fig. 4). These temporal differences between scenarios reduce the

1005 advantage of more intensive scenarios (with plantation on natural forests) in terms of their  
1006 contribution to climate change mitigation. In the context of the climatic crisis emergency (Ripple  
1007 et al., 2019), can we afford a strategy leading to carbon storage in 70 years but with much higher  
1008 emissions in the coming three decades? In addition, planning over the long term is a more risky  
1009 strategy, considering high uncertainties regarding climate change, socio-economical parameters  
1010 and policies.

1011 Besides these considerations on land use strategies, there are additional reasons for which a  
1012 mixed approach combining timber production from natural forests and from plantations may be  
1013 the more suitable. Trees from plantation and natural forest generally do not have the same  
1014 properties, and species recommended for plantation differ from those logged in natural forest  
1015 (Morel et al., 2017 ; Nicolini and Morel, 2016). Although planted trees often have a lower  
1016 durability, lesser mechanical properties, less aesthetic value and smaller size at harvest (Morel et  
1017 al., 2017) than timber from natural forests, they would be suitable for many local uses (such as  
1018 construction, furniture-making and other indoor uses), and their light weight would even be an  
1019 advantage for building (Morel et al., 2017). Some relatively marginal but high added value uses  
1020 would however require timber from natural forest (J. Beauchêne and B. Clair, personal  
1021 communication, Schimleck et al. (2013)). In addition, a strategy only based on plantation is likely  
1022 to be more risky than a mix of plantation and logging in natural forest. Although the response of  
1023 plantation species to threats such as climate change or pathogen attack remains an open question  
1024 (Kunert and Cárdenas, 2015), the low tree diversity of plantation make them likely to be less  
1025 resilient to such disturbance because of a lower insurance effect (Yachi and Loreau, 1999),  
1026 especially in monoculture (Kunert and Cárdenas, 2015 ; Guariguata et al., 2008). A lower than  
1027 expected productivity of plantations (scenario *Plantation risk*) would worsen the carbon balance

1028 of timber production, and increase the pressure on natural forest in order to maintain the targeted  
1029 overall timber production (Fig. 5).

### 1030 4.3 *Recommendations for the wood sector*

1031 By comparing the carbon balance of several prospective scenarios of development of the wood  
1032 sector, we were able to make the following recommendations to forest practitioners, policy  
1033 makers and researchers:

- 1034 • *Increase the share of plantation wood in the total production:* we recommend a mixed  
1035 approach combining a share of plantation timber supplemented by timber from natural  
1036 forest. Such a mixed-approach would provide a higher diversity of species and wood  
1037 properties better adapted to the diversity of wood uses. Considering the scarcity of non-  
1038 forested land in French Guiana, keeping a part of wood production in natural forests would  
1039 reduce the area of land needed for plantation and hence the need to deforest to establish  
1040 them, which is a practice responsible for important emissions, especially over the short  
1041 term (Fig. 4). A diversified portfolio of timber production practices would allow the  
1042 mitigation of risks arising from environmental and socio-economical changes over the long  
1043 term.
- 1044 • *Improve practices in natural forests:* Although, French Guiana forest managers and loggers  
1045 have been engaged in RIL for almost two decades (ONF, 2016), the implementation of RIL  
1046 practices can still be improved. The possibility to log at higher intensity when using RIL,  
1047 together with better access to eco-sensitive markets enabled by forest eco-certification,  
1048 could be incentives for the loggers to invest in improved RIL practices. In addition,

silvicultural practices, which have showed promising effects for carbon recovery, need to be tested at large scales (Ruslandi et al., 2017a). Forest managers and researchers should increase efforts to monitor impacts of these changes in practices on the residual stands, as data remains scarce globally (Ellis et al., 2016). LiDAR technology could provide good opportunity for medium scale and relatively low-cost monitoring (Ellis et al., 2016 ; Rangel Pinagé et al., 2019) .

- *Mitigate the negative impact of the plantation establishment phase:* When land availability allows, plantation should be established on non-forested lands (such as abandoned agricultural or mining areas) and previously logged forests, as deforestation is by far the more impacting phase with carbon emissions occurring in the coming three decades, when the challenge of climate change mitigation is the more pressing. (Fig. 3, Fig. 4). In addition, when established on forested land, plantations should be carried out over several cycles, so that the carbon debt of deforestation can be repaid over a longer term (Fig. 3 g-h).
- *Develop technical guidelines to improve and monitor plantation productivity:* Suitability of species, especially native ones, in Amazonia still deserve attention (Machado et al., 2018 ; Nicolini and Morel, 2016), especially in the context of climate change. Mixed-species plantations, especially of native species, are particularly promising in this context albeit rarely implemented, as they could ensure better productivity and better response to climate change, due to complementarity and the insurance effect among species (Kunert and Cárdenas, 2015 ; Guariguata et al., 2008). Monitoring plantation dynamics over the

long term and periodically reassessing technical choices will allow adaptive management of plantations (Guariguata et al., 2008).

- *Optimise the use of woody byproducts for timber and energy production:* The use of logging damage as fuelwood in natural forest is a good way to improve carbon balance (Fig. 3) while contributing to meet the increasing energy needs (Fig. 5). This should encourage the wood sector to invest in improving techniques and machinery of fuelwood collection (Fig. 3). Although not tested by our model, using big branches from harvested trees and logging damage as round-wood could also improve carbon balance. Optimising the uses of woody byproducts at all phases of the plantation (deforestation when necessary, thinning and final harvest), preferentially for high value uses (timber and round-wood) then as fuelwood, can also contribute to improve the carbon and economic balance of plantation.
- *Consider several ecosystem services, including biodiversity conservation, and the trade-off between them:* Our model focuses on one ecosystem service, climate change mitigation through carbon sequestration. Future research should include more ecosystem services, and identify trade-offs amongst them. Piponiot et al. (2019) showed that there is no scenario of timber production that can maximise the provision of all ecosystem services and, therefore, policy makers will need empirical evidence on which to base their choice of strategies. Trajectories of forest biodiversity after logging are especially poorly understood (Mirabel et al., 2020) and rarely modelled. In a time of unprecedented threats to biodiversity due to human activities (Cardinale et al., 2012), the strategic choices of the wood sector need to carefully evaluate and minimise impacts on forest flora and fauna.

## 5 Conclusions

Our study shows how a temporally-explicit and territory scale model of carbon balance calibrated with local data can be used as a prospective tool for decision-making. It can also serve as a retrospective tool to account for emissions from past logging, and can be easily adapted to other tropical forest contexts. A key finding of the comparison of prospective scenarios is that producing timber from a combination of intensified logging in natural forests and plantations, while aiming to reduce logging damage, is a promising way to increase timber production at the scale of the territory without increasing pressure on natural forests. Further studies should aim at studying post-logging dynamics of other environmental services than carbon sequestration, and especially biodiversity conservation, in order to provide a more comprehensive evidence-based tool for decision-making.

### Availability of data and materials

Most data used for model calibration have already been published (Nicolini and Morel, 2016 ; Piponiot et al., 2016b). Data from Guyafor and Arbocel are available upon request to the scientific director of the Paracou Station (<https://paracou.cirad.fr>). R codes of the model are available on GitHub ([https://github.com/EcoFoG/C\\_balance\\_forest\\_FG](https://github.com/EcoFoG/C_balance_forest_FG)).

### Author contributions

**Géraldine Derroire:** Conceptualisation, Methodology, Formal analysis, Validation, Data curation, Writing - original draft, Visualisation, Supervision. **Camille Piponiot:** Conceptualisation, Methodology, Validation, Data curation, Writing - review and editing. **Laurent Descroix:** Conceptualisation, Methodology, Validation, Data curation, Writing - review and editing. **Caroline**

1111 **Bedeau:** Validation, Data curation, Writing - review and editing. **Stéphane Traissac:** Validation,  
1112 Writing - review and editing. **Olivier Brunaux:** Validation, Writing - review and editing. **Bruno**  
1113 **Hérault:** Conceptualisation, Methodology, Validation, Writing - review and editing, Supervision,  
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1126 **Declaration of competing interest**

1127 The authors have no conflict of interest to declare.

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