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1 Title: *LoggingLab*: an R package to simulate reduced-impact selective
2 logging in tropical forests using forest inventory data

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40

41 Highlights (see attached files)

42 Abstract

43 Even where Reduced-Impact Logging (RIL) practices are applied, selective logging causes substantial
44 damage to tropical forests. To further reduce selective logging damage, the practices that cause the
45 most damage need to be identified and alternatives tested. To this end, we developed the R package
46 *LoggingLab*, a spatially-explicit and individual tree-based selective logging simulator and
47 demonstrated its functions using data from French Guiana. *LoggingLab* explicitly simulates damage
48 during each stage of the selective logging process taking into account topography and hydrography,
49 which are main constraints on logging. Most *LoggingLab* parameters can be easily adjusted to a wide
50 range of local contexts. *LoggingLab* can also be coupled with forest dynamics models to simulate the
51 long- term effects of different selective logging scenarios.

52

53 Graphical abstract (see attached files)

54 Keywords

55 Timber production; Sustainable forest management; Logging damage; Spatially explicit individual-
56 based simulator; Selective logging; French Guiana.

57 1. Introduction

58 Tropical forests carry the highest terrestrial biodiversity in the world (Barlow et al., 2018) and play an
59 important role in the mitigation of climate change (Malhi et al., 2008) as well as the maintain of food
60 security and health for many people (Brandon, 2014). They cover 1,834 million hectares (45% of the

61 world's forests; FAO, 2021), of which over 400 million hectares (c.a. 20%) are classified as production
62 forests (Asner et al., 2009; Blaser et al., 2011). Timber extraction and logging are identified as the main
63 causes of tropical forest degradation, and account for 53% of its emissions (Hosonuma et al., 2012;
64 Pearson et al., 2017). Beyond the few trees harvested per hectare (Gräfe et al., 2021), selective logging
65 impacts are mostly due to collateral damage (Derroire et al., 2021). Selective logging can lead to a
66 substantial reduction in biomass: usually between 10 and 30%, the biomass loss can reach around 60%
67 under high logging intensity, as found by Pinard & Putz (1996) in Malaysia and Rutishauser et al.,
68 (2015) in the Amazon. The recovery of pre-logging biomass can take a few decades to more than a
69 century, that depend on the logging intensity (Derroire et al., 2021; Pinard & Cropper, 2000;
70 Rutishauser et al., 2015).

71
72 Practices to reduce selective logging impacts have therefore been proposed under the name of
73 Reduced-Impact Logging (RIL). RIL practices already existed in temperate regions to optimise
74 exploitation (Dykstra, 2003; Sist, 2000), and have been promoted in tropical countries from the 1980s-
75 90s (Esteve & Lepitre, 1980; Krzeszkiewicz, 1959). In contrast to conventional selective logging, RIL
76 relies on pre-harvesting planning to optimise logging operation (Boltz et al., 2003; Johns et al., 1996;
77 Pinard & Putz, 1996). As a result, RIL practices considerably reduce the environmental impacts
78 compared to conventional selective logging (CL) (Ellis et al., 2019; Vidal et al., 2016). Pinard & Putz
79 (1996) showed that 23% less biomass is lost with RIL than with CL, and RIL damages 26% fewer
80 unharvested trees than CL. According to Boltz et al. (2003), RIL results in 90-129% less canopy area
81 loss and up to 4 times less ground disturbance than CL. But RIL practices as currently applied still lead
82 to significant damage with, for example, up to 37% biomass loss with RIL even at a very low intensity
83 of 10.7 m³ per hectare (Bryan et al., 2010). Even with RIL, selective logging also changes forest
84 composition, with an increase in the abundance of smaller light-demanding species (Arets et al., 2003;
85 Huth & Ditzer, 2001). The impact on the volume of commercial species is also important. With typically
86 used logging intensities (~20 m³/ha) and logging cycles (30-40 years), the rate of timber recovery in
87 logged natural forests is not sufficient to recover the amount logged by the end of a logging cycle
88 (Huth & Ditzer, 2001; Pioniot et al., 2019; Putz et al., 2012; Shearman et al., 2012). In their best-case
89 scenario, Sist & Ferreira (2007) observed a recovery of only 50% of the initial commercial volume 30
90 years after RIL at 21 m³/ha in Indonesia. The composition of communities of large (≥50 cm) and, even
91 more so, very large trees (≥110 cm) is more affected than the composition of communities of smaller
92 trees, by the selective logging of trees from 35 cm DBH. The maximum cutting diameter should
93 therefore be considered and reduced (Bousfield et al., 2023). There is therefore an urgent need to
94 assess the efficiency of RIL practices to reduce logging impacts, in order to further improve logging
95 practices, increase economic performance and preserve the ecosystem and associated services

96 (Hiltner et al., 2017; Putz et al., 2022; Sist & Ferreira, 2007). The disaggregation of the contribution of
97 each operation to overall damage and the experimentation of different practices can help to identify
98 the most effective ways to reduce damage.

99

100 The assessment of logging damage has evolved over time to be less costly and more accurate. Initially,
101 and still today, post-harvest diagnostics are carried out in the field in order to quantify logging damage
102 and lost timber volumes (Guitet, 2005). However, these field assessments are relatively expensive and
103 are therefore applied to limited areas (Gond & Guitet, 2009). The development of remote sensing has
104 made it possible to quantify canopy changes on a large scale by identifying tree gaps and trails
105 produced by logging (Asner et al., 2002). Thus, remote sensing can facilitate post-harvest diagnostics
106 by identifying highly impacted areas and reduce human and time costs of post-harvest diagnostics.
107 However, remote sensing has difficulty to detect degradation that does not alter the canopy (Asner
108 et al., 2002; Grace et al., 2014; Pearson et al., 2014). Moreover, remote sensing does not provide a
109 detailed analysis of the practices that cause this damage and is therefore of limited interest to identify
110 effective new practices (Gond & Guitet, 2009). The combination of field measurements and remote
111 sensing has however allowed substantial improvements to the assessment of logging damage. This
112 approach, together with the development of standardised indices of carbon emissions caused by
113 logging made it possible, for example, to diagnose and compare the carbon impact of logging
114 practices. This enabled the identification of a subset of RIL practices that promote the reduction of
115 greenhouse gas emissions, an approach called RIL-C (Reduced-Impact Logging for Climate Change
116 Mitigation) (Pearson et al., 2014; Griscom et al., 2014). Assessment of logging damage, either on the
117 ground or by remote sensing, is usually carried out in logging concessions, and is therefore limited to
118 logging practices already implemented. Foresters have set up experimental plots to test a new set of
119 practices. Some of these plots have become permanent inventory plots on which periodical re-census
120 of trees allow to study the logging impact on the forest structure, productivity, biodiversity and carbon
121 fluxes over time (Bertault et al., 1999; Finegan & Camacho, 1999; Gourlet-Fleury et al., 2004; Sist et
122 al., 2015). Experimental plots therefore allow us to study the long-term impacts of logging (Hérault &
123 Pioniot, 2018; Mirabel et al., 2020; Pioniot et al., 2016). However, they usually do not explicitly
124 quantify and spatialize damage, such as the harvested trees, areas affected by skid trails and logging
125 decks, and volume of collateral damage (*i.e.* trees killed by trails and secondary windfall).

126

127 Logging simulators are developed to address the limitations of field-based and remote-sensing
128 assessment of damage and to help the development of better harvesting practices. At lower human
129 costs and in less time, logging simulators can test many scenarios (*i.e.* combination of parameters and

130 technical instructions that constitute a particular experiment). They can generate virtual data and
131 perform virtual experiments under conditions beyond those of current field experiments. They also
132 allow to simulate large-scale experiments with a diversity of treatments over a large area and with a
133 large number of replicas (Maréchaux et al., 2021). When coupled to forest dynamics simulators,
134 logging simulators can help predict long term dynamics of forest after logging. Logging simulators have
135 been developed to describe conventional, selective and/or reduced-impact logging, in tropical or
136 temperate contexts. They have different degrees of realism and accuracy, based on the objectives for
137 which they were designed (Table S1). Some simulators do not model individual trees explicitly and
138 may therefore lack (i) the explicit definition of harvesting intensity (FATES Huang et al., 2020), (ii) the
139 choice of harvestable species (FORMIX Bossel & Krieger, 1991; FATES Huang et al., 2020), or (iii) the
140 definition of a minimum cut diameter (GuyaSim Rossi et al., 2015). Yet, these three logging parameters
141 are of primary importance to diagnose the selective logging practices that have the greatest impact.
142 In addition, all the current simulators of tropical logging ignore the topography and the hydrographic
143 network, which are important spatial constraints to the machines that spatially structure the logging
144 operations and the damage they cause. Few tropical logging simulators spatially and explicitly simulate
145 skid trails and felling gaps, the SYMFOR model being the only known example within our knowledge
146 (E. J. M. M. Arets, 2005). In contrast, simulators that do not take into account the spatial structure of
147 trails and felling have to consider damage as an input of the simulator. These logging simulators do
148 not quantify the damage caused by each logging practice and cannot be used to identify, compare and
149 propose ways to limit the consequences of these practices. In summary, to date there is a need for a
150 logging simulator that includes topography and offers enough parameters to allow a fine optimisation
151 of current practices.

152

153 Here, we present a new individual-based and spatially-explicit selective logging simulator: *LoggingLab*.
154 In particular, we are proposing RIL practices in this simulator, as a way to assess and demonstrate the
155 efficiency of these practices to reduce the impact of logging. *LoggingLab* was developed as an R
156 package because R is a widely used programming language in ecology (Atkins et al., 2022; Lai et al.,
157 2019), which allows the connection with other tools, through the R packages ecosystem. *LoggingLab*
158 was developed to diagnose and quantify in a spatially explicit manner the impacts of selective logging,
159 so that the reported damage is a consequence of the simulated logging and not an *a priori* choice of
160 the user. It simulates the different selective logging stages taking into account the topography and the
161 hydrographic network, the main spatial constraints for mechanisation. *LoggingLab* can be used
162 together with any individual-based and spatially explicit forest dynamics simulator like TROLL
163 (Maréchaux & Chave, 2017) or SEIB–DGVM (Sato et al., 2007) to observe the effects of selective

164 logging over time on the forest stand and the resilience of each forest to different selective logging
165 scenarios. It was developed in partnership with the French National Forest Office to realistically
166 describe selective logging practices implemented in French Guiana, while proposing a large number
167 of parameters to be a flexible tool that can be adapted to a variety of selective logging practices.
168

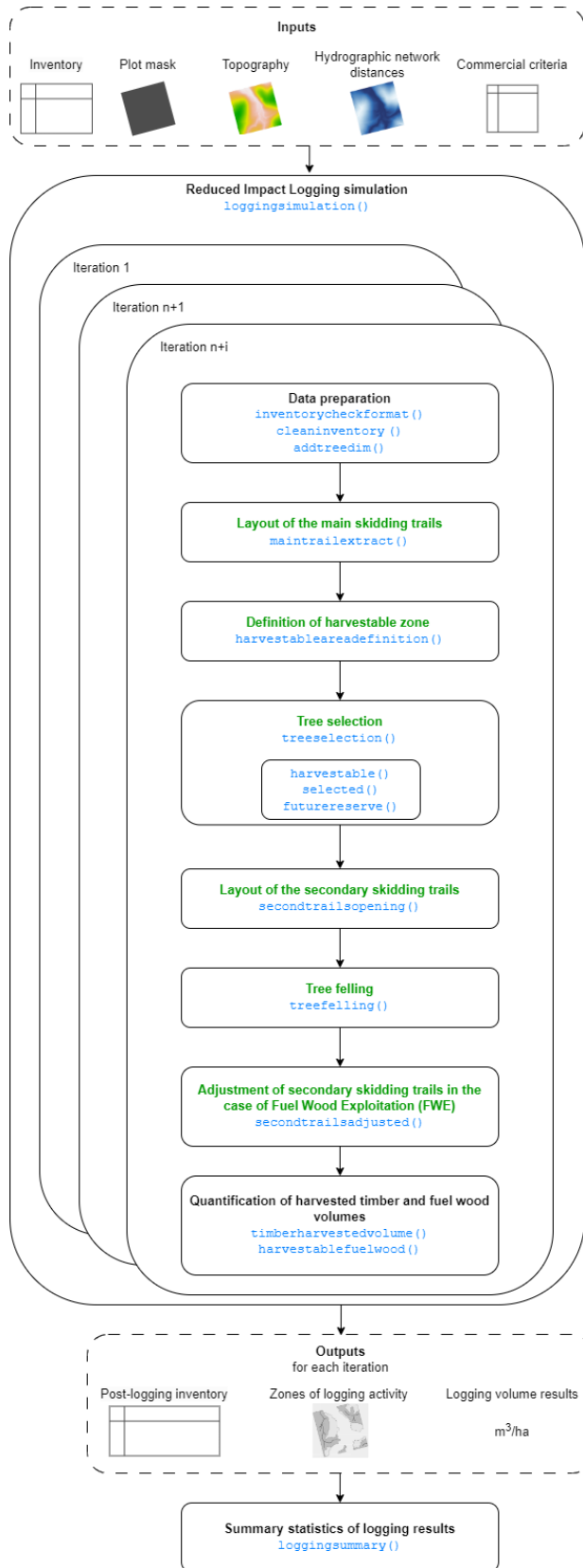
169 2. Methods

170 2.1. Reduced-Impact Logging

171 RIL is implemented in various ways around the world, in response to economic and environmental
172 constraints. The most commonly used practices are: (i) pre-harvest inventory of trees of commercial
173 species and above the minimum exploitable diameter (map and measurement), which allows a
174 selection of trees to be harvested and the design of an optimised trail network to collect these logs,
175 with a minimum length of the trail network, (ii) topography-based planning (slopes, hydrographic
176 network) that allows the optimal location of infrastructure (roads, trails, logging decks) and thus to
177 reduce the impacted area, (iii) directional tree felling to limit damage due to secondary tree fall,
178 especially on trees of interest (those to be exploited in the next campaign (Future Crop Trees (FCTs)),
179 and trees chosen for reproduction (seed trees)) (Dykstra, 2003; Sist, 2000).

180 2.2. Simulations of the different steps of selective logging in 181 LoggingLab

182 *LoggingLab* simulates timber harvesting according to Reduced-Impact Logging (RIL) practices in a
183 forest plot, that require a spatialised census as well as the plot's geographic features. *LoggingLab* also
184 includes the possibility to harvest fuel wood as a by-product of timber production (detailed in S4). It
185 covers the different logging steps, from the definition of harvestable zones to the tree felling, and
186 returns a quantification of timber volume harvested and logging collateral damage (*i.e.* trees killed by
187 trails and secondary windfall). It proposes a function to simulate the whole selective logging process:
188 `loggingsimulation()` but is also intended to be modular as each function that simulates a given stage
189 of the selective logging process (described below) can be used independently (Figure 1).



190
191

192 Figure 1: Flowchart of the *LoggingLab* R package. In green the Reduced-Impact
193 Logging steps realised in reality, in black the added steps in the simulator and in blue
194 the names of the functions that perform these steps.

195 2.2.1. Layout of the main skid trails

196 *LoggingLab* does not aim to model the main skid trails and the damage they cause, as these trails are
197 located outside the few hectare forest inventory plots that provide the data for simulation. In real
198 conditions, the main trails would be located between these plots. These trails however need to be
199 simulated as they provide access to the zones to harvest. In the absence of information on the position
200 of the main trail, the simulator randomly draws a single entry point per harvestable zone, on the edge
201 of the plot adjacent to an harvestable zone (`maintrailextract ()`) (Figure 6). However, the user can
202 provide a shapefile with the main trail network, that *LoggingLab* will use to get the entry point.

203 2.2.2. Definition of the harvestable zone

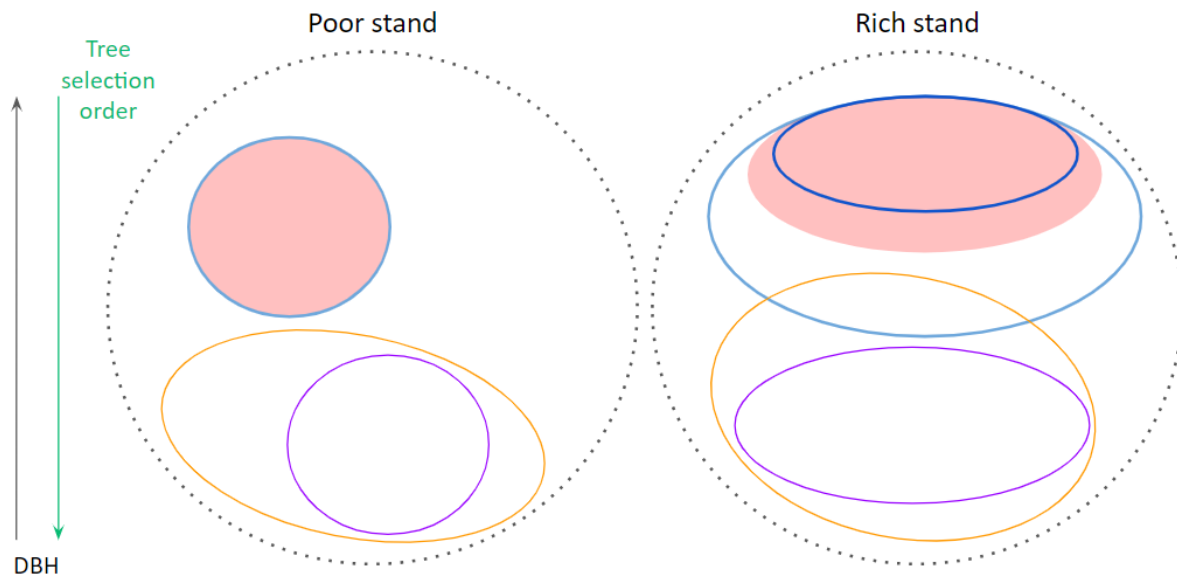
204 The harvestable zone is defined under certain conditions linked to the technical constraints of the
205 machines used. Topography is the main limitation. It is only possible to log on a slope inferior to a
206 certain threshold (See S3: for the default values of slopes and distances thresholds). The bottomlands,
207 the hydrographic network and the riparian buffer zones must be avoided (See S3: for the default
208 values taken into account to define riparian buffer zones). The function `harvestableareadefinition`
209 defines the harvestable zones and machine-accessible zones within the plot. The harvestable zone
210 may be larger than the machine-accessible zone if a skid cable is used: the machine will only circulate
211 on the machine zone but the cable may collect a tree in a buffer zone around the machine zone, thus
212 extending the harvestable zone beyond the machine zone (Figure 6).

213 2.2.3. Tree selection

214 The tree selection consists to identify the harvestable trees (`harvestable()`), trees that will be
215 harvested in the next campaigns: Future Crop Trees (FCTs) (*future trees*), and trees that should be
216 protected from harvest as they were chosen as seed trees (*i.e.* trees kept for reproduction) (*reserve*
217 *trees*) (`futurereserve()`). The function `treeselection` implements the selection process. A tree is
218 harvestable if it meets all the following criteria: it (1) is in the harvestable zone, (2) belongs to a
219 commercial species, (3) has a diameter above the harvestable diameter, and (4) has no visible defect
220 (holes, broken crowns, deformed trunks). In addition, if the considered tree belongs to an aggregative
221 species (*i.e.* forming clusters of conspecific individuals), the tree must be less than a maximum distance
222 from other conspecific individuals to be considered harvestable (`IsolateTreeMinDistance`), to keep

223 single individuals of this species as seed trees (See S3: for the default value of the
224 *IsolateTreeMinDistance* and other advanced logging parameters). The trees that will actually be
225 harvested are selected among the harvestable trees (`selected()`), in ascending order of their
226 commercial interest (1st, 2nd or more economic ranks entered in the *speciescriteria* argument, see
227 section 2.3.), and in descending order of harvestable volume of the tree until the target volume
228 (*objective*) is reached. If the total harvestable volume of the plot is higher than the target volume
229 (*objective*), the Minimum Felling Diameter (*MinFD*) is increased (*UpMinFD*) in order to harvest the
230 largest trees preferentially. If the harvestable volume is too low, the user can choose between: (1) to
231 increase the commercial species list (diversification) to reach the objective, (2) to harvest without
232 having reached its target volume, or (3) do not harvest the plot. A proportion of the designated trees
233 will be found to be hollow when surveyed by the logger. If the simulated scenario (Table 1) only
234 includes timber production, hollow trees are not harvested and additional healthy harvestable trees
235 are chosen to meet the target volume. If the simulated scenario (Table 1) only includes timber
236 production, hollow trees are not harvested and additional healthy harvestable trees are chosen to
237 meet the target volume. The Future Crop Trees (FCTs) (*future trees*) belong only to species of the first
238 economic rank (*i.e.* strongest economic interest), with a diameter between the minimum diameter
239 threshold chosen for the FCTs (*FutureTreesMinDiameter*), and the minimum harvestable diameter of
240 the species (*MinFD* or *UpMinFD*) (See S3: for the default value of the *FutureTreesMinDiameter* and
241 other advanced logging parameters). The FCTs (*future trees*) are preserved if this practice is selected
242 by the user and if possible (alternative orientation of the treefall, alternative passage for the trail)
243 during harvesting. Among the FCTs, a number of *reserve trees* equal to the number of harvested trees
244 is randomly selected. By default, protection of *reserve trees* is favoured over the FCTs when skid trails
245 are laid out (Figure 2) (See S3: for default values of the advanced logging parameters).

246



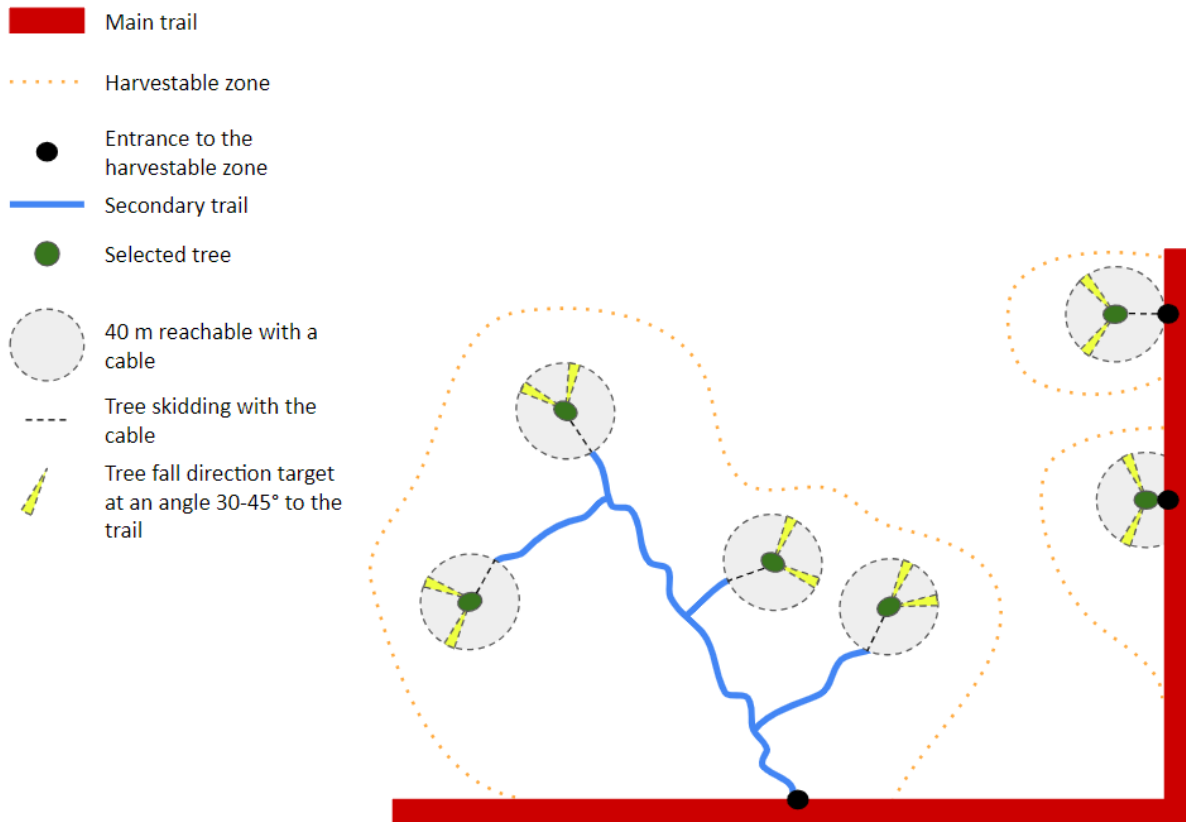
247

248 Figure 2: The tree selection in Reduced-Impact Logging (RIL). Black circles: all trees in the plot; Light
249 blue: the harvestable trees; Dark blue: the harvestable trees with raised minimum DBH (*MinDBH*).
250 Tree selection: Red area: selected trees for logging. Orange circles: Future Crop Trees (FCTs) (*future*
251 *trees*); Purple: reserve trees, both chosen among 1st economic rank species only. Dotted lines: all
252 species; Solid lines: commercial species.

253 2.2.4. Layout of secondary skid trails

254 Secondary trails join the main trails and the selected trees through zones accessible to the machines
255 (`secondtrailsopening()`). The trails do not necessarily have to reach every tree, as the machines
256 have a synthetic cable to pull them (Figure 3). The trails are therefore designed to pass between the
257 trees, approaching them at the maximum cable or grapple length. For one of the parameters proposed
258 in *LoggingLab* (`winching = "2"`), the grapple is preferred to the cable, however, when the slope does
259 not allow the grapple to access the tree, the cable is used (See S3: for functions arguments description)
260 (See S3 Figure 1). This simulation choice is aimed to test situation when grapple is favoured over cable
261 as it is less costly and time consuming, but this do not mean that we recommend the use of grapple
262 over cable, as the grapple cause more damage because it requires the machine to go closer to the
263 cutted tree to harvest it (Putz et al., 2022). The design of secondary trails layout uses a Dijkstra
264 algorithm with directed spatial weights (Sales et al., 2019) in order to minimise their length, according
265 to RIL principles, while respecting longitudinal and transverse slope thresholds for reasons of human
266 and mechanical safety. The allocation of a width to the trails allows to account for the mortality of all
267 the trees situated on the trails. If a weight is given to them, large trees can be avoided to reduce the
268 impacted biomass and because they would push over and leave holes on the trail. The secondary trail

269 layout is computed sequentially so as to integrate, at each step of the algorithm, already designed
 270 trails and reuse them preferentially. This specific approach aims to harvest several trees with the same
 271 trail and thus allow a reduced trail area compared to a unique minimization step (Picard et al., 2006).
 272
 273



274
 275 Figure 3: Trail design when winching is done with a cable.

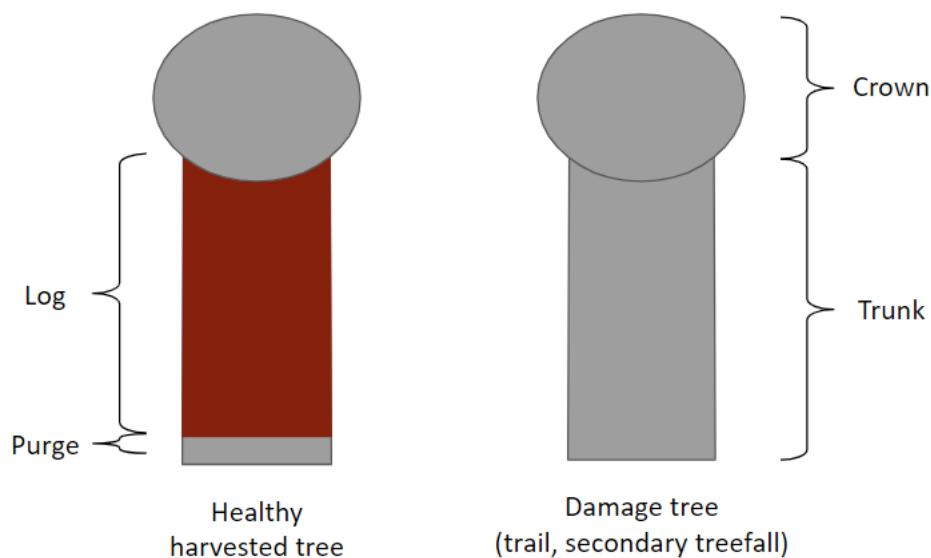
276 2.2.5. Tree felling

277 Three felling orientation rules are proposed to the user: (i) the tree is felled foot towards the nearest
 278 trail (main or secondary), (ii) in addition to this condition, tree felling avoids FCTs (*future trees*) and
 279 reserve trees, (iii) in addition to these two previous conditions, the tree is angled towards the trail, to
 280 optimise the skidding of the tree. When the angle to optimise skidding is chosen between 30° and 45°,
 281 it produces a branched structure that allows easier skidding, and thus reduces skidding damage
 282 (Hendrison, 1990). The orientation of tree felling can fail and in this case the angle of fall depends on
 283 the natural orientation of the tree, its crown and the topography. In *LoggingLab*, the failure of the
 284 felling direction is simulated with a probability chosen by the user, and results in a random orientation.
 285 In the simulator, `treefelling()` simulates all these felling possibilities according to the user's choice

286 (See S3: for the description of the functions arguments and of the advanced logging parameters)
287 (Figure 6).

288 2.2.6. Quantify harvested timber

289 When harvest planning is complete, the simulator quantifies the production. The timber harvested
290 volume (`timberharvestedvolume()`) includes the log of healthy trees harvested for timber, and the
291 healthy part of the log of hollow trees ($\frac{2}{3}$ of the tree trunk) if they are also harvested (Figure 4).
292



293

294 Figure 4: Part of the tree valuable for timber (brown) and tree parts not harvested (grey). The
295 unused part (*i.e.* defects, decay and buttresses) of the trunk of the healthy harvested trees (named
296 "purge" within the simulator) (default value: $0.14 \text{ m}^3/\text{m}^3$ of volume of timber harvested).
297

297

298 2.3. Data requirement and input

299 The main input data is a tree census (*inventory*) for which trees are (i) measured (Diameter at Breast
300 Height, DBH), (ii) spatialised and (iii) botanically identified (in the case of logging inventory using
301 vernacular/commercial name, a correspondence with botanical name will have to be made). The data
302 requirements for the input inventory can be adjusted to the data availability and to the expectation
303 of the user. The more comprehensive the input data are, the more detailed and informative the output
304 will be. As the main objective of *LoggingLab* is to assess logging damage, we recommend that the
305 whole tree community is provided in the inventory. If the inventory covers only a subset of the whole
306 tree community, the user will have to take this into account to interpret the outcomes. In particular,

307 (i) for the DBH cut-off, we recommend to include inventory with a minimum DBH as little as possible.
308 10 or 20 cm DBH is a common threshold used in forest inventory, and inventory with a similar
309 minimum DBH will allow comparison with other contexts; (ii) the spatial coordinates (x, y) of all trees
310 that are considered in the inventory need to be provided for *LoggingLab* to be able to simulate the
311 fate of the tree after logging. (iii) the botanical identification of the commercial species needs to be
312 provided, at least for trees big enough to be harvested, as the botanical identification is a criterion
313 used to choose harvestable trees. The botanical identification of the other trees is optional, but not
314 providing it would restrict the outputs to indices that do not need botanical identification. To simulate
315 a realistic logging operation, the topography is taken into account from a Digital Terrain Model (DTM)
316 of the inventoried plot (*topography*). The hydrographic network also represents a major constraint for
317 logging, so the definition of the zone to harvest takes into account the relative vertical and horizontal
318 distances from the nearest channel network (*creekdistances*). In case the user does not already have
319 a map of these hydrological features, we propose a script to generate them using a raster of the Digital
320 Elevation Model (<https://vincyanebadouard.github.io/LoggingLab/articles/CreekDistancesRmd.html>).
321 In order to ensure the correct delimitation of the plot, a mask (*i.e.* spatialised polygon) of the plot
322 (*plotmask*) is required. The table of species criteria (*speciescriteria*) allows the user to specify the
323 commercial species, the species commercial interest (1st, 2nd or more economic ranks) and species
324 harvestable diameters (*MinFD*, *UpMinFD*, *MaxFD*). A table for volume parameters
325 (*volumeparameters*) allows to compute the harvestable volume of each tree. Different parameter
326 values can be given for different geographic zones when the volume allometry differs from one study
327 site to another (See S3: for the description of the functions arguments).

328 2.3.1. Parameterisation of *LoggingLab*

329 *LoggingLab* proposes predefined Reduced-Impact Logging scenarios (Table 1) based on practices
330 applied in French Guiana, or a manual mode to choose between all possible combinations of practices.
331 The practices are the volume to extract (*objective*), the economic rank of the species to harvest
332 (*diversification*), the maximum distance at which trees can be retrieved from the trail (*winching*), the
333 type of directional felling (different objectives of directional felling that condition the angle of felling,
334 *directionalfelling*) (See S3 for functions arguments description). Note that the *LoggingLab* includes a
335 possibility to harvest fuel wood as a by-product of logging. As this practice may not be very common
336 outside of our study site, we only present its implementation in detail in S4.

Scenario	RIL2 experimental	RIL2	RIL3
Objective (m³/ha)	25	25	30
Diversification	No	No	Yes
Winching			
Grapple (6m)	No, skid trail to tree foot	No	Yes
Cable (40m)		Yes	Yes
Direction felling			
Orientation angle to the trail	No	No	Yes
Avoid future crop trees and reserve trees	No	No	Yes

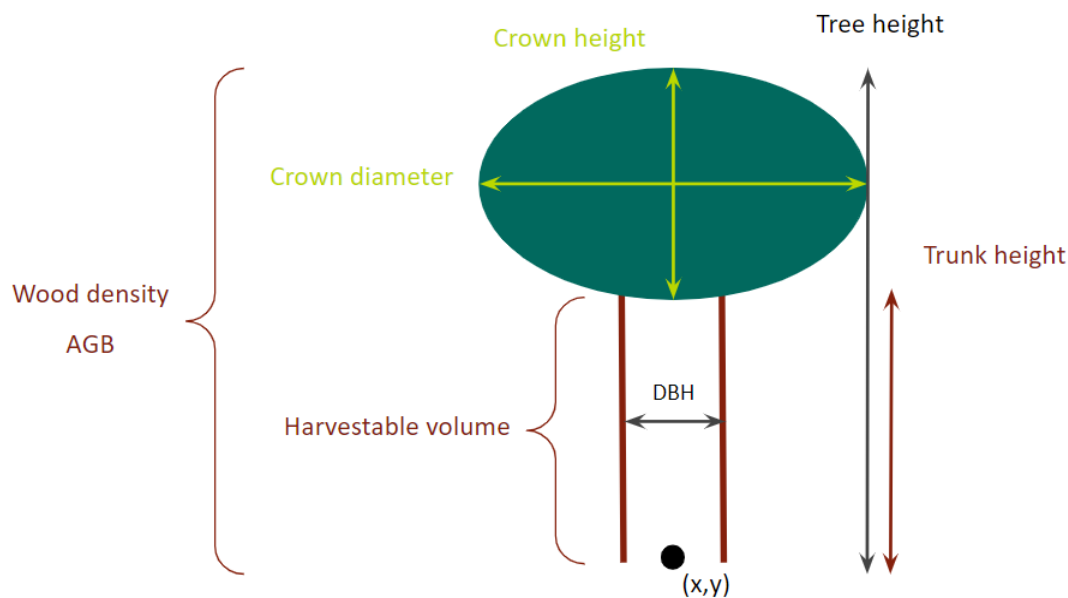
337 Table 1: Description of the default parameters of the Reduced-Impact Logging (RIL) predefined
338 scenarios proposed in the *LoggingLab* R package (See S3: for details and S4 for additional scenarios
339 that include use of logging by-products for fuel wood).

340

341 It is possible to use a predefined scenario and change only one or a few parameters, by specifying only
342 the parameters that differ from those of the predefined scenario. The user can also access and modify
343 all the numerical values (e.g. slopes limits, trail width, cable length) and models (eg. volume, crown
344 allometries, tree defects probability, probability to die under a felled tree) to define a custom selective
345 logging operation (*advancedloggingparameters*) (See S3: for the default values of the
346 *advancedloggingparameters*). *LoggingLab* allows the user to integrate repetitions over several
347 iterations (*iter*) to explore the uncertainties of the different selective logging steps, whose computing
348 time can be reduced with the built-in parallelisation of the simulations (*cores*).

349 2.3.2. Data preparation

350 Before the simulation, the data format is checked (`inventorycheckformat()`) and “cleaned”
351 (`cleaninventory()`): only alive trees larger than the minimum inventory diameter (`MinDBHValue`),
352 within the inventoried plot are kept. The dimensions of each tree (tree, trunk and crown heights,
353 crown diameter, harvestable volume, wood density, and AboveGround Biomass (AGB)) are computed
354 from their Diameter at Breast Height (DBH) using the `addtreedim()` function (See S3: for the
355 description of the allometries and their sources) (Figure 5).
356



357
358 Figure 5: Tree dimensions computed in *LoggingLab* from the input DBH (Diameter at Breast Height).

359 3. Example application of *LoggingLab*

360 3.1. Command line

361 In the following example 30 iterations of a manual scenario (equivalent to scenario **RIL3 with fuelwood**
362 **& hollow trees** in Table 1) are run on the example data of Plot 6 in Paracou, with other parameters set
363 to default values.

```
364  
365 Rslt <- loggingsimulation(  
366   inventory = Paracou6_2016,  
367   plotmask = PlotMask, topography = DTMParacou,  
368   creekverticaldistance = CreekDistances$distvert,  
369   creekhorizontaldistance = CreekDistances$disthorz,  
370   speciescriteria = SpeciesCriteria,  
371   volumeparameters = ForestZoneVolumeParametersTable,  
372   scenario = "manual", objective = 30,
```



```

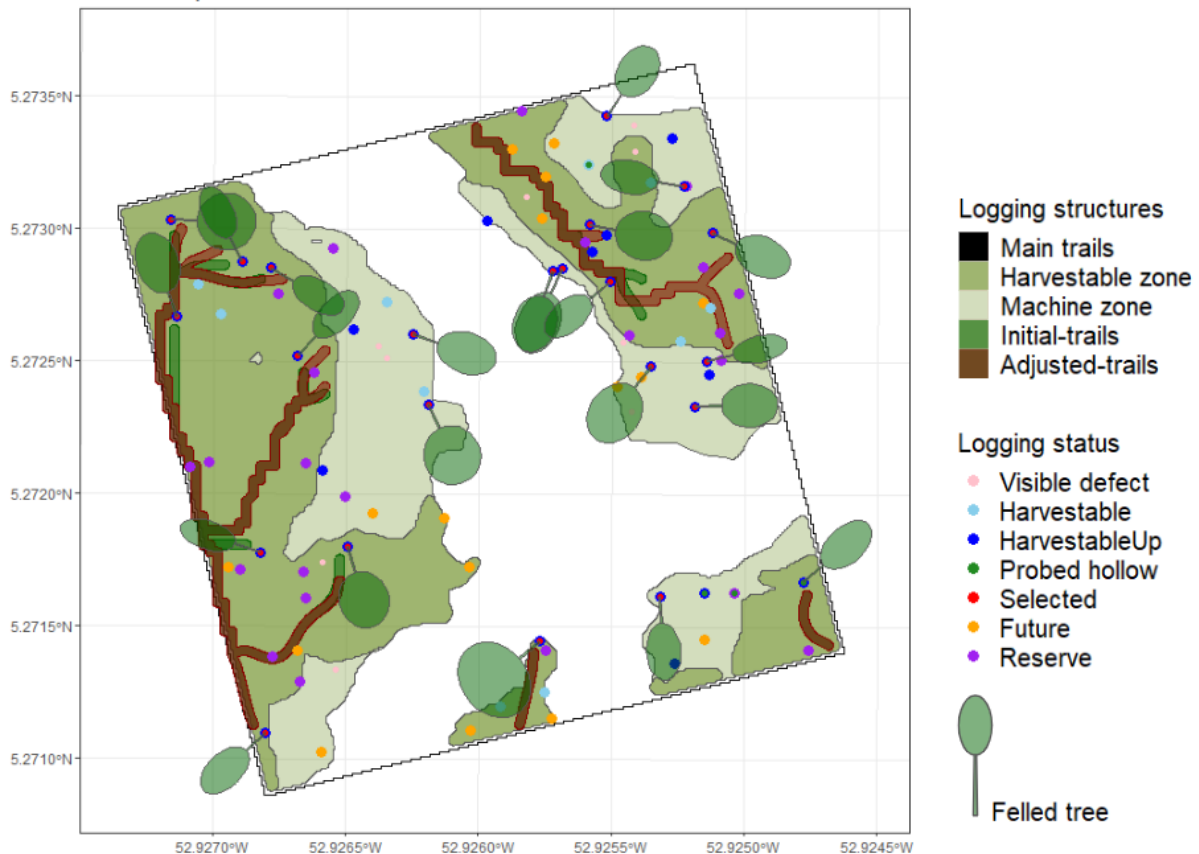
373 fuel = "2", winching = "2", directionalfelling = "2",
374 diversification = TRUE, specieslax = FALSE,
375 objectivelax = TRUE,
376 crowndiameterparameters = ParamCrownDiameterAllometry,
377 advancedloggingparameters = loggingparameters(),
378 iter = 30, cores = 30)

```

379 3.2. Package outputs

380 `loggingsimulation()` returns the forest inventory with new columns that include the tree
381 dimensions, the logging status (“harvestable”, “non-harvestable”, “future”, “reserve”, or “selected”),
382 the death cause (trails opening, under a felled tree, harvested), and a column with the coordinates of
383 the felled trees silhouettes (Figure 6) for each iteration (See Table S2: for the metadata of the
384 *LoggingLab* output inventory). Each simulation produces spatial objects such as the harvestable zones
385 (*HarvestablePolygons*) and the trail layout (Figure 6). The simulator also returns the collected timber,
386 as well as several values related to logging operation and short-term damage (harvestable area,
387 volume of collateral damage, trails density etc...). The numeric outputs of each simulation can then be
388 summarised with `loggingsummary()`, which provides summary statistics of volume production and
389 damage across iterations (Table 2).

Paracou plot 6 - RIL3 with fuelwood & hollow trees



390

391 Figure 6: Summary plot of *LoggingLab* outputs with the simulation presented in example simulation,
392 for one iteration.

	Unit	Mean	Sd	Q1 (25%)	Median	Q3 (75%)
Harvestable area	ha	3.7	0.0	4.0	3.7	4.0
Objective volume	m ³	112.4	0.0	112.0	112.4	112.0
Initial harvestable volume	m ³	182.2	8.7	178.0	181.8	187.0
	m ³ /ha	49.2	0.0	44.5	49.1	46.8
Timber logged volume	m ³	106.6	2.8	105.0	107.3	109.0
	m ³ /ha	28.8	0.0	26.3	29.0	27.3
No hollow timber logged volume	m ³	96.6	8.4	92.0	98.3	103.0
	m ³ /ha	26.1	0.0	23.0	26.6	25.8
Timber extracted volume (timber volume after purge)	m ³	93.1	1.6	92.0	93.6	94.0
	m ³ /ha	25.2	0.0	23.0	25.3	23.5
Fuel wood biomass	ton	151.5	8.8	148.0	151.3	155.0
	ton/ha	40.9	0.0	37.0	40.9	38.8
Logging residual biomass	ton	71.6	6.1	68.0	71.2	75.0
	ton/ha	19.4	0.0	17.0	19.2	18.8
Total forest biomass lost	ton	296.5	14.7	290.0	296.6	304.0

Trails density	m/ha	104.7	10.0	101.0	104.2	111.0
Adjusted trails density (for fuel wood recovery)	m/ha	107.2	9.3	105.0	109.1	112.0

394 Table 2: Summary of the numeric outputs of iterations of the simulation example (see section 3.1.)
395 computed with `loggingsummary()`, which provides summary statistics of volume production and
396 damage across 30 iterations. Please note that all volumes in m³/ha and biomass in ton/ha are per
397 exploitable hectare, not per plot hectare. “Total forest biomass lost” is the total forest biomass lost
398 due to logging (the sum of the AGB of all dead trees, whatever the death cause. For “Adjusted trails
399 density” definition see S4: for details.

400 4. *LoggingLab* evaluation

401 4.1. *Validation of LoggingLab outputs*

402 Practitioners from the National Forestry Office of French Guiana validated the realism of the
403 simulations on the basis of numerical outputs (timber, and collateral damage volumes, trail density,
404 proportion of dead trees by category) and graphical outputs (spatialisation of exploitable areas and
405 trails). In addition, following a RIL2 scenario at 20 m³/ha with data from French Guiana, *LoggingLab*
406 determined a collateral damage volume (*i.e.* trees killed by trails and secondary windfall) of 47.67
407 m³/ha [28.33,62.47] in agreement with values obtained by statistical model using data from the same
408 region: 41.54 m³/ha [13.55,90.25] (Derroire et al., 2021).

409 4.2. *Limitations and perspectives of development*

410 Several further developments could be implemented in a future version of *LoggingLab*. (1) The current
411 version of *LoggingLab* requires an important computational time to perform several iterations.
412 Despite the parallelisation of the code, the informatic resources remains important (e.g. 22 minutes
413 of computing time for the 30 iterations of the simulation presented in the example simulation (see
414 section 3.1.), for 30 cores) and a computing cluster may be required. It would be interesting in a future
415 version of *LoggingLab* to translate the most time-consuming part of the code (the spatialised part)
416 into C++ to reduce computation time, and integrate it into the main R code. (2) *LoggingLab* has been
417 developed to test different RIL practices and therefore does not allow to simulate a non-optimised
418 trail design to describe Conventional Logging (CL). As there is no planning phase in CL, the trees to
419 harvest are not mapped before logging. The logger therefore collects trees from one to the next,

420 without optimised trail design, that result in a higher trail density. Conventional secondary trails can
421 be provided by the user because *LoggingLab* is modular (each function simulate a given stage of the
422 selective logging process can be used independently). An algorithm to simulate tree to tree collection
423 could be implemented in a future version of *LoggingLab*. Other CL practises (non-directional felling,
424 to collect trees at their base, no particular intention to avoid FCTs and reserve trees) are already
425 implemented in *LoggingLab*. (3) *LoggingLab* does not simulate main trails and logging decks. The
426 reason for this is that the simulator has been designed to work on inventory plots that include all
427 species and a large range of size classes, to be able to assess the impacts on the whole tree community.
428 Such plots generally only cover a few hectares. Large-scale structures as main trails and logging decks
429 would therefore be located outside the plot. In case the user would like to use *LoggingLab* on large
430 logging plots (several hundred hectares), the user could provide *LoggingLab* with the main trails and
431 logging decks generated by another tool, and *LoggingLab* would calculate the collateral damage
432 (`mortalityunderpolygon()`). The algorithms to create main trails and logging decks may be
433 implemented in a future version of *LoggingLab*.

434 5. Discussion

435 *LoggingLab* was designed on the basis of past, current and future Reduced-Impact Logging practices
436 in French Guiana. However, the simulator has been designed to be as accessible and flexible as
437 possible, in order to simulate local selective logging practices in other contexts. Flexibility was made
438 possible by offering the possibility to change all default numerical parameters and allometries, and by
439 proposing an open tool, with code accessible online. *LoggingLab* can be widely used for ecological
440 studies of the short-term impacts of RIL on the forest ecosystem, such as impacts on floristic diversity
441 or carbon stock. *LoggingLab* can also be coupled with a Dynamic Vegetation Model (DVM) to study
442 the long-term effects of selective logging, and the resilience of the forest ecosystem to this
443 disturbance in interaction with other ones such as climate change. As the simulation of selective
444 logging implemented in *LoggingLab* is much more detailed than the one implemented in most forest
445 dynamics simulators, this coupled use would improve long-term predictions and widen the range of
446 tested logging practices. This coupling can be done by using the forest inventory returned by
447 *LoggingLab* with the life status of each spatialised tree after logging as an input of individual-based
448 and spatially explicit forest dynamics simulators. *LoggingLab* can also be used as a planning tool for
449 selective logging operations by forest managers, to define the harvestable zone, identify the trees to
450 harvest according to the logging objectives, and design the optimal trail layout to collect these trees
451 (but see *Limitations* part).

452 In conclusion, the ambition of *LoggingLab* is to provide a simple method to test a wide range of
453 selective logging practices and better assess the quantity and sources of logging damage in a wide
454 range of ecological and wood production contexts in tropical forests. Its *in silico* approach allows the
455 assessment of selective logging at no cost beyond the cost of forest inventories, and is therefore
456 particularly useful for the design of less destructive logging practices.

457 6. Software availability

458 *LoggingLab* is an R package for all operating systems (Windows, Linux, Mac OS). It is a free and open
459 source tool (version 1.0.0 with GPL-3 licence, requiring R \geq 4.1) available on GitHub
460 (<https://github.com/VincianeBadouard/LoggingLab>), and can be installed within the R environment
461 using the command `devtools::install_github("VincianeBadouard/LoggingLab")`. The code is
462 available at <https://github.com/VincianeBadouard/LoggingLab>, and a vignette (i.e. a tutorial) is
463 available for this package (<https://vincyanebadouard.github.io/LoggingLab/index.html>). *LoggingLab* is
464 automatically tested and controlled under CRAN criteria for all operating systems. To facilitate its
465 portability, we also integrated *LoggingLab* into a singularity container:
466 <https://github.com/sylvainschmitt/singularity-LoggingLab>.

467
468 We encourage users to report any issues and/or desired extensions on our active issues page
469 (<https://github.com/VincianeBadouard/LoggingLab/issues>).

471 Author contributions

472 G.D., S.S. and V.B. conceptualised the study. O.B. and C.B. provided information on logging practices
473 in French Guiana and checked the realism of the algorithm and its outputs. V.B. designed the
474 architecture of the package, created the R package and managed its collaborative development, with
475 inputs from G.D., S.S., G.S. and T.G. V.B., G.S. and T.G. wrote the code. V.B. and M.R. developed some
476 of the models implemented in the package. V.B. wrote the package documentation and the unit tests.
477 S.S. supervised the development of the package and checked the code. G.D. checked the package
478 documentation. M.R. beta tested the package under development. V.B. led the writing of the
479 manuscript, with inputs from G.D. and S.S.. All authors contributed critically to the manuscript and
480 gave final approval for publications.

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491 Declaration of competing interest

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

494 Appendix A. Supplementary data (see attached files)

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