

1   **Title:** The global exposure of species ranges and protected areas to forest management

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3   **Running Title:** Conservation and forest management

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6   Authors: Martin Jung<sup>1\*</sup>, Matt Lewis<sup>1</sup>, Myroslava Lesiv<sup>2</sup>, Andy Arnell<sup>3</sup>, Steffen Fritz<sup>2</sup> &

7   Piero Visconti<sup>1</sup>

8

9   1 Biodiversity Ecology and Conservation Research Group, International Institute for Applied

10 Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

11   2 Novel Data Ecosystems For Sustainability Research Group, International Institute for

12 Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

13   3 UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC),

14   219 Huntingdon Road, Cambridge CB3 0DL, United Kingdom

15

16   \* Corresponding Author (jung@iiasa.ac.at)

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18   **Abstract:**

19

20   The majority of vertebrate species globally are dependent on forests, most of which require

21 active protection to safeguard global biodiversity. Forests, however, are increasingly either

22 being disturbed, planted or managed in the form of timber or food plantations. Because of a

23 lack of spatial data, forest management has commonly been ignored in previous conservation

24 assessments. Here we show – using a new global map of forest management - that disturbed

25 and human managed forests cover the distributional ranges of most forest-associated species.

26 Even more worrying, protected areas are increasingly being established in areas dominated by

27 disturbed forests. Our results imply that species extinction risk and habitat assessments might

28 have been overly optimistic with forest management practices being ignored. With forest

29 restoration being in the centre of climate and conservation policies in this decade, we caution

30 that policy makers should explicitly consider forest management.

31

32   **Keywords:** Species distribution, Forest management, Extinction risk, Threat mapping,

33   Forest specialism, Vertebrate diversity, Forest restoration, Plantations

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36   **Introduction:**

37       Forests cover approximately 27% of the earth's land surface (Buchhorn et al. 2020;

38       Jung et al. 2020). They are the exclusive habitat of 54.5% of terrestrial vertebrate and many

39       other plant, fungi and invertebrate species (Gibson et al. 2011; IUCN 2012; Hill et al. 2019),

40       and can directly or indirectly benefit humankind through ecosystem services such as food or

41       water, something particular relevant for the over 1.6 billion living within close proximity of a

42 forest (Newton et al. 2020). Increases in human population and demand for food, non-timber  
43 and timber products, are resulting in forests in tropical, temperate and boreal regions being  
44 increasingly disturbed or modified by humans (Lewis et al. 2015; Curtis et al. 2018). Changes  
45 in forest use and management can affect the structural integrity of forests (Ghazoul et al. 2015;  
46 Lewis et al. 2015), ultimately reducing the size and connectivity of forest patches (Haddad et  
47 al. 2015) and affecting forest biodiversity (Hill et al. 2019). Yet, while a loss in forest cover  
48 can reduce local species richness (Melo et al. 2018) and increase the extinction risk of many  
49 species (Tracewski et al. 2016; Santini et al. 2019), it is not fully understood to what extent  
50 biodiversity is exposed to forest disturbances and management globally.

51 Forests are commonly disturbed and anthropogenically managed (Lewis et al. 2015).  
52 Forest disturbances can be caused by both natural causes (Thom & Seidl 2016), such as  
53 wildfires or insect outbreaks, and anthropogenic causes, such as selective logging and edge  
54 effects (Dantas de Paula et al. 2016; Matricardi et al. 2020), both of which can drive a forest to  
55 a ‘degraded’ state (Ghazoul et al. 2015; Chazdon et al. 2016). Edge effects include roads or  
56 nearby artificial land-use types that can reduce forest carbon biomass (Silva Junior et al. 2020)  
57 and affect local microclimates (Ewers & Banks-Leite 2013; Hardwick et al. 2015). Increasingly  
58 disturbed and degraded forests have become the focus of policy attention (Hansen et al. 2020;  
59 Newton et al. 2020), with a recent study having found that the amount of ongoing forest  
60 degradation already surpasses deforestation in the Brazilian Amazon (Matricardi et al. 2020).  
61 In addition to natural forest disturbance, many forests across the world are anthropogenically  
62 managed, for instance by active planting of forests for production of timber and non-timber  
63 products (Chazdon et al. 2016). Anthropogenically exploited trees and timber plantations cover  
64 most of western Europe, Southern China, Japan and America (Jung et al. 2020), and  
65 agroforestry has long been recognized as a traditional form of land management, often using

66 many native tree species (Zomer et al. 2016). Yet, the extent to which forest-associated  
67 biodiversity is exposed to different forest management types is unclear.

68 Owing to the reduction and simplification of structural complexity, disturbed and  
69 planted forests often have considerably lower biodiversity value (Chazdon et al. 2016).  
70 Disturbances and edge effects are commonly identified as a driver of worsening conditions in  
71 protected areas (Laurance et al. 2012), impacting local biodiversity (Pfeifer et al. 2017). And  
72 while (even exotic) forest plantations can potentially connect or form a tree-covered buffer  
73 around natural forest patches (Brokerhoff et al. 2008; Pellikka et al. 2009), there is mounting  
74 evidence that especially mono-culture plantations, such as pine or oil palm plantations, provide  
75 little or only reduced benefits for biodiversity (Farwig et al. 2008; Newbold et al. 2015).  
76 Although mixed, traditional management forms such as agroforestry can provide critical  
77 habitat (Hemp 2006; Bhagwat et al. 2008) and maintain a comparable high level of biodiversity  
78 (Jung et al. 2017), they also commonly have an altered species composition (Harvey &  
79 González Villalobos 2007). Yet, most current global forest pressure maps (Malhi et al. 2014;  
80 Lewis et al. 2015; Grantham et al. 2020) or frameworks for conservation or restoration  
81 assessments have ignored managed forests (Grantham et al. 2020; Hansen et al. 2020), or  
82 included them for a limited number of countries (Hill et al. 2019), presumably because of a  
83 lack of spatial data.

84 Remote sensing can assist in reliably identifying forest disturbances and management  
85 types. Fine-scale differences in remote sensing observations combined with visual evidence of  
86 selective logging or human structures nearby allow the separation of (visually) undisturbed  
87 from disturbed forests (Dantas de Paula et al. 2016; Curtis et al. 2018). Similarly, trees that  
88 were planted in regular spacing, such as timber or fruit plantations can be identified and  
89 delineated from high-resolution satellite imagery. Here previous studies have used single or  
90 multiple satellite observations to map the world's intact forests (Potapov et al. 2008), small-

91 scale disturbances caused by selective logging (DeVries et al. 2015) or regional gradients of  
92 different management (Pfeifer et al. 2016). Yet, until recently, no global remote-sensing  
93 derived maps of forest management types existed, with earlier attempts instead relying on  
94 several environmental predictors, little independent training or validation data (Schulze et al.  
95 2019), or only being available at coarse scale (Curtis et al. 2018). The Nature Map Initiative  
96 has produced a new global high-resolution layer describing not only undisturbed and disturbed  
97 forests, but also several types of forest management identifiable from remote sensing.

98 In this study we investigate the exposure of forest-associated biodiversity to different  
99 types of forest management globally. Specifically, we combine estimates of the distribution of  
100 forest-associated vertebrate species with a novel, remote-sensing derived global map of forest  
101 management for the year 2015 (Fig. 1). We hypothesize that *(i)* the distributional range of  
102 forest-associated species is to a large degree covered by forests that are either disturbed or  
103 under some form of forest management, *(ii)* species threatened by extinction or threats  
104 associated with disturbances or forest extraction are disproportionately affected by parts of  
105 their range covered by disturbed or managed forests, and that *(iii)* protected areas are  
106 increasingly established in forests that cannot be considered undisturbed. Collectively, these  
107 hypotheses would suggest that several forest-associated species are confined to marginal intact  
108 habitats and addressing the management of these forests is critical to revert global biodiversity  
109 declines and improve the ecological state of forests globally.

110

## 111 **Methods:**

112

113 Data on disturbed and planted forests came from a novel global forest management layer  
114 produced for the year 2015 at 100m resolution (Lesiv et al. submitted, 2020). The global forest  
115 management layer has in total six different classes, namely undisturbed (no visual signs of

116 human impact), disturbed (visual impacts such as selective logging, clear cuts or built-up roads  
117 and human structures), and replanted forest (with a rotation period longer than 20 years), as  
118 well as woody plantations (with a rotation period of up to 15 years) and oil palm plantations,  
119 and agroforestry (which includes fruit tree plantations, shelterbelts or isolated trees on tropical  
120 pastures). We stress that the identification of managed forests was limited to those forms that  
121 are visually identifiable by remote sensing. The forest management layer was created entirely  
122 from remote sensing, combining high resolution training data, satellite time series and machine  
123 learning and shows overall good accuracy (81%) with independent validation data. The layer  
124 is described in full elsewhere and we refer to (Lesiv et al. submitted, 2020) for a more detailed  
125 description.

126 From the forest management layer we only considered plantations that had at least 10%  
127 tree cover fraction according to the global Copernicus Land cover product (Buchhorn et al.  
128 2020) and following FAO definitions of forest. Opposed to other products of human impact on  
129 forests (Grantham et al. 2020), the forest management layer does not depend on any ‘scores’,  
130 stacking of arbitrarily selected land-use layers or definitions of ‘intactness’, but instead  
131 identifies forest management and disturbances directly from remote sensing. While this makes  
132 the mapped classes in our opinion more transparent, robust and replicable, we acknowledge  
133 that many forms of fine-scale forest disturbance can not reliably be detected from satellite  
134 imagery alone (Peres et al. 2006), which makes any estimates presented conservative.

135 For data on forest-associated vertebrate species distribution, we used spatial data on the  
136 ranges of amphibians (5,547), birds (8,434), reptiles (4,369, although we stress that not all  
137 reptiles globally have been assessed yet) and mammals (4,032) from the global IUCN Red List  
138 (ver 2019-2, (IUCN 2019)). We filtered the IUCN provided range data using standard criteria,  
139 e.g. by selecting only those parts of a species’ range where (i) it is extant or possibly extinct,  
140 2) where it is native or reintroduced and 3) where the species is seasonally resident, breeding,

141 non-breeding, migratory or where the seasonal occurrence is uncertain. Lastly, we limited our  
142 analyses only to those species that are ‘forest-associated’, which we define as any species for  
143 which ‘Forest’ is listed as known habitat preference according to IUCN. Lastly we obtained  
144 data on the threat status (e.g. CR, EN, VU, NT, LC, DD) of all selected species as well as -  
145 where available - data on IUCN listed threat types, such as for example ‘2.2 Wood & Pulp  
146 Plantations’ or ‘5.1 Hunting & trapping terrestrial animals’, which we broadly grouped into  
147 threat groups (See SI Table 1) and those with medium or high impact on a species.

148 In addition to data on the potential distribution of forest-associated vertebrate species,  
149 we also extracted similar statistics for all protected areas designated in or after 1995 available  
150 through the World Database on Protected Areas (IUCN & UNEP-WCMC 2020) from Google  
151 Earth Engine. We only selected established protected areas and furthermore excluded  
152 UNESCO-MAB Biosphere Reserves, following WDPA guidelines (Bingham et al. 2019).

153 We then summarized for each forest-associated species and protected area the amount  
154 of forest area (in ha) under each form of forest management. Protected areas which had no  
155 forest cover within their boundary were excluded from the analyses. To test whether forest area  
156 and management type differed among threatened (i.e. all CR, EN and VU) and non-threatened  
157 species, we used a logistic regression model fitted in a Bayesian framework using default  
158 uninformative priors (Bürkner 2018). Conditional model estimates were derived by  
159 summarizing the posterior in a mean estimate and 95% credible interval. We investigated  
160 model convergence by assessing the rhat statistic (all ~1.0) and the Markov chain Monte Carlo  
161 (MCMC) chains visually (SI Fig. 2). All data extractions and preprocessing were conducted on  
162 Google Earth Engine (Gorelick et al. 2017) and visualized in R (Wickham 2016; R Core Team  
163 2019).

164

165 **Results:**

166 About 55% of the world's forests were disturbed or managed in 2015. We found that 12,293  
167 forest-associated vertebrate species (or 55.5% of all considered species) had disturbed or  
168 human managed forests as the most common type of forest within their range (Fig. 2, SI Table  
169 2), and among reptiles, twice as many forest-associated species had most of their range now  
170 occupied by disturbed or planted forests (Fig. 2). Worryingly, forests within the ranges of 1,122  
171 forest-associated species were predominantly of woody and oil-palm plantation and  
172 agroforestry type (SI Fig. 1, SI. Tab. 1).

173 The amount of forest under different management types available to forest-associated species  
174 affected whether a species was classified as threatened by extinction. We found that an increase  
175 in forest area decreased extinction risk across all forest-associated species (SI Fig. 1). However  
176 species with a greater amount of undisturbed, disturbed and agroforestry forested areas in their  
177 range were more likely to be classified as non-threatened (Fig. 3a). In contrast, an increase in  
178 woody or oil palm plantation area did not decrease extinction risk probability nor did any  
179 difference in the amount of replanted forest (Fig. 3a). Species classified as non-threatened had  
180 overall larger amounts of undisturbed and disturbed forest within their range as well as a greater  
181 proportion of replanted small forest fragments present than for comparable threatened species  
182 (Fig. 3b, SI Fig. 3). Critically, the amount and distribution of forest area under different  
183 management types for data deficient species mirrored that of threatened species (Fig. 3b). If  
184 the distribution of unmanaged, disturbed and managed forests in a species range is any  
185 indication, this suggests that forest-associated data deficient vertebrate species are, in average,  
186 more likely to be at high risk of extinction than not.

187 Furthermore, we found that, for species with available threat information, disturbed  
188 forests were the most common forest management type (SI Fig. 4). Agroforestry tended to be  
189 more often the dominant type of forest management within the range of species threatened by  
190 wood harvesting, persecution and subsistence farming (SI Fig. 4). Interestingly, many species

191 which - according to IUCN - are strongly impacted by wood harvesting, did not have  
192 significantly more woody or fruit plantations in their ranges than the other forest management  
193 types.

194 Forests in terrestrial protected areas were under differing management types. Globally,  
195 protected areas contained 301 million ha of undisturbed forest (1.17% of all undisturbed forest),  
196 121 million ha disturbed forest (0.5% of all disturbed forest) as well as 36.1 million ha of  
197 planted or managed forest (0.3% of all managed forest). Yet, irrespective of any IUCN assigned  
198 category of protection, the dominant forest management type within protected areas was  
199 disturbed forest, followed by replanted and then undisturbed forests (Fig. 4a). Interestingly, the  
200 majority of new protected areas designated between the years 2000 and 2010 are dominated by  
201 disturbed and replanted forest in the year 2015 (Fig. 4b), while few protected areas  
202 predominantly contain undisturbed forest. Predictably, few protected areas were established  
203 over predominantly woody or fruit plantations, indicating that protection measures mainly  
204 aimed at conserving forest that is not under intensive use by humans.

205

206 **Discussion:**

207 Humans have altered the majority of forests across the world, with 55% of forests being either  
208 disturbed or managed by humans. Our results show that over half of the ranges of forest-  
209 associated vertebrate species across the world are covered by either disturbed or human  
210 managed forests (Fig. 2), with the amount being particularly high for species threatened by  
211 extinction (Fig. 3). Furthermore, we show that many designated protected areas are already  
212 dominated by disturbed and replanted forests (Fig. 4), highlighting both the value of past forest  
213 restoration measures as well as the need to step up protection of remaining undisturbed forests.

214 Replanting forest is considered to be a primary target for restoring degraded habitats.

215 Interestingly, our results indicate that increasing or decreasing the amount of planted forest

216 within forest-associated species ranges has little influence on whether the species is currently

217 classified as threatened by extinction (Fig. 3). This could indicate that most previous forest

218 restoration efforts have either not yet explicitly benefitted forest-associated vertebrate species,

219 or lag effects due to outdated IUCN assessments or past land use change affect the conservation

220 status (Chazdon et al. 2008; Jung et al. 2019; Veldman et al. 2019). For example, areas

221 previously covered by native tree species in Kenya have been increasingly afforested using

222 exotic pine trees, often with little benefit for native species (Farwig et al. 2008; Pellikka et al.

223 2009). Human planted forests are not necessarily bad for biodiversity (Carnus et al. 2006), they

224 are in fact essential if we are to subject large tracts of degraded, previously forested land to

225 habitat restoration (Chazdon 2008; Chazdon et al. 2008) and climate mitigation efforts. Yet

226 those planted forests need to be established in places where they do not displace natural

227 habitats, such as forests or savannas (Veldman et al. 2019), or native tree species, and do not

228 negatively impact the livelihood of local communities in developing countries (Malkamäki et

229 al. 2018). Thus, further afforestation and reforestation efforts should be carefully evaluated

230 with regards to local contexts and their potential benefits for biodiversity conservation.

231 Our results also have important implications for conservation applications that use

232 species habitat preferences and land-cover maps to refine species ranges to Area of Habitat

233 (AOH) maps (Brooks et al. 2019). Because, most existing AOH use exclusively land cover

234 products (Rondinini et al. 2011; Ficetola et al. 2015), thus ignoring forest management, it

235 follows that AOH might be grossly overestimated if populations of forest-associated species

236 are not able to persist in disturbed or managed forests. Novel hybrid maps have been developed

237 that alleviate some of these issues by accounting for both land-cover and land-use (Jung et al.

238 2020), however, these maps do not thematically consider all possible forms of management

239 that might be relevant for ecological or conservation studies. We suggest that more evidence is  
240 needed on the persistence of forest-associated species in disturbed and managed forests to  
241 ensure that maps of habitat-based refinements are fit for purpose.

242 While the global forest management map is the most detailed spatial-explicit  
243 quantification to date, we acknowledge that not all forms of anthropogenic disturbances can  
244 likely be detected from remote sensing (Peres et al. 2006), thus our estimates will likely be an  
245 underestimate. This is exemplified by the fact that although many forest-associated species are  
246 known to be sensitive to anthropogenic threats (Maxwell et al. 2016), we found few differences  
247 between species threatened by disturbances or wood harvesting (SI Fig. 4). We can also not  
248 rule out that some types of forests have been misclassified, which can impact our analyses  
249 (Sexton et al. 2016; Estes et al. 2018). Furthermore, we also highlight that our analysis does  
250 not take into account species occurrence and relative abundance across forest management  
251 types (we performed only range overlaps) and many - particularly disturbance sensitive -  
252 species do not necessarily inhabit all forests everywhere (Pfeifer et al. 2017). More work is  
253 needed on the impact of disturbances and wood harvesting on species local occurrence,  
254 population density and persistence, as well as more detailed mapping of forest management  
255 types at national and regional scales.

256 As we move into a decade of ecosystem restoration, we urge conservationists and policy  
257 makers to consider different types of forest management. Critically, ignoring forest  
258 management and focussing on forest cover alone, can give the misleading impression of no-  
259 net forest loss when in fact native, undisturbed forests are being replaced by woody plantations  
260 or getting disturbed (Tropek et al. 2014). With an increasing proportion of the Earth's forests  
261 being disturbed or managed, we need to better account for and investigate the impact of forest  
262 management on the persistence of species populations and the effectiveness of conservation  
263 efforts.

264 **Code availability** Code used for the analysis and extracted data will be made openly  
265 available upon acceptance <To be inserted >  
  
266 **Data availability** The global forest management layer will be made openly available as part  
267 of another article. Data on the distribution of vertebrate species and protected areas can be  
268 requested from the respective data providers, namely IUCN and Birdlife International. Data on  
269 threats status and existing threats are available from the IUCN Red List. Extracted data for each  
270 species is made available in SI Table 2 and the code repository.

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513

514 **Figure legends**

515 Fig. 1: Global map of forest management types at ~100m resolution. Insets highlight the (a)  
516 remaining undisturbed forest in the Atlantic Forest region, (b) planted forests in  
517 central and northern Europe and (c) undisturbed forest amid palm oil and fruit  
518 plantations in Malaysia and Indonesia. Background shows a half-transparent Digital  
519 Elevation Model.

520

521 Fig. 2: Dominant forest management type across all forested areas within each vertebrate  
522 species range. Numbered labels and x-axis show the total number of species. Colours  
523 and legend as in Fig. 1. Icons are public domain from phylopic.org

524

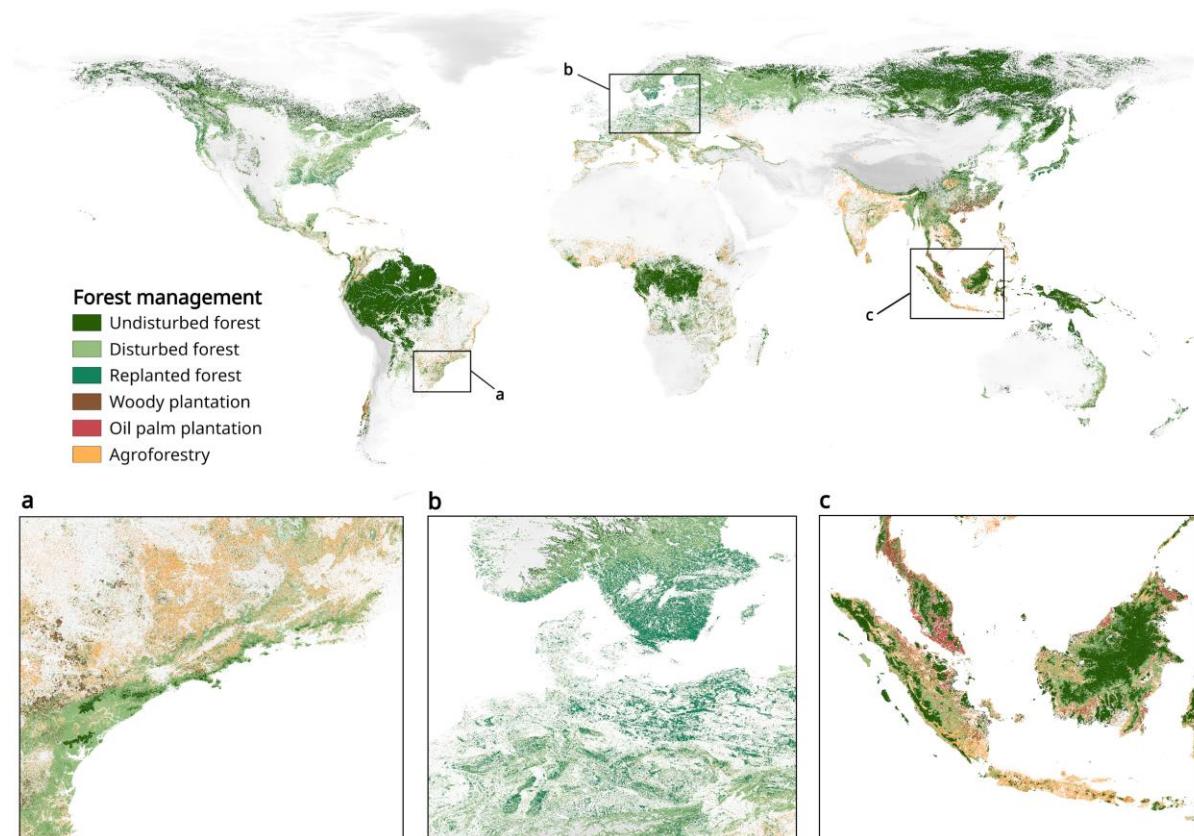
525 Fig. 3: Marginal effect of an increase in forest area (log-transformed) on extinction risk  
526 probability, i.e. the probability that a species is classified as threatened according to  
527 IUCN. (a) Lines are mean estimates sampled from the model posterior with  
528 uncertainty bands showing the 95% credible interval. (b) Distribution of log10-  
529 transformed forested area estimates across species with different threat statuses  
530 according to IUCN. Colours as in Fig. 1

531

532 Fig. 4: Dominant forest management type across (a) protected areas with different IUCN  
533 categorization and (b) number of newly designated protected areas in the last 25 years  
534 grouped by dominant forest management type. Colours as in Fig. 1.

535

536 **Figures**

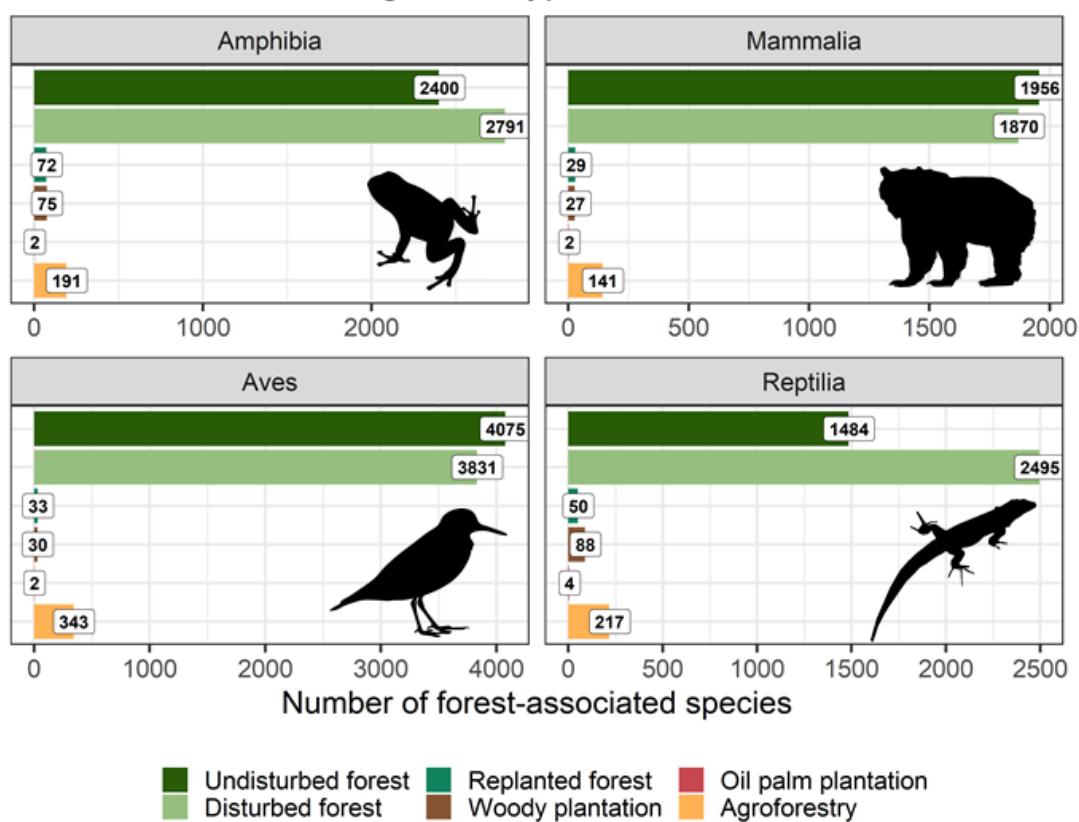


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538 *Figure 1: Global map of forest management types at ~100m resolution. Insets highlight the*  
539 *(a) remaining undisturbed forest in the Atlantic Forest region, (b) planted forests in central*  
540 *and northern Europe and (c) undisturbed forest amid palm oil and fruit plantations in*  
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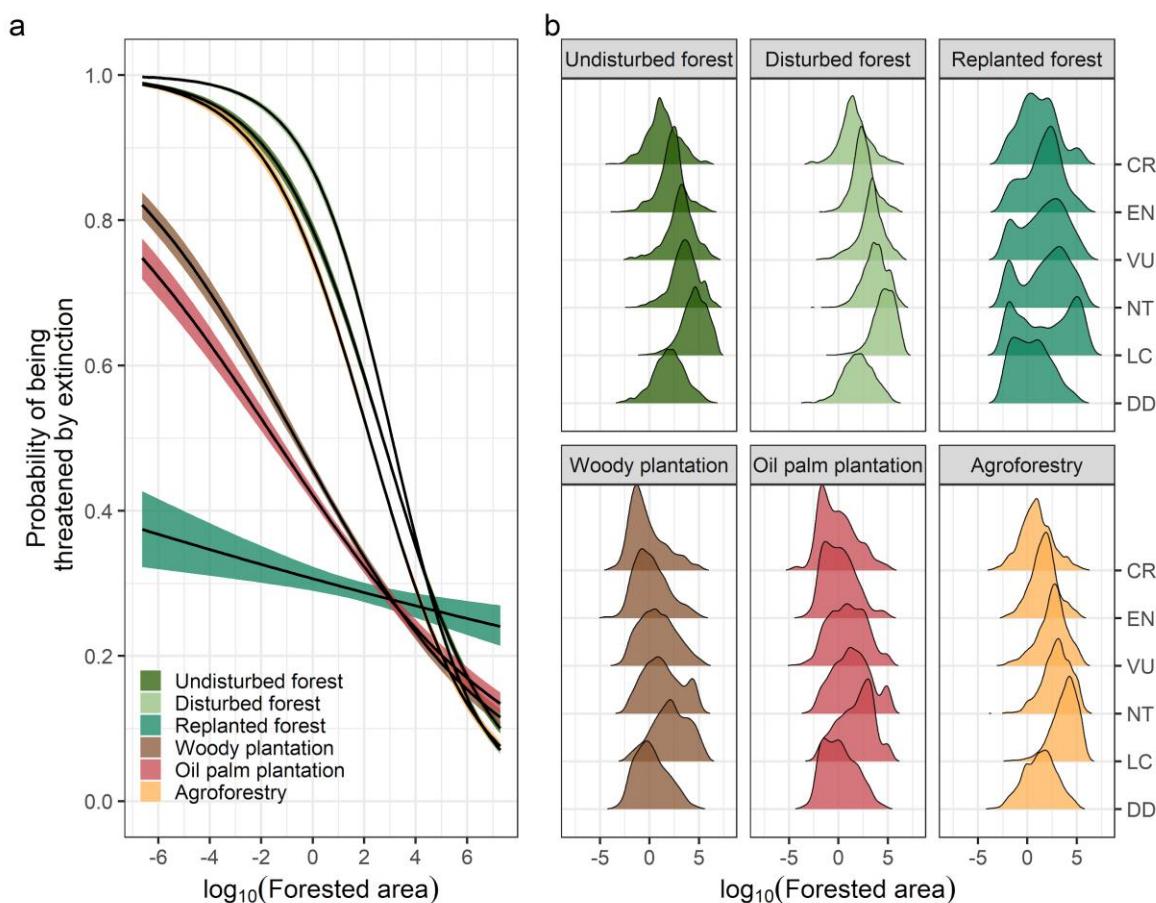
## Dominant forest management type



543

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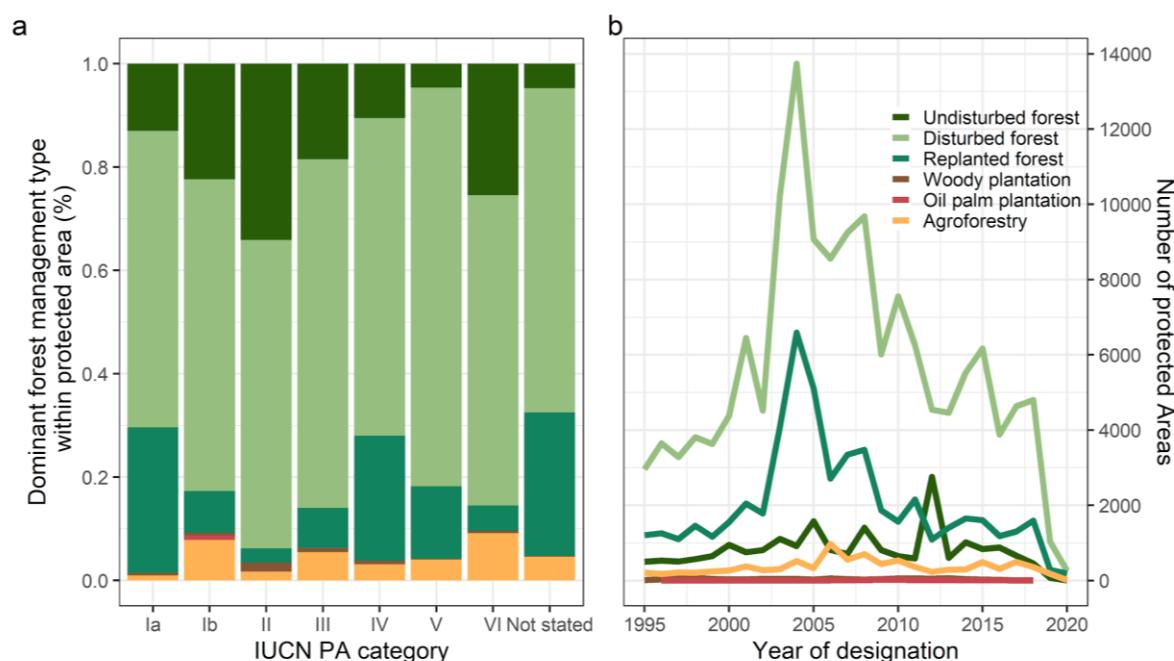


548

549 *Figure 3: Marginal effect of an increase in forest area (log-transformed) on extinction risk*

550 *probability, i.e. the probability that a species is classified as threatened according to IUCN.*

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552

553 Figure 4: Dominant forest management type across (a) protected areas with different IUCN  
554 categorization and (b) number of newly designated protected areas in the last 25 years  
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