

1 **Pathways of human development threaten biomes' protection and their**  
2 **remaining natural vegetation**

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21 economic pathways

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23 **Running title:** Threatening the remaining natural vegetation

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26

27 **Abstract**

28 Protected areas have been one of the most commonly applied conservation tools to prevent  
29 ecosystem degradation. International conservation targets have been created to incentivize  
30 widespread expansion of protected area networks, but this call might clash with expected  
31 future land use change. Here we investigated how future land use trajectories (2015-2090),  
32 representing a wide range of plausible future scenarios would impact the remaining areas of  
33 primary vegetation under different protection levels across the world's biomes. We then  
34 highlight areas under greater risk of conflict between conservation (highly protected) and  
35 land use expansion (high projected change), and areas where these two can better co-exist  
36 (lower protection with high projected change and/or high protection with low projected  
37 change).

38 While the most positive pathway of development led to the least loss of primary vegetation  
39 globally, this was not observed in all biomes. Further, we found no significant correlation  
40 between existing extent of protection and average proportion of vegetation loss.  
41 Mediterranean Forests, Woodlands & Scrub had the largest projected loss occurring in the  
42 highest protected areas. Tropical Forests in Central Africa and the Boreal Forests of North  
43 Euro-Asia and Canada emerge as the areas where most projected change occurs, and existing  
44 protection is still low. Areas in India and Southeast Asia emerge as potential areas for  
45 intervention as they have significant projected loss of primary vegetation, and considerably  
46 low protection.

47 Our results can help inform policy and decision-makers to prevent such conflicts and support  
48 the development of management actions. These policy and management actions should target  
49 conservation in areas under expected great pressure of change with high ecological value  
50 (e.g., composed mainly by primary vegetation), but still not protected. This study also opens  
51 the discussion to the future of current protected areas and to the potential to expand the  
52 existing network of protected areas.

53

54 **Introduction**

55 Humans have been degrading and shaping landscapes worldwide for many centuries  
56 (Ellis & Ramankutty, 2008). In fact, in 1700, nearly half of the terrestrial biosphere was wild,  
57 whereas by 2000, the majority of the terrestrial ecosystems was already converted into  
58 agricultural lands and settlements, leaving less than 20% of semi-natural areas and only a  
59 quarter left wild (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty, 2010). This trend  
60 of human modification of landscapes is expected to continue as human population keeps  
61 increasing and, as a consequence, so does the demand for agricultural and forest products  
62 (Boserup, 2017). Moreover, as humans convert natural habitats (Gibbs et al., 2010), the  
63 world's biomes and ecoregions become more degraded, jeopardizing these as habitats for  
64 species and hampering the benefits people derive from them (Díaz et al., 2018; Hoekstra,  
65 Boucher, Ricketts, & Roberts, 2005). A central challenge of achieving sustainability is,  
66 therefore, how to preserve natural ecosystems while enhancing food production (Lambin &  
67 Meyfroidt, 2011).

68 Protected areas have long been used as important conservation tools to prevent  
69 ecosystem degradation and preserve biodiversity and ecosystem services vital to sustain  
70 human livelihoods (Watson, Dudley, Segan, & Hockings, 2014). As such, the number of  
71 protected areas has increased greatly since the 1990s (Anthamatten & Hazen, 2015).  
72 However, the overall coverage of these areas is still rather low, i.e. roughly 12-13%  
73 (Anthamatten & Hazen, 2015; Brooks, Da Fonseca, & Rodrigues, 2004; Jenkins & Joppa,  
74 2009), reducing to 9.3% when considering well-connected protected areas (Saura, Bastin,  
75 Battistella, Mandriuci, & Dubois, 2017). There is, nonetheless, international pressure to  
76 increase this coverage, especially by the establishment of international conservation targets,  
77 such as the Aichi Targets, specifically Target 11, which states that by 2020 at least 17% of  
78 terrestrial areas are conserved through well-connected systems of protected areas  
79 (<https://www.cbd.int/sp/targets/>). This call to expand protected areas might clash with the  
80 expected expansion of agricultural lands for food production and other types of land use  
81 change.

82 The relationship between the effectiveness and the placement of these protected areas  
83 has been a great source of debate. Claims have been made that protected areas are often  
84 located in remote areas (Joppa & Pfaff, 2009), isolated and with low population densities  
85 (Baldi, Texeira, Martin, Grau, & Jobbág, 2017), thus using the landscape characteristics

86 (higher slope, further from roads and cities) to explain why they suffer less degradation  
87 (Schulze et al., 2018). Others, however, have shown the ‘pulling’ effect of these areas, with  
88 land cover change occurring closer to protected areas than in more distant unprotected lands  
89 (Guerra et al. in review). Simultaneously, it has been shown that pressure on protected areas  
90 has increased over time (Geldmann, Joppa, & Burgess, 2014), particularly in developing  
91 countries threatened by resource (over)exploitation (Schulze et al., 2018). Nonetheless, there  
92 is mounting evidence that protected areas have a positive influence in maintaining the natural  
93 habitats (Paiva, Brites, & Machado, 2015), and on their ability to sustain higher levels of  
94 biodiversity (Gray et al., 2016; Thomas & Gillingham, 2015); with the differences mostly  
95 attributable to differences in land use between protected and unprotected sites (Gray et al.,  
96 2016).

97 Thus, to maximize conservation outcomes, it is crucial to identify areas with the  
98 greatest potential to expand protected areas. Nevertheless, this comes with the risk of  
99 ineffective outcomes due to land use change and uncoordinated actions between countries  
100 (Pouzols et al., 2014). Previous studies have shown that under different scenarios of land use  
101 change it might become infeasible to achieve the 17% of terrestrial land protected, which  
102 when combined with increasing land use change threatens a high number of species (Pouzols  
103 et al., 2014). Also, a continued decline of primary vegetation lands within the areas  
104 surrounding protected areas is expected thus leading to an increasingly heterogeneous matrix  
105 of primary and human-modified landscapes (Beaumont & Duursma, 2012).

106 For the foreseeable future, the fate of terrestrial ecosystems and the species they  
107 support will continue to be intertwined with human systems, as most of the remaining natural  
108 areas are now embedded within anthropogenic mosaics of land use. However, the rate and  
109 location of land use change required to meet the demand for commodities are highly  
110 uncertain as it depends on the trajectories of development that might unfold in the future. In  
111 this regard, a set of Shared Socio-economic Pathways (SSPs), associated with the  
112 Representative Concentration Pathways (RCPs), have been developed by the climate  
113 science community (O’Neill et al., 2017, 2014; Van Vuuren et al., 2011). Working under the  
114 Intergovernmental Panel on Climate Change (IPCC) auspices, these SSPs and RCPs describe  
115 different scenarios of human development trajectories that would result in different climate  
116 futures based on land use change projections and greenhouse gas emissions over the 21<sup>st</sup>  
117 century (Popp et al., 2017; Riahi et al., 2017). In particular, the SSPs explore a wide range of  
118 scenarios on climate change mitigation and adaptation, on technological improvements, on

119 economic developments and population growth, covering a range of futures from a  
120 sustainable and environmentally-friendly world (SSP1) to a world continued to be dominated  
121 by fossil fuels (SSP5) (Riahi et al., 2017). Each SSP has its own storyline with associated  
122 projected land use change (Table 1), as described in (Popp et al., 2017).

123

124 **Table 1** – Short description of the five Shared Socio-economic Pathways (SSPs) storylines  
125 with particular focus on the associated consequences for land use change (adapted from Popp  
126 et al. 2017). For a detailed description of the narratives of each SSP, please see Popp et al.  
127 2017 and Riahi et al. 2017.

SSP Name	Short description
SSP1: sustainability - taking the green road	The world transitions gradually to a more sustainable path, focusing more on environmental friendly practices, and healthier diets. Land use regulation is enforced, and crop yields increase rapidly, leading to lower rates of conversion.
SSP2: middle of the road	The world does not shift significantly from historical patterns. Land use regulation is incomplete and crop yields slowly decline over time. Before 2030 there are no incentives towards avoided deforestation and afforestation.
SSP3: regional rivalry - a rocky road	The world evolves in an unsustainable manner, focusing on domestic production of food (with unhealthy diets) and energy. Land use regulation is practically non-existent and crop yields decline over time. Forest mitigation activities are limited.
SSP4*: inequality - a road divided	The world moves towards increasing inequalities, such as land use regulation and crop yields increase occur only in richer countries. Medium level of healthy diets and limited incentives for avoided deforestation and afforestation before 2030.
SSP5: fossil-fueled development - taking the highway	The world focus on technological improvements as a path to sustainability. Land use regulation is incomplete, but crop yields increase rapidly leading to lower conversion rates. Unhealthy diets focused on animal products consumption lead to high waste.

128 \* SSP4 has two land use projections based on two possible RCP combinations.

129

130 As a major driver of biodiversity and ecosystem services change, with significant  
131 impacts on climate and ultimately human well-being, is thus important to understand how  
132 current conservation areas might be impacted by these projections of future land use change.  
133 Therefore, the main objective of this study was to investigate how future land use trajectories,  
134 representing a wide range of plausible future scenarios (the five SSPs), would impact areas of

135 primary vegetation under different protection, across the world's biomes from 2015 through  
136 2090. With such analysis, we aimed to highlight areas under greater risk of conflict between  
137 conservation (highly protected) and land use expansion (high projected change), and areas  
138 where these two can better co-exist (lower protection with high projected change and/or high  
139 protection with low projected change). Such results could help inform policy and decision-  
140 makers to prevent such conflicts and support the development of management actions  
141 targeting conservation in areas under expected great pressure of change and high ecological  
142 value (e.g., composed mainly by primary vegetation), but still not protected (i.e., potential  
143 areas to expand existing network of protected areas).

144

## 145 **Methods**

### 146 *Input Data and Sources*

147 We used the land use projections provided by the dataset of the Land Use Harmonized  
148 v2.0 project (<http://luh.umd.edu/>) (Hurtt et al., 2011; Hurtt et al., 2016). The dataset, which  
149 was produced within the context of the World Climate Research Program Coupled Model  
150 Intercomparison Project (CMIP6), contains a harmonized set of land use scenarios that are  
151 consistent between historical reconstructions and future projections. In detail, it contains  
152 annual land use maps, produced by different integrated assessment models (IAMs) for each  
153 SSP, from 2015 through 2100 at 0.25° resolution, with the proportion of each pixel covered  
154 by each one of 12 land use classes (Table S1). In this study, we focused specifically on the  
155 loss of primary vegetation land (both forested and non-forested) given that protected areas are  
156 mainly implemented to protect pristine environments and not human-modified lands (Baldi et  
157 al., 2017; Paiva et al., 2015). The resolution of the land use time series dataset determined the  
158 spatial unit of analysis, and for each SSP we obtained a different time series of projected land  
159 use change according to the assumptions of each pathway (Table 1, see details in Riahi et al.,  
160 2017), and the model used to spatialize these assumptions (Popp et al., 2017). As we intended  
161 to focus our analysis only on the loss of primary vegetation, we aggregated the original land  
162 use classes into two: primary and modified as detailed in Table S1.

163 One limitation of our study is the fact that the categories of land use provided by the  
164 LUH2 project are spatially and descriptively coarse. Although these categories have greatly  
165 improved since LUH1 (Beaumont & Duursma, 2012), these still do not allow us to  
166 discriminate exactly the land use matrix within each 0.25 x 0.25° grid cell. This means that

167 our analysis is blind to the detailed spatial configuration of loss in primary vegetation, i.e.,  
168 whether a projected 10% loss in primary vegetation is adjacent to existing loss, or spread  
169 homogeneously across the grid cell.

170 Furthermore, we used the entire geodatabase of the World Database of Protected  
171 Areas (Brooks et al., 2004; Dubois et al., 2016), as of October 2018, to obtain the geographic  
172 location of all current protected areas in the world. From this dataset we produced a raster  
173 with the same extent and cell size as the land use dataset, containing the proportion of each  
174 grid cell that is covered by protected areas (regardless of its category of protection and not  
175 double-counting overlapping conservation status). We then classified each grid cell as  
176 belonging to one of the following five classes: 0 (no protection), 0-25%, 25-50%, 50-75%,  
177 >75% protected.

178 Finally, we used the biomes of the world (Figure S1) as made available by (Eric  
179 Dinerstein et al., 2017). From these data, we classified each of our  $0.25 \times 0.25^\circ$  grid cell as  
180 belonging to only one biome, according to the majority class that covered that grid cell. This  
181 step allowed us to segment our global analysis and further understand the distribution and  
182 trends associated with each biome. All subsequent analyses were performed using the three  
183 datasets described above: land use change, protected areas and biomes.

184

#### 185 *Land use change analyses*

186 We started our analyses by investigating the coverage of primary and modified areas  
187 in the present day (i.e., 2015) at the global scale, per biome and per class of protection. Next,  
188 we determined the proportion of primary and modified land that is under protection, as well  
189 as the average protection level of the grid cells within each biome. A correlation between the  
190 proportion of primary vegetation and proportion of protection was then tested for the  
191 hypothesis that higher protection classes would contain higher levels of primary vegetation.  
192 Such a hypothesis was assessed both globally and across biomes.

193 For each one of the SSPs investigated in this study, we assessed how much loss of  
194 primary vegetation is projected to occur, globally, per biome and per grid cell from 2015  
195 through 2090, using a decadal interval. Such analysis was performed considering the whole  
196 dataset (i.e., regardless of the level of protection), as well as stratified by the five protection  
197 classes described before, i.e., to assess whether the loss in primary vegetation across SSPs

198 was significantly different across classes of protection. The significance across biomes and  
199 protection classes was assessed using a non-parametric Kruskal-Wallis test and subsequent  
200 pairwise comparison Mann-Whitney U-tests, using the Bonferroni correction, where  
201 relevant, using the statistical programme R (R Core Team, 2018).

202 To assess trends over time (from 2015 through 2090 on decadal intervals), we then  
203 computed a temporal vector for each grid cell depicting the loss of primary land over time,  
204 and implemented a linear regression, accounting for temporal autocorrelation, i.e., using a  
205 GLS algorithm, to identify the speed of change associated to each grid cell. Finally, the  
206 median slope values of the regressions across SSPs were computed and compared with the  
207 values of protection by overlaying the two datasets. A similar procedure was followed to  
208 compare the speed of change with original primary vegetation extent at the grid cell level.  
209 Moreover, we accumulated the values of change (2015-2090) at the biome, scenario and  
210 global scales, to make the same assessment considering the accumulated values, rather than  
211 the local (grid cell) values.

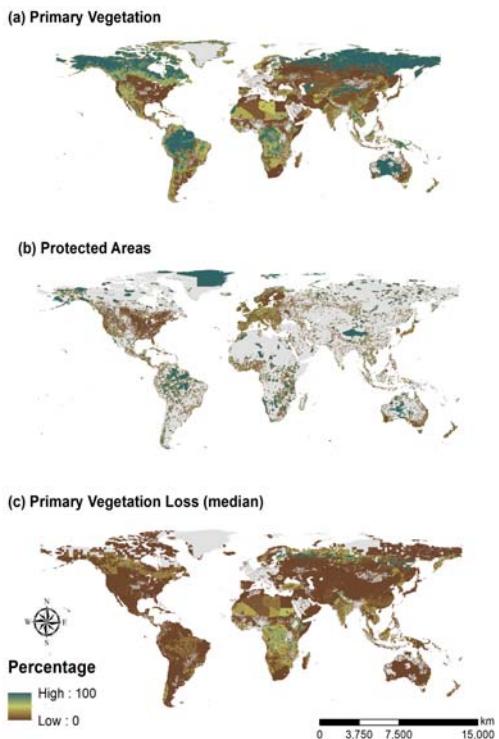
212

## 213 **Results**

### 214 *Distribution of protected areas and primary vegetation areas globally and across biomes*

215 We found that at the global scale by 2015, 14% of the land surface (excluding water  
216 bodies) was under some level of protection (Figure 1b, Table 2). Considering cells under  
217 protection, on average each grid cell included 16% of protected land (standard error [s.e.] =  
218 0.06%; Figure S2), with a highly skewed distribution of 61% of cells unprotected, 19% with  
219 under 25% of the land protected, and only 11% of the grid cells were highly protected  
220 (>75%). These proportions varied significantly across biomes (Kruskal-Wallis [KW] test;  $H$   
221 = 13,345, p-value <0.001), with the highest protection coverage in Montane Grasslands &  
222 Shrublands (27%), Flooded Grasslands & Savannas (25%), and Mangroves (24%) (Table 2).  
223 Only six out of the fourteen biomes had a protection coverage above the 17% Aichi Target,  
224 with Temperate Grasslands, Savannas & Shrublands being the least protected with only 4%  
225 (Table 2). If we analyse the protection of primary vegetation at the grid cell level, we found  
226 that the distribution of cells under different levels of protection was highly skewed towards  
227 unprotected or low protection (0-25%) globally, with again significant differences across  
228 biomes (KW test;  $H$  = 13,393, p-value < 0.001, Table 2). In this regard, the maximum  
229 proportion of unprotected cells occurred in Deserts & Xeric Shrublands (78%) and the

230 minimum in the Mangroves biome (35%). Contrarily, the highest proportion of highly  
231 protected cells (>75%) occurred in the biome Tundra (25%), and the minimum in Temperate  
232 Grasslands, Savannas & Shrublands (1%). On average, the highest protection coverage per  
233 grid cell was found in the Montane Grasslands & Shrublands (28%  $\pm$  0.32, s.e.), and the  
234 lowest values were found for Temperate Grasslands, Savannas & Shrublands (4%  $\pm$  0.03,  
235 s.e.) (Figure S2).



236

237 **Figure 1** – Percentage of the grid cell covered in (a) primary vegetation in 2015, (b)  
238 protected area and (c) median loss of primary lands across all SSPs by 2090, relative to 2015  
239 (individual losses per SSP are shown in Figure S3).

240 Considering our 2015 baseline (Figure 1a), we found that, at the global scale, there  
241 was a remaining 38% of areas considered as primary vegetation (forested or non-forested),  
242 and 62% of the land had been modified from its natural state. Further, we found a weak  
243 positive relationship ( $t$ -value = 2.99,  $p$ -value = 0.06) between protection level and proportion  
244 of natural areas (Table S2), i.e. more natural areas in higher protection cells. At the biome  
245 level, there was once again sharp differences, where Temperate Grasslands, Savannas &  
246 Shrublands was the biome with the lowest percentage of primary vegetation areas (8%), as  
247 opposed to Tundra that was the highest (88%) (Table 2). Within 57% of the biomes, there

248 was indeed a significant linear increase in the proportion of natural areas when considering  
249 the protection level (Table S2). However, such coverage varied greatly when analyzed by  
250 class of protection (Table 2), both globally and per biome. The average proportion of natural  
251 areas per biome varied significantly both without considering the protection level (KW test;  
252  $H = 35,245$ , p-value < 0.001), and when considering the cell protection (KW test;  $H = 57,812$ , p-value <0.001). In nine out the fourteen biomes, primary vegetation areas were  
253 found in greater proportion than modified areas in the highly protected grid cells. On the  
254 other hand, in two biomes (Tundra and Boreal Forests/Taiga) primary vegetation areas were  
255 observed in higher proportion in unprotected cells.

257 **Table 2** – Percentage (%) of biome currently protected or considered primary vegetation, as a  
258 whole, as well as considering only the area under different protection classes (from  
259 unprotected [0] to more than 75% protected [>75]).

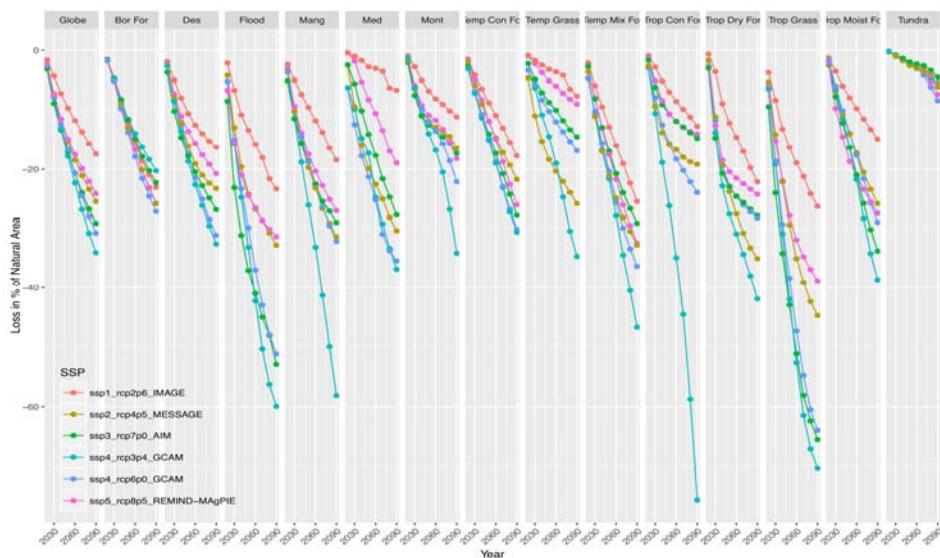
Biome Name	Use	Whole	0	0-25	25-50	50-75	>75
Tropical & Subtropical Moist Broadleaf Forests	Protected	22.34	50.6	21.82	7.4	5.27	14.91
	Primary	54.04	46.10	44.28	59.35	73.90	89.18
Tropical & Subtropical Dry Broadleaf Forests	Protected	9.49	63.52	23.4	5.97	3.49	3.62
	Primary	37.41	34.53	34.98	51.03	61.32	73.62
Tropical & Subtropical Coniferous Forests	Protected	13.27	49.95	30.97	8.48	5.62	4.98
	Primary	46.29	46.73	38.54	50.89	61.63	69.18
Temperate Broadleaf & Mixed Forests	Protected	12.19	36.66	45.39	9.65	4.73	3.58
	Primary	16.72	17.94	15.13	17.32	18.97	30.93
Temperate Conifer Forests	Protected	17.07	38.56	37.19	10.23	6.29	7.72
	Primary	36.53	34.70	38.83	34.56	35.26	46.35
Boreal Forests/Taiga	Protected	10.7	70.44	15.82	3.91	2.87	6.96
	Primary	64.6	68.43	51.38	62.58	71.32	83.37
Tropical & Subtropical Grasslands, Savannas & Shrublands	Protected	14.47	65.86	16.21	4.8	3.4	9.73
	Primary	28.73	26.85	19.98	32.56	40.03	51.43
Temperate Grasslands, Savannas & Shrublands	Protected	4.22	65.74	28.76	2.93	1.25	1.32
	Primary	8.07	8.16	5.69	15.31	24.80	38.03
Flooded Grasslands & Savannas	Protected	24.92	54.34	15.93	6.96	5.35	17.42
	Primary	25.54	16.18	24.51	26.73	31.30	54.37
Montane Grasslands & Shrublands	Protected	27.4	53.68	14.42	4.91	4.49	22.5
	Primary	20.01	16.72	21.04	31.25	34.43	23.04
Tundra	Protected	10.35	66.26	4.57	2.33	2.11	24.72
	Primary	88.47	96.26	82.15	86.72	87.72	95.51
Mediterranean Forests, Woodlands & Scrub	Protected	17.53	35.56	39.03	12.5	6.59	6.32
	Primary	17	19.36	11.15	22.05	26.44	26.41
Deserts & Xeric Shrublands	Protected	10.95	77.94	9.11	2.88	2.26	7.81
	Primary	31.29	28.53	28.43	37.38	44.69	57.46

	Protected	24.16	35.25	30.38	12.64	8.87	12.86
Mangroves	Primary	29.99	29.00	31.14	48.93	54.31	61.35
Globe	Protected	14.20	61.30	19.23	5.07	3.40	11.00
	Primary	38.25	29.00	31.14	48.93	54.31	61.35

260

261 *Projected changes in primary vegetation areas (2015-2090) globally and per biome*

262 Each of the five scenarios of land use change (SSPs) led to an overall loss of primary  
263 vegetation areas from 2015 through 2090 (Figure 2, Table 3). At the global scale, this loss  
264 varied between -17.4% in SSP1 to -34.1% in SSP4 (RCP3.4), with an average of -26.84%  
265 (2.39% s.e.) across all scenarios (Figure 1c shows median value across all SSPs, whereas  
266 Figure S3 shows accumulated change in each individual SSP). Over time, when accumulated  
267 globally, the speed of primary vegetation loss (slope of regression,  $\beta$ ) is sharper in SSP4  
268 (RCP3.4) and slower in SSP1 ( $\beta = -0.45$  and  $\beta = -0.22$ , respectively), and the same was  
269 observed when considered the local (grid cell average) values ( $\beta = -0.50$  and  $\beta = -0.32$ ,  
270 respectively, Figure S4). Further, this loss was higher in pixels with an initial higher  
271 proportion of primary vegetation in 2015 ( $t = 180.03$ ,  $df = 258,540$ ;  $p$ -value < 0.001).



273 **Figure 2** – Decadal loss in primary vegetation until 2090, relative to 2015 (in %), globally  
274 and per biome, for each of the five land use scenarios (SSPs). Full biome names, Trop Mois  
275 For: Tropical & Subtropical Moist Broadleaf Forests; Trop Dry For: Tropical & Subtropical  
276 Dry Broadleaf Forests; Trop Con For: Tropical & Subtropical Coniferous Forests; Temp Mix  
277 For: Temperate Broadleaf & Mixed Forests; Temp Con For: Temperate Conifer Forests; Bor  
278 For: Boreal Forests/Taiga; Trop Grass: Tropical & Subtropical Grasslands, Savannas &

279 Shrublands; Temp Grass: Temperate Grasslands, Savannas & Shrublands; Flood: Flooded  
280 Grasslands & Savannas; Mont: Montane Grasslands & Shrublands; Med: Mediterranean  
281 Forests, Woodlands & Scrub; Des: Deserts & Xeric Shrublands; Mang: Mangroves.

282

283 We found strong variations across biomes within each scenario (KW test; average  $H =$   
284 54,510, 3596 s.e., p-value < 0.001) and across scenarios within each biome (KW test; average  
285  $H = 6,664, 2805$  s.e., p-value < 0.001). The projected change in primary vegetation across  
286 SSPs, varied from a minimum of -76% in SSP4 (RCP3.4) in Tropical & Subtropical  
287 Coniferous Forests, Savannas & Shrublands to a maximum of -4.5% in SSP3 in Tundra  
288 (Table 3). On average, Tundra is the least impacted biome (-6.25%, 0.58 s.e.), whereas  
289 Tropical & Subtropical Grasslands, Savannas & Shrublands is the highest impacted biome (-  
290 51.7%, 7.2 s.e.). As expected, both globally and in all but two biomes (Tundra and Boreal  
291 Forests/Taiga), SSP1 was the least harmful scenario, and interestingly, SSP1 was not the best  
292 scenario for the two most highly protected biomes (Tundra and Boreal Forests), where SSP4  
293 (RCP3.4) led to fewer losses (Figure S3 and S4).

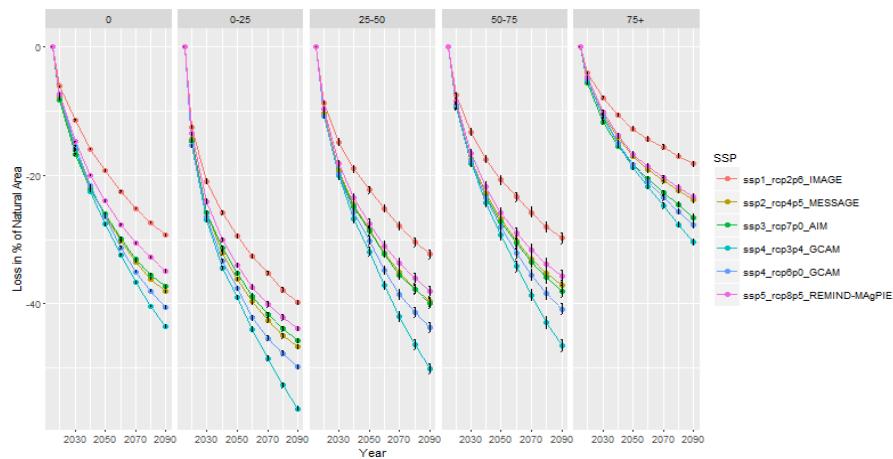
294 **Table 3** – Loss in primary vegetation area in each of the land use scenarios, relative to 2015  
295 (in %), per biome and globally.

Biomes	SSP1	SSP2	SSP3	SSP4a	SSP4b	SSP5
Tropical & Subtropical Moist Broadleaf Forests	-14.89	-25.82	-33.82	-38.72	-28.98	-27.45
Tropical & Subtropical Dry Broadleaf Forests	-22.13	-35.11	-27.82	-41.93	-28.27	-24.25
Tropical & Subtropical Coniferous Forests	-12.74	-19.16	-14.77	-75.74	-23.94	-14.03
Temperate Broadleaf & Mixed Forests	-25.44	-32.82	-29.14	-46.72	-36.41	-32.47
Temperate Conifer Forests	-17.72	-21.74	-27.79	-30.64	-30.16	-26.01
Boreal Forests/Taiga	-23.07	-25.83	-22.29	-20.28	-27.15	-25.76
Tropical & Subtropical Grasslands, Savannas & Shrublands	-26.27	-44.74	-65.61	-70.40	-64.07	-38.89
Temperate Grasslands, Savannas & Shrublands	-7.65	-25.81	-14.51	-34.75	-16.84	-8.99
Flooded Grasslands & Savannas	-23.36	-32.82	-52.88	-59.93	-51.24	-31.41
Montane Grasslands & Shrublands	-11.15	-16.41	-17.30	-34.20	-22.12	-18.21
Tundra	-5.67	-6.11	-4.48	-5.46	-8.42	-7.37
Mediterranean Forests, Woodlands & Scrub	-6.66	-30.40	-27.71	-36.92	-35.47	-18.92
Deserts & Xeric Shrublands	-16.25	-23.28	-26.83	-32.63	-31.15	-20.75
Mangroves	-18.41	-31.39	-29.01	-58.14	-32.16	-27.00
Globe	-17.40	-25.47	-29.15	-34.09	-30.79	-24.14

296

297 *Projected changes in natural areas (2015-2090) globally and per biome considering*  
298 *protection*

299 When considering the protection level of each grid cell we found that the areas under  
300 greatest threat of conversion are mostly located in the unprotected and 0-25% categories  
301 (Figure 3), although there was still a large proportion of change in the highly protected areas  
302 (varying from -18% to -30%, in SSP1 and SSP4a, respectively). Further, there was no  
303 significant correlation found between protection coverage and average proportion of  
304 vegetation loss ( $t = 1.83$ ,  $df = 258,540$ ;  $p\text{-value} = 0.07$ ).



305

306 **Figure 3** – Decadal average loss until 2090 (relative to 2015 in %) within each scenario of  
307 land use change (SSPs) considering the protection coverage of each grid cell.

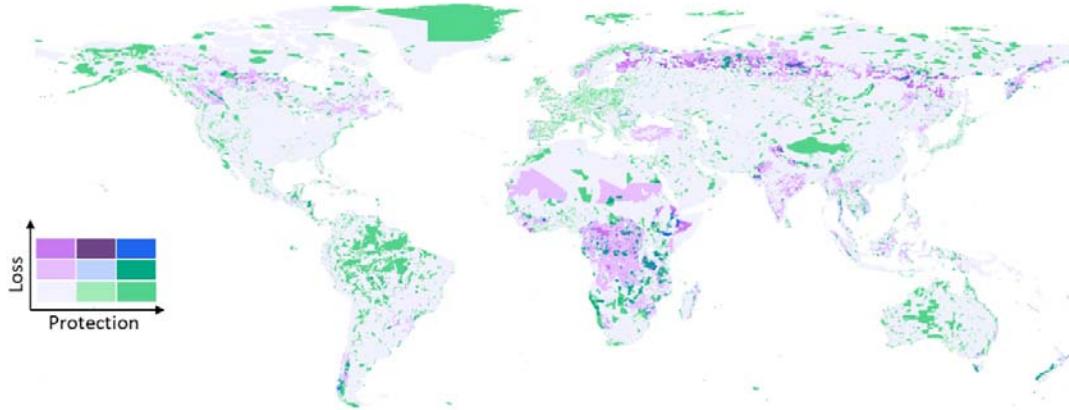
308

309 When averaging the overall change between 2015 and 2090 (across all scenarios), we  
310 found significant differences across biomes and protection level (Table S3). In detail, in the  
311 majority of the biomes the protection class with the highest projected loss in primary  
312 vegetation is either unprotected (in 7 out of 14 biomes) or low protection (0-25%, in 5 out of  
313 14 biomes). In the Mediterranean Forests, Woodlands & Scrub the largest projected loss  
314 occurred in the highest protected grid cells, despite comprising the lowest proportion of cells  
315 in the Biome with only 6.32% of the grid cells falling in this protection category (Table 2).

316 Finally, in order to highlight areas for intervention to prevent projected losses from  
317 occurring, we overlapped the overall (and trend) in projected primary vegetation loss (2015-  
318 2090), with the protection class (Figure 4). We found that the Tropical Forests in Central

319 Africa and the Boreal Forests of North Euro-Asia and Canada emerge as the areas where  
320 most projected change occurs in areas where existing protection coverage is still low.  
321 Similarly, areas in India and Southeast Asia emerge as potential areas for intervention as they  
322 have significant projected loss of primary vegetation, and considerably low (0-25%)  
323 protection.

324



325

326

327 **Figure 4** – Projected primary vegetation loss (median across SSPs, individual results for each  
328 SSP in Figure S5) from 2015 through 2090, overlapped with proportion of protected (0-25%,  
329 25-75%, >75%).

330

### 331 **Discussion**

332 Despite international conservation efforts, particularly in relation to the expansion of  
333 protected areas worldwide (Thomas & Gillingham, 2015), we have been unable to slow down  
334 the destruction of natural habitats, as recently highlighted by the IPBES Global Assessment  
335 (Díaz et al., 2019) and the near real time monitoring platform for forests, Global Forest  
336 Watch (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018). One of the key elements of  
337 biodiversity targets is the ability to preserve environmental representativeness, which has not  
338 driven protected area expansion, with the focus placed on factors such as low productive  
339 value, population and tourism (Baldi et al., 2017). The presence of natural areas (primary  
340 vegetation) was highly skewed towards certain biomes (most under the desired 17% protected  
341 coverage Aichi Target), and according to the modelled data used in our study, the weak

342 relationship between the extent of the remaining natural areas and the extent of protection  
343 across biomes, suggests that we are endangering the representativeness of all biomes (as  
344 desired by the Aichi targets). These regions include some of the most biologically distinctive,  
345 species-rich ecosystems on Earth, such as tropical forests, thus compromising the  
346 preservation of genetic resources from a wide variety of life on Earth. Further, as highly  
347 protected cells tended to contain larger proportions of natural areas, the remaining natural  
348 areas of the world are becoming confined to current protected areas. This pattern highlights  
349 the need to ensure the efficacy of these areas in preventing further degradation, which has not  
350 always been the case (e.g., Rosa, Rentsch, & Hopcraft, 2018; Soares-Filho et al., 2010).  
351 Further, there is a dichotomy between proportion of area covered and ‘connectivity’ of the  
352 protected areas network, for instance, biomes such as Temperate Grasslands, Savannas &  
353 Shrublands emerged as having a high proportion of coverage (almost a quarter), but very  
354 fragmented, with a low proportion of full protected grid cells (1%), suggesting low  
355 connectivity (Saura et al., 2017).

356 As we essentially failed to achieve the targets proposed by the CBD by 2020  
357 (Amengual & Alvarez-Berastegui, 2018), the new conservation agenda, at the global scale, is  
358 under discussion, with a great focus on restoring degraded ecosystems. For instance, the UN  
359 declared 2021-2030 as the Decade for Ecosystem Restoration, and recent studies (Bastin et  
360 al., 2019) state that planting forests (afforestation) would be the cheapest solution to address  
361 climate change. Nevertheless, it is critical to aid restoration with the preservation of the  
362 remains of natural vegetation as these contain the highest biodiversity levels (Newbold et al.,  
363 2015), genetic diversity, bank seeds, even in small patches (Wintle et al., 2019).  
364 Independently of the scenario followed, the current human development trajectories all lead  
365 to further primary vegetation loss. Despite numerous studies drawing attention to the  
366 disparities in habitat loss and protection (Hoekstra et al., 2005), and showing that halting  
367 agricultural expansion, increasing agriculture efficiency, shifting diets and reducing waste  
368 (Foley et al., 2011; Lambin & Meyfroidt, 2011), would greatly help preserve existing  
369 habitats, the climate change community still largely ignores these aspects in their ‘most  
370 positive’ views of the world. Moreover, the recent IPBES call for transformative change in  
371 our society to preserve global biodiversity, make these novel visions (Rosa et al., 2017)  
372 influencing human development critically needed for our sustainability. In this context, our  
373 results show that even under the best possible scenario (SSP1) we will continue the  
374 ‘anthropogenization’ of our world (Ellis et al., 2010). This means that further biodiversity

375 loss is unavoidable unless we act now to prevent further expansion of land use into natural  
376 ecosystems (Pouzols et al., 2014).

377 Serious efforts to conserve the remaining 38% of natural areas need to target regions  
378 of the world where land use change is expected to happen, thus avoiding or minimizes the  
379 chances of that change to occur (pro-active rather than reactive conservation). On the one  
380 hand, tropical forests in Central Africa and Southeast Asia, as well as natural vegetation in  
381 India, emerge as highly likely to be destroyed (under all scenarios) and where protection  
382 coverage is still low. As land use is a highly locked-in process (Guerra et al. under review),  
383 i.e. once it changes it rarely reverses, this is the moment to rally internationally, support these  
384 nations, and act before we lose these amazingly rich biodiversity hotspots. On the other hand,  
385 Boreal forests, which still have low protected coverage (11%), are likely to undergo extensive  
386 land use change particularly under more ‘aggressive’ scenarios. Such areas may experience  
387 even more important biological loss under the context of climate change, with impact on  
388 species distribution (Tuanmu et al., 2013) and on carbon sequestration (Melillo et al., 2016).

389 Recent calls for more ambitious conservation targets (Mace et al. 2018), including to  
390 protect half of the Earth’s land area (Dinerstein et al., 2019; Dinerstein et al., 2017), seem  
391 unlikely under the projected changes and given that we failed to achieve existing ones. This is  
392 further highlighted by our inaction to address head-on the issue of feeding a growing  
393 population with current dietary requirements (Mehrabi et al. 2018) or the teleconnections of  
394 dispersed impacts between regions of the globe (Marques et al., 2019). More than defining  
395 new area-based targets, a new paradigm that explicitly connects targets with indicators of  
396 desired conservation outcomes (Barnes et al., 2018) needs to account for the expected  
397 conflict between land use change (Wolff et al. 2018), protection of remaining native  
398 vegetation, and restoration of degraded ecosystems under climate change. Apart from  
399 improving the efficacy of existing protected areas, new conservation and restoration  
400 mechanisms need to be developed to address this wicked challenge. Independently, proactive  
401 conservation of the remaining natural vegetation is key to ensure the preservation of  
402 biological diversity, aid the recovery of degraded habitats, and help to mitigate climate  
403 change.

404

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