

1 Forest change within and outside protected
2 areas in the Dominican Republic, 2000-2016

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13 Abstract

14 We used Landsat-based estimates of tree cover change to document the loss and gain
15 of forest in the Dominican Republic between 2000 and 2016. Overall, 2,795 km² of forest were
16 lost, with forest gain occurring on only 393 km², yielding a net loss of 2,402 km² of forest, a
17 decline of 11.1% or 0.7% per year. Deforestation occurred in all of the major forest types in the
18 country, and ranged from a 13% decline in the area of semi-moist broadleaf forest to a 5.9%
19 loss of cloud forest, mostly attributed to agriculture. Fire was a significant driver of forest loss
20 only in Hispaniolan pine (*Pinus occidentalis*) forests and, to a lesser extent, in adjacent cloud
21 forest. Deforestation rates were lower within protected areas, especially in dry and semi-moist
22 broadleaf forests at lower elevations. Protected areas had a smaller, and generally negligible,
23 effect on rates of forest loss in pine forest and cloud forest, largely due to the effects of several
24 large wildfires. Overall, rates of deforestation in the Dominican Republic were higher than
25 regional averages from across the Neotropics and appeared to have accelerated during the
26 later years of our study period. Stemming deforestation will likely require enforcement of
27 prohibitions on large-scale agricultural production within protected areas and development of
28 alternatives to short-cycle, shifting agriculture.

29 Introduction

30 Human well-being is linked inextricably with the fate of the planet's forests. Forests
31 provide goods and income to the rural poor throughout the developing world [1], generate
32 employment for more than 10 million people throughout the world [2], yield renewable flows of
33 raw materials for commercial and domestic use, sustain stable flows of clean water [3,4], buffer
34 against local extremes of climate [5], and regulate global climate and carbon cycles [6,7].
35 Indeed, the very persistence of modern human societies may be incompatible with the
36 conditions created by ongoing deforestation [8]. The survival of an uncounted number of non-
37 human species also depends on the persistence of forested landscapes.

38 Efforts to conserve Earth's remaining forests, and to understand the consequences of
39 their disappearance, demand estimates of where, and at what rate, forest loss is occurring
40 [9,10]. Reliable national-level data on forests is urgently needed to inform policies on forest
41 conservation, sustainable development, and climate-change mitigation. A significant contribution
42 to these efforts was made by Hansen et al. [9], who provided satellite-based estimates of global
43 forest cover at a relatively fine temporal and spatial scale. Those data have been used
44 subsequently to generate regional estimates of deforestation [11], estimates of loss of specific
45 forest types [12], and country-specific descriptions of forest change [13]. Although analyses at
46 planetary and regional scales provide useful insights for efforts to limit the deleterious
47 consequences of global change [14] or meet global sustainable development goals [15],
48 smaller-scale analyses, especially at the national or sub-national level, are useful because they
49 align more closely with the level at which policies on forest use and conservation are
50 implemented. Thus, country-specific analyses of deforestation allow for the evaluation of the
51 efficacy of conservation interventions and, ideally, implementation of adaptive changes as
52 needed.

53

54 Here, we examine spatial and temporal patterns of change in forest cover in the
55 Dominican Republic (DR) between 2000 and 2016 using Hansen et al.'s [9] forest-cover dataset
56 and its annual updates. In particular, we document changes in the extent of forest cover, by
57 forest type, and examine the efficacy of the nation's system of protected areas - the country's
58 primary conservation tool - in stemming forest loss. We focused on the DR for several reasons.
59 First, as a middle-income country, it is broadly reflective of the changing dynamics and
60 challenges faced globally in conserving forests in developing countries experiencing rapid
61 economic growth: the DR's average economic growth of 5.3% over the past 25 years has been
62 among the strongest in Latin America and the Caribbean [16]. Second, it supports an
63 outstanding number of forest-dependent endemic plants and animals [17,18], many of which are
64 threatened with extinction [19]. Third, very little published, quantitative information exists on the
65 status of forests in the DR. Only two studies have produced quantitative estimates of change in
66 forest cover [20,21], and none that we are aware of have produced estimates specific to the
67 different forest types in the country. In quantifying recent changes in the extent of different forest
68 ecosystems in the DR, we hope to provide an initial evaluation of forest-specific conservation
69 policies, identify spatial hotspots of deforestation and forest types at greatest risk, and to
70 suggest fruitful areas for investment of conservation resources.

71 **Methods**

72 **Quantifying forest change**

73 We estimated annual changes in forest cover in the DR between 2000 and 2016 using
74 version 1.4 of the Hansen et al. [9] tree cover data, accessed through the Google Earth Engine
75 [22]. The baseline year for these data is 2000, at which time percent tree cover was estimated in
76 every 30-m pixel. Tree cover was defined by Hansen et al. [9] as all vegetation >5 m tall. In
77 each subsequent year, every pixel can either remain in a forested state or undergo
78 deforestation, which is defined as the transition to an entirely unforested state at the Landsat
79 pixel level. Partial removal of forest canopy is not considered loss in the scope of this analysis.
80 Forest gain, conversely, is defined as the transition from unforested to >50% tree cover during
81 the period 2000-2012; forest gain is not calculated on an annual basis nor does it include
82 regrowth after 2012. We used the per-pixel estimate of tree cover in 2000 as our baseline such
83 that our estimates of the area of forest cover lost or gained are corrected for initial conditions.
84 For example, a pixel (900 m²) that was estimated to have had 25% tree cover in 2000, and that
85 was identified as having been deforested between 2000 and 2016, was calculated to have
86 contributed a loss of 225 m² of forest (i.e., total pixel area multiplied by the percent of forest
87 cover in 2000).

88 We calculated change in the extent of forest in two ways. First, we estimated change
89 from 2000-2016 for all areas identified as forested in 2000 by Hansen et al. [9]. This provides a
90 broad overview of changes in tree cover across the country, including not only in natural forest
91 but also in heavily managed areas like forested parks in urban areas or agroforestry plantations.
92 To gain insight into patterns of change in naturally forested areas, we also generated separate
93 estimates of change for each major forest type identified in the 1996 land-cover map of

94 Tolentino and Peña [23], which provides the only pre-2000 estimate of land-cover types across
95 the country. For this portion of the analysis, we focused only on natural, unmanaged forests,
96 thus excluding urban parks, tree plantations (e.g., mango [*Mangifera* spp.], coconut [*Cocos*
97 *nucifera*], and oil palm [*Elaeis guineensis*]), and shade crops (e.g., coffee [*Coffea arabica*] or
98 cacao [*Theobroma cacao*]).

99 The forest types considered in the second analysis include Hispaniolan pine (*Pinus*
100 *occidentalis*) forest, which was classified by Tolentino and Peña [23] into both an open (“bosque
101 conífera abierto”) and closed-canopy (“bosque conífera denso”) category; cloud forest (“bosque
102 nublado”); moist broadleaf forest (“bosque húmedo”); semi-moist broadleaf forest (“bosque
103 semihúmedo”); and dry forest (“bosque seco”). Pine forests occur at the highest, coldest
104 elevations of the Sierra de Bahoruco, Sierra de Neiba, and Cordillera Central. Cloud forest
105 usually arises at the lower elevational limit of pine, in areas with mild temperatures, abundant
106 precipitation, and persistent ground-level clouds. Cloud forest transitions into moist broadleaf
107 forest at lower elevations where average annual precipitation drops below ~2,000 mm [23].
108 Moist broadleaf forest occupies a broad elevational range, from near sea level in wet areas in
109 the north of the country, such as Los Haitises, to ~1800 m on drier mountain slopes, such as the
110 southern slope of Sierra de Bahoruco. Semi-moist broadleaf forest occurs in coastal areas and
111 on mountain slopes as a transitional zone between dry forest and moist broadleaf forest. Dry
112 forest is the only non-evergreen forest, found at relatively low elevations (< 500 m) with a warm,
113 dry, and seasonal climate. Unlike the other forest types, most extant dry forest is secondary
114 forest in the process of recovering from past anthropogenic disturbances [23].

115 **Separating wildfire from other causes of forest loss**

116 Fire can be a significant driver of vegetation dynamics in the DR, especially in montane
117 forests [24], so to examine the role of wildfire as an agent of forest loss we used the monthly,
118 MODIS-based estimates of the global area burned [25]. We aggregated monthly estimates of
119 area burned for each year and assumed that forest loss was caused by fire for any pixel in the
120 Hansen et al. [9] data that was within the boundaries of a burned area and was estimated as
121 having been deforested in that year.

122 **Quantifying forest change within protected areas**

123 The DR has an extensive national protected area system, covering 26% of its territory
124 [26]. To examine whether forest within formally protected areas showed different patterns of
125 change, we calculated forest change and area burned for each protected area within the DR.

126 **Results**

127 **Quantifying forest change**

128 Trees covered 21,494 km² of the DR in 2000, roughly 45% of its total land area.
129 Deforestation removed 2,795 km² of this tree cover by 2016, while reforestation or afforestation

130 occurred on only 393 km², a net loss of 2,402 km², reducing forest cover to roughly 40% of the
 131 territory. This amounts to an 11.1% decline in forest cover at the national level over the period of
 132 analysis, an annual deforestation rate of 0.7%.

133 Considering only the DR's major natural forest types, forest cover shrank from 9,517 km²
 134 in 2000 to 8,644 km² in 2016, a net loss of 9.2% (Table 1). Depending on forest type, this
 135 change ranged from -5.9% in cloud forests to -13.1% in semi-moist forests. The extent of loss
 136 varied among years but, with the exception of dry forest, tended to increase after 2010 (Fig 1).
 137 Forest gain was negligible in all of the natural forest types.

138

139 **Table 1. Changes in the estimated areal extent of forest in the Dominican Republic**
 140 **between 2000 and 2016 for the 6 forested land-cover types identified in national land-**
 141 **cover mapping.**

Forest type (original classification name)	Area (km ²), 2000	Area (km ²), 2016	Area lost (km ²)	Area gained (km ²)	Net change (%)	Percent loss due to fire
Closed-canopy pine (conifera denso)	1660.1	1503.0	157.6	0.6	-10.5	48.2
Open-canopy pine (conifera abierto)	638.7	566.7	72.3	0.3	-12.7	56.1
Cloud forest (latifoliado nublado)	951.8	898.9	53.0	0.2	-5.9	31.1
Moist broadleaf (latifoliado húmedo)	2566.6	2362.2	206.7	2.3	-8.7	6.8
Semi-moist broadleaf (latifoliado semihúmedo)	1527.0	1350.1	179.3	2.4	-13.1	3.2
Dry (seco)	2173.1	1962.9	214.7	4.5	-10.7	3.4

142

143 **Fig 1. Deforestation rates in the Dominican Republic from 2000-2016 in each of the**
 144 **country's major upland forest types.** The extent of deforestation (solid black line) varied
 145 among years and among the six major forest types. When smoothed via loess (solid blue line;
 146 shaded interval is 95% confidence interval), deforestation appeared to accelerate after 2010,
 147 with the exception of dry forest.

148

149 **Fire as a deforestation driver**

150 Fire accounted for a significant amount of loss in the Hispaniolan pine forests, in both
151 open- and closed-canopy types (Table 1). However, most of the loss caused by fire occurred in
152 a single year (Fig 2). In closed-canopy pine forest, fires in 2005 accounted for roughly 77% of
153 the area burned between 2000 and 2016; in open-canopy pine, 50%; in cloud forest, 53%; and
154 in moist broadleaf, 55%. Lesser peaks occurred in 2014 for both pine forest types (12% and 6%
155 of total area burned over the course of the study for closed-canopy and open-canopy,
156 respectively) and again in 2015 with losses for closed-canopy pine (4%), open-canopy pine
157 (10%), cloud forest (19%), and moist broadleaf (32%). Fire accounted for relatively little loss in
158 area among the dry and semi-moist broadleaf forest types.

159
160 **Fig 2. Relative importance of fire and other sources as agents of forest loss in major**
161 **upland forest types of the Dominican Republic, 2000-2016.** Declines in the extent of the six
162 major forest types in the Dominican Republic were driven in most years by forest loss from
163 sources other than fire (blue lines); significant losses due to fire were apparent only in 2005, as
164 shown by the gap between the amount of forest lost to all sources (orange lines) and the
165 amount of forest lost to sources other than fire. Lesser peaks in area burned were apparent in
166 2015 for both pine types and cloud forest.

167 **Protected area deforestation**

168 Rates of deforestation within protected areas largely mirrored overall trends in forest
169 change, except for dry and semi-moist broadleaf forests where forest loss was substantially
170 lower within protected areas (Table 2). Within protected areas, forest accounted for 7,381 km² in
171 2000, covering 57% of the land. By 2016, forest cover had shrunk by 670 km² (-8.5%) and
172 covered only 52% of the land in protected areas.

173 Protected areas offered little defense against fire, either. Fire accounted for significant
174 amounts of the estimated loss of both pine and cloud forests within protected areas (Table 2). In
175 fact, of the three forest types experiencing significant losses due to fire, nearly all of the burned
176 area occurred within protected areas: for closed-canopy pine forest, 96% of the burned area
177 was within a protected area; for open-canopy pine forest, 91%; and for cloud forest, 91%.

178 Extent of forest loss varied substantially among protected areas for all forest types. The
179 largest losses in pine forests occurred in José del Carmen Ramírez National Park (JC Ramírez),
180 largely due to the large 2005 fire, followed by Sierra de Bahoruco National Park (Bahoruco) due
181 to sources other than fire (Figs. 3 and 4; S1 File).

182 Cloud forest losses within protected areas ranged from <1 km² in Armando Bermúdez
183 National Park to 11 km² in JC Ramírez, or 17% of that park's extant cloud forest (Fig. 5; S1
184 File). Roughly half (51%) of the cloud forest lost in JC Ramírez was due to the same wildfires
185 that burned through the park's pine forests. Other parks experiencing substantial loss of cloud
186 forest were Valle Nuevo National Park, which lost 7.7 km² (4.1% of its extent in 2000), and
187 Bahoruco, which lost 7.6 km² (8.2%). Loss of cloud forest in these two parks was driven
188 primarily by processes other than fire (only 26.3% and 8.8%, respectively, of the deforestation in
189 each was caused by fire).

190

191 **Table 2. Changes in the estimated areal extent of forest within formally protected areas in**
 192 **the Dominican Republic between 2000 and 2016 for the 6 forested land-cover types**
 193 **identified in national land-cover mapping.**

194

Forest type (original classification name)	Percent protected	Area (km ²), 2000	Area lost (km ²)	Area gained (km ²)	Net change (%)	Percent loss due to fire
Closed-canopy pine (conifero denso)	81.6	1354.2	126.2	0.4	-10.3	47.3
Open-canopy pine (conifero abierto)	56.9	363.1	49.4	0.2	-15.7	54.7
Cloud forest (latifoliado nublado)	78.1	743.6	39.2	0.2	-5.5	20.9
Moist broadleaf (latifoliado humedo)	43.8	1122.4	73.1	0.5	-6.9	7.7
Semi-moist broadleaf (latifoliado semi-humedo)	40.0	610.4	43.3	0.5	-7.5	1.2
Dry (seco)	49.1	1066.8	43.6	0.3	-4.2	1.8

195

196 **Fig 3. Area of closed-canopy Hispaniolan pine (*Pinus occidentalis*) in the Dominican**
 197 **Republic within protected areas that remained intact or was deforested (due to fire or**
 198 **other causes) between 2000 and 2016.** Forest loss in the three most important protected
 199 areas - all classified as national parks (IUCN Category II) and collectively accounting for 67% of
 200 the total protected area for this forest type - varied due to the higher losses from wildfire in José
 201 del Carmen Ramírez National Park. Loss of forest cover from other sources was similar across
 202 the three protected areas.

203

204 **Fig 4. Area of open-canopy Hispaniolan pine (*Pinus occidentalis*) in the Dominican**
 205 **Republic within protected areas that remained intact or was deforested (due to fire or**
 206 **other causes) between 2000 and 2016.** Forest loss in the three most important protected
 207 areas - all classified as national parks (IUCN Category II) and collectively accounting for 72% of
 208 the total protected area for this forest type - varied due to the higher losses from wildfire in José
 209 del Carmen Ramírez National Park and to deforestation from causes other than fire in Sierra de
 210 Bahoruco National Park.

211

212 **Fig 5. Area of cloud forest in the Dominican Republic within protected areas that**
 213 **remained intact or was deforested (due to fire or other causes) between 2000 and 2016.**
 214 Forest loss in the eight most important protected areas - all classified as national parks (IUCN
 215 Category II) except for Alto Bao, a forest reserve (IUCN Category V), and collectively

216 accounting for 94% of the total protected area for this forest type - was mostly due to sources
217 other than fire. Fire was an important source of deforestation only in José del Carmen Ramírez
218 National Park; Sierra de Bahoruco National Park and Valle Nuevo National Park both lost large
219 areas of cloud forest from causes other than fire.

220
221 Moist broadleaf forest losses were greatest in Los Haitises National Park, which lost 26
222 km² (14.6%), almost all (94.2%) due to causes other than fire (Fig. 6; S1 File). Bahoruco
223 experienced significant losses of moist broadleaf forests, too (8.6 km², or 8.4% of the amount
224 estimated to exist in 2000). Although fire was not generally an important cause of loss of this
225 forest type, the 2005 fires that burned in JC Ramírez accounted for 71.4% of the observed moist
226 broadleaf deforestation in that park, which totaled 4.1 km².

227
228 **Fig 6. Area of moist broadleaf forest in the Dominican Republic within protected areas**
229 **that remained intact or was deforested (due to fire or other causes) between 2000 and**
230 **2016.** Forest loss in the twelve most important protected areas for moist broadleaf forest, which
231 collectively account for 75% of the total protected area for this forest type, was concentrated in a
232 single National Park (IUCN Category II), Los Haitises, and was due almost entirely to causes
233 other than fire.

234
235 Loss of semi-moist broadleaf forest was most pronounced in Bahoruco (13.9 km², or
236 15.5% of the 2000 total extent) and Cotubanamá National Park (formerly Del Este National
237 Park; 6 km², or 2%; Fig. 7; S1 File). Bahoruco also led all parks in the amount of dry forest
238 eliminated, with 7.8 km² (5.1%) lost over the course of this study (Fig. 8; S1 File). Despite its
239 relatively small size, Cerro Chacuey Natural Reserve was another noticeable hotspot of
240 deforestation, losing 4.7 km² or 35.2% of its extant dry forest (S1 File). Fire was unimportant as
241 a driver of deforestation of both semi-moist broadleaf and dry forests in this study.

242
243 **Fig 7. Area of semi-moist broadleaf forest in the Dominican Republic within protected**
244 **areas that remained intact or was deforested (due to fire or other causes) between 2000**
245 **and 2016.** Deforestation in semi-moist broadleaf forest was concentrated in two National Parks
246 (IUCN Category II), Punta Espada and Sierra de Bahoruco. Collectively these four protected
247 areas account for 75% of the total protected area for this forest type. Fire was an insignificant
248 cause of deforestation in this forest type.

249
250 **Fig 8. Area of dry forest in the Dominican Republic within protected areas that remained**
251 **intact or was deforested (due to fire or other causes) between 2000 and 2016.** Loss of
252 protected dry forest was relatively high in Sierra de Bahoruco National Park. Collectively these
253 seven protected areas account for 72% of the total protected area for this forest type. Fire was
254 an insignificant cause of deforestation in dry forest.

255
256

257 Discussion

258 Forest cover in the DR shrank substantially between 2000 and 2016, from nearly 45% to
259 just under 40% of its territory, an overall decline of 11.1% and an annual deforestation rate of
260 0.7%. This rate was much higher than the 0.38% annual net rate of deforestation estimated for
261 the tropics as a whole by Achard et al. [11] and for the mainland Neotropics in particular [27].
262 However, our estimated deforestation rate is comparable with the long-term 0.71% annual rate
263 of forest loss estimated for the Amazon forest of Brazil [28].

264 Other recent studies, all using satellite sensor data, have reported qualitatively similar
265 changes: Heino et al. [21] estimated that forest cover in the DR declined by 1,863 km² between
266 2000 and 2012 (or 7% out of an estimated total area of 26,952 km², a ~0.6% annual decline),
267 while Sangermano et al. [20], using a different approach, estimated a slightly slower rate of
268 deforestation in the DR between 2000 and 2011, reporting a net loss of 518 km² (or 5.3% of
269 total forest area, a ~ 0.5% annual decline). Furthermore, in keeping with our finding of
270 widespread deforestation in all forest types and without respect to protected-area status, both
271 Heino et al. [21] and Potapov et al. [10] reported significant declines in the extent of intact forest
272 in the DR. In these studies, intact forest was defined as forest blocks > 500 km² in area and
273 minimally influenced by human activity, essentially all of which falls within the boundaries of
274 protected areas in the DR. Potapov et al. [10] found a 29% decline in the extent of intact forest
275 in the DR between 2000 and 2013, mostly due to losses caused by fire, whereas Heino et al.
276 [21] estimated an 8.6% decline in intact forest.

277 In contrast to these trends, the Food and Agriculture Organization (FAO), using reports
278 provided by the government of the DR, reported a 33.4% increase in forest cover between 2000
279 and 2015, an annual gain of 1.9% (FAO 2015). The methodology underlying this estimate is not
280 identified in the FAO report, but it was probably derived from the national land-cover and
281 vegetation maps produced by the Ministry of the Environment of the DR every few years.
282 Elsewhere, national reports used by the FAO have been criticized as unreliable [29] and several
283 studies have documented significant discrepancies between international estimates and
284 nationally reported estimates of forest loss [9,30]. Furthermore, Romijn et al. [31] rated as low
285 the capacity of the DR to carry out forest inventories and to monitor change in forest area, both
286 of which are essential in generating reliable national reports on forest change. Given this, and
287 given the consistency of estimates produced by international studies, we consider it unlikely that
288 reforestation exceeded deforestation and instead have high confidence that the total area of
289 forest in the DR declined from 2000-2016.

290 One possible source of error in our estimates of net deforestation is that our estimates of
291 gain in the area of each forest type apply only to pixels falling within the mapped distribution of
292 each forest type. Because we based our estimates of change in each forest type on its 1996
293 mapped distribution, we cannot rule out the possibility that areas categorized as another land-
294 cover type in 1996 (e.g., subsistence agriculture) could have regrown into one of the forest
295 types we analyzed. This would not have been captured by our analysis, thus leading us to
296 underestimate forest gains during the period. However, the total gain in tree cover across all of
297 the agricultural or otherwise anthropogenic land-cover types in the 1996 land-cover map was
298 only 24 km², so even if all of this gain reflected reversion to native forest cover, which is unlikely,
299 it would account for only a small fraction of the 874 km² of forest lost. Thus, we are confident

300 that afforestation of agricultural or developed lands could not have materially affected our
301 estimates of net loss.

302 As has been reported in other studies of deforestation in the Neotropics [30,32], we also
303 found that deforestation in the DR tended to accelerate over time, with the exception of dry
304 forest loss, which showed some evidence of a decline in the extent of deforestation after 2010.
305 This slowing deforestation rate in dry forests could be because of the substitution of propane
306 gas for wood charcoal – the main historical use of dry-forest trees – as the primary cooking fuel
307 in the DR [33], a phenomenon also observed in Puerto Rico [34]. Charcoal trade went from
308 roughly 1.6 million sacks in 1982 to just 49,000 in 2005, and its use as cooking fuel went from
309 90% of households in 1980 to just 10% in 2006 [35]. Although there are still some hotspots of
310 illegal charcoal trade [36], especially in areas near the border with Haiti, quantifying its
311 importance is difficult. Nonetheless, the widespread shift away from charcoal as the leading
312 cooking fuel in the DR likely explains much of the observed drop in dry-forest deforestation
313 rates.

314 **Loss by forest type and drivers**

315 Outside of areas known to have burned, the data that we used do not provide direct
316 insight into the drivers of forest loss. However, we can reasonably speculate that, with the
317 exception of pine forests, the most likely cause for the observed forest loss is expanding
318 agriculture. This is not only consistent with our field observations, but also in agreement with the
319 findings from a comprehensive, national-level assessment which ranked agriculture as the
320 leading cause of deforestation, accounting for 55% of forest loss in the DR [37]. In comparison,
321 the same study attributed only 26% of deforestation to timber harvesting, firewood collection,
322 and wood-charcoal production.

323 The important role of agriculture in forest clearing in two montane national parks has
324 also been highlighted in recent reports by Wooding and Morales [38] for Nalga de Maco
325 National Park and León et al. [39] for Sierra de Bahoruco National Park. Both studies describe
326 the expansion of a similar commercial agricultural system, consisting of sharecropping in a
327 shifting-agriculture system established between a landless Haitian farmer and a Dominican who
328 claims land ownership. Sharing arrangements can vary, but usually the farmer keeps most of
329 the crop, which is typically short-cycle crops. León et al. [39] also described the recent
330 establishment of more permanent forest conversion in the form of avocados (*Persea americana*)
331 grown for export, plantations of which have actively expanded inside Sierra de Bahoruco
332 National Park since 2008. The problem of agriculture within protected areas is not limited to
333 montane parks, however; a study on the drivers of deforestation in the low-elevation Los
334 Haitises National Park also identified farming as the leading cause. In this case, deforestation
335 was driven by increased exports of taro root (*Colocasia esculenta*), the leading crop inside the
336 Park [40].

337 Fire was the leading cause of forest-cover decline in Hispaniolan pine forests. Pine trees
338 and their associated understory plants are not only resilient to fire, but depend on it for seed
339 dispersal and germination [41] and thus, absent any additional disturbance, burned pinelands
340 will likely recover [42]. Of concern, however, is evidence of emerging changes in fire regime that
341 may pose a long-term threat to these forests. Whereas lightning during dry seasons was

342 probably the leading cause of fire ignition in the past, today human activities are. The DR's
343 National Fire Management Strategy has identified as the leading causes of forest fires, in order
344 of importance: farming activities (especially land preparation for short-cycle crops), renewal of
345 cattle grazing pastures, intentional fires in protest against authorities, and accidental fires
346 caused by abandoned cooking fires from hunters and parrot poachers [43]. Furthermore, the
347 strategy highlights a new and complex threat: the expansion of the invasive molasses grass
348 (*Melinis minutiflora*), which is highly flammable and has already been implicated in forest fires
349 [43]. Changes in the seasonality, frequency, or intensity of fire may negatively affect even
350 relatively resilient pine forests, let alone broadleaf forests that are ill-adapted to fire.

351 Cloud forest also experienced substantial losses due to fire. However, unlike pine forest,
352 it is far less resilient to fire. Not only is cloud forest exceedingly slow to recover after fire [44],
353 but exposure to repeated fire can lead to its replacement by other forest types [42]. The fire-
354 related losses of cloud forest that we documented, therefore, may be permanent. This is very
355 concerning as these montane forests not only host most of the unique, threatened species on
356 the island, but also intercept water from rain and clouds year-round (e.g., [45]), allowing lowland
357 human communities to thrive even in extremely dry areas. The 2005 fires that produced most of
358 the fire-related deforestation in pine and cloud forests were exacerbated by drought conditions
359 brought about by an El Niño event in late 2004 [24]. The climate of the DR is expected to grow
360 warmer and drier under most scenarios of climate change [46], raising the possibility that fire -
361 probably historically unimportant as a driver of change in cloud forest [24] - may become a far
362 more important threat to cloud forest in the future.

363 **The impact of protected areas**

364 Protected areas lost less tree cover than did unprotected areas, as has been shown
365 previously both in the DR [20] and in other parts of the world [47–50]. However, protected areas
366 also varied in terms of the degree of protection they afforded. Three mountain-based National
367 Parks in particular - Sierra de Bahuco, José del Carmen Ramirez, and Valle Nuevo - exhibited
368 consistently high rates of deforestation across multiple forest types. A fourth National Park, Los
369 Haitises, located at sea level, had notably high rates of deforestation in its predominant forest
370 type, moist broadleaf forest. These four areas all share a common problem: expanding
371 agriculture or cattle ranching operations. These activities are feasible in these protected areas
372 because they have a relatively humid climate, and in the case of the three mountain parks,
373 milder temperatures, conditions which allow for profitable farming operations without expensive
374 watering systems. This is consistent with a recent global study on protected areas under
375 pressure, which estimated that 21% of land within protected areas in the DR faced intense
376 human pressure [51]. The low management effectiveness in some of the DR's protected areas
377 was also highlighted by a report from Sánchez [52], in which he measured a number of key
378 management variables for the leading 35 protected areas (out of a total of 118 areas at the
379 time). Of these, only four obtained a satisfactory management score (above 75%). Of the
380 remaining 31 areas that failed to receive a passing score, ten showed evidence of ongoing
381 decline in management effectiveness during the course of the three-year study. The lack of
382 basic management attributes such as clear knowledge of protected area boundaries and the
383 existence of management plans drove most of these low scores. From our observations in the

384 field, besides a limited capacity to enforce existing protected-area laws, political patronage, local
385 power structures, and corruption also play a role in limiting the effectiveness of protected areas.

386 Our findings also suggest that protected areas were more effective in reducing
387 deforestation at lower elevations, particularly in dry forest. However, this could be attributed to
388 several factors besides protection status, including the shift away from wood charcoal as
389 cooking fuel in the DR, as well as the limitations that local climatic conditions impose on the
390 development of agriculture and cattle ranching. These activities are only possible in dry forest
391 sites with abundant, nearby freshwater resources, and often only after sizeable investments in
392 irrigation infrastructure. Financing such investments often requires land titles, which can be
393 difficult to obtain in legally protected areas. This agrees with the findings of Joppa and Pfaff [48],
394 who also found that protected areas appear more secure when established in areas not highly
395 valued for extractive resource uses. The apparently greater effectiveness of protected areas in
396 areas of dry forest in the DR may thus simply reflect the low profitability of exploiting the
397 resources that they contain, in contrast to the relatively lucrative opportunities afforded by the
398 export-oriented agriculture that can be carried out in protected areas with more suitable climatic
399 conditions.

400 **Policy implications**

401 Although not typically considered a hotspot of deforestation, rates of forest loss in the
402 DR are higher than regional averages and show no sign of decelerating. Our results reveal
403 ongoing deforestation across the country, especially in moist forest types that are more valuable
404 for agricultural development. Protected areas offered only modest reductions in deforestation for
405 most forest types, highlighting a general lack of management effectiveness. As nations continue
406 to expand their protected-area systems, there is an urgent need to undertake objective
407 assessments of their effectiveness in meeting their goals, especially those pertaining to forest
408 conservation. Satellite images and forest-cover analysis platforms, such as Global Forest
409 Watch, offer an inexpensive and objective way to achieve this.

410 Continued deforestation in the DR poses a risk to the flow of critical ecosystem services,
411 especially the provision of water by upland forests to lowland human communities, including the
412 major cities and agricultural regions. Ongoing deforestation will also threaten the achievement
413 of a number of the DR's sustainable development goals, as well as meeting its Intended
414 Nationally Determined Contribution under the Paris Agreement within the United Nations
415 Framework Convention on Climate Change (UNFCCC). Widespread forest loss will also hinder
416 the DR's commitments to halt biodiversity loss as a party to the Convention on Biological
417 Diversity, by placing at greater risk many unique, globally threatened species that depend on
418 the country's forests.

419 Addressing deforestation will require a better understanding of its causes. Although fire
420 is an important driver of loss of forest cover in Hispaniolan pine forest, and occasionally in
421 adjacent cloud forest, the vast majority of deforestation is driven by clearing for agricultural
422 production [53]. More research into the local drivers of deforestation, its key actors, and
423 associated social dynamics are needed. Efforts to stem deforestation will almost certainly
424 involve stricter limits on large-scale agricultural commodity production within protected areas
425 and the development of alternative livelihood opportunities for those practicing shifting

426 agriculture. Shifting agriculture is in great part enabled by customary systems of land tenure in
427 many rural areas of the DR that persist despite contravening laws and policies established by
428 the central government. The critical role of land tenure in reducing deforestation, particularly
429 under the REDD+ (Reducing Emissions from Deforestation and Forest Degradation)
430 mechanism of the UNFCCC has been highlighted by a growing number of studies around the
431 world [e.g., 54,55]. Addressing these issues is not easy, but will be crucial for securing the
432 future of forests in the DR and in many other countries facing similar development pressures.

433 **Acknowledgements**

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435 **References**

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611 **Supporting information**

612 **S1 File. Change in extent of major upland forest types**
613 **within protected areas in the Dominican Republic,**
614 **2000-2016.**

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Forest area (km²) lost

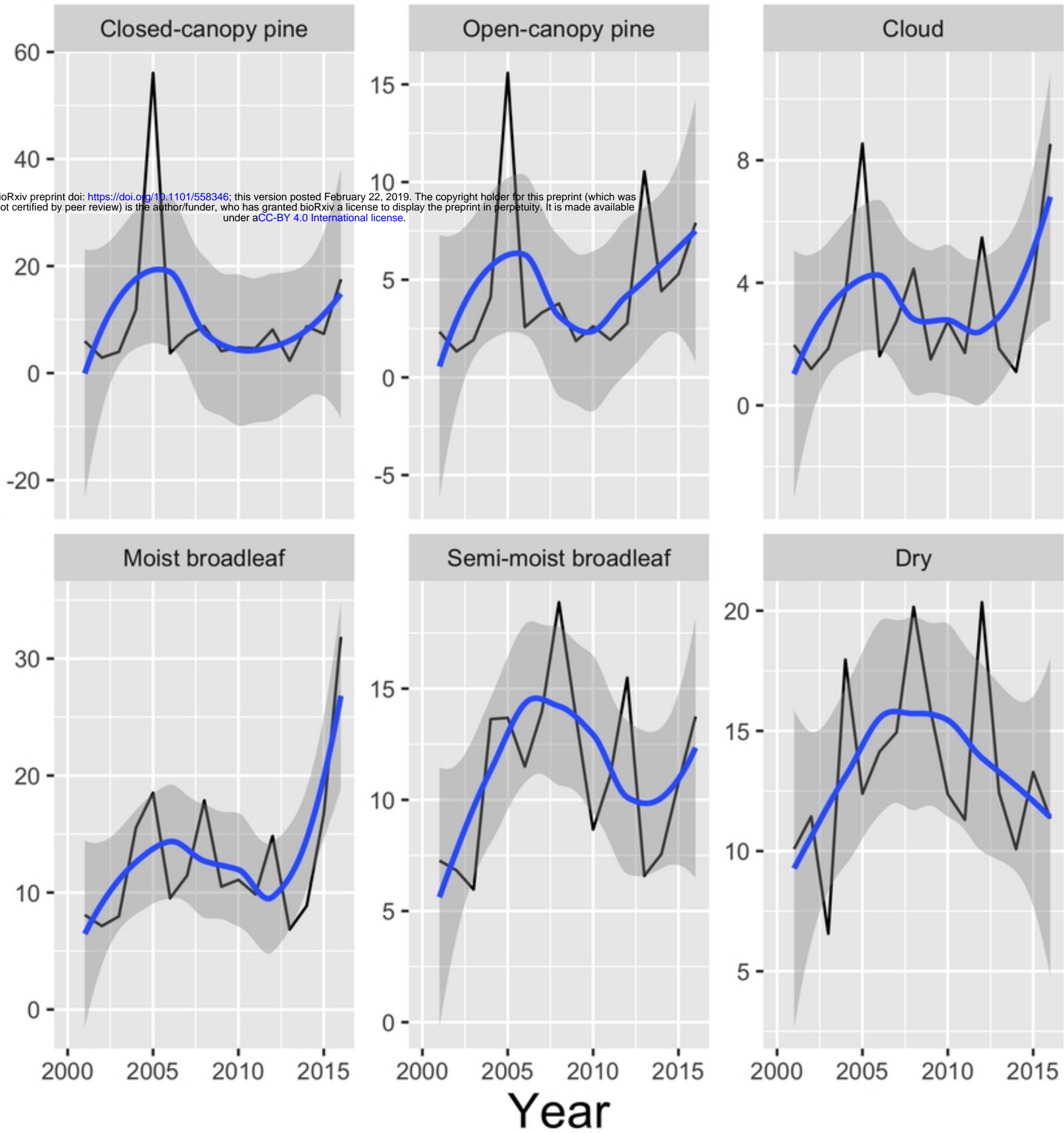


Figure 1

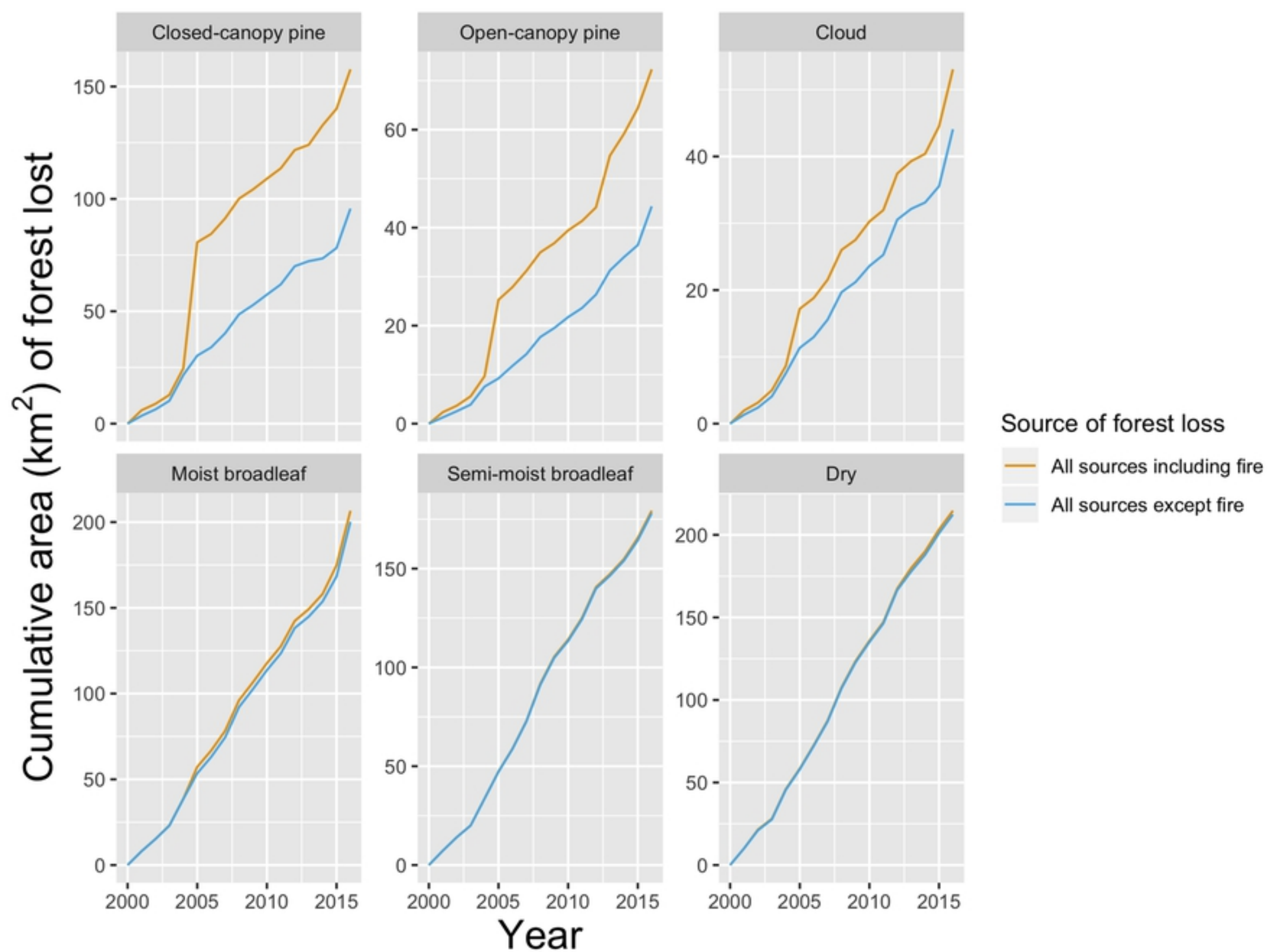


Figure 2

Area (km²) of protected closed-canopy pine forest

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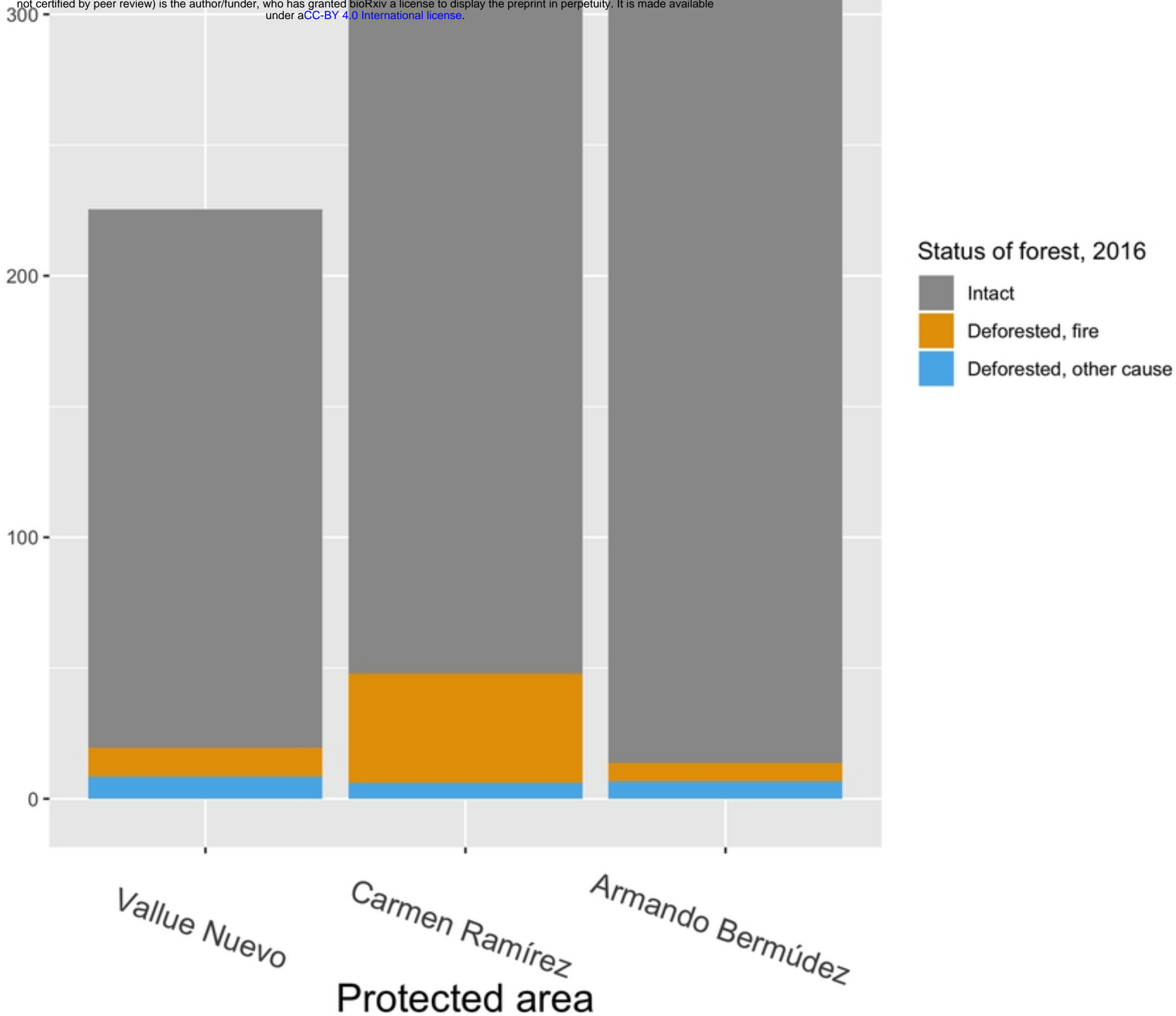


Figure 3

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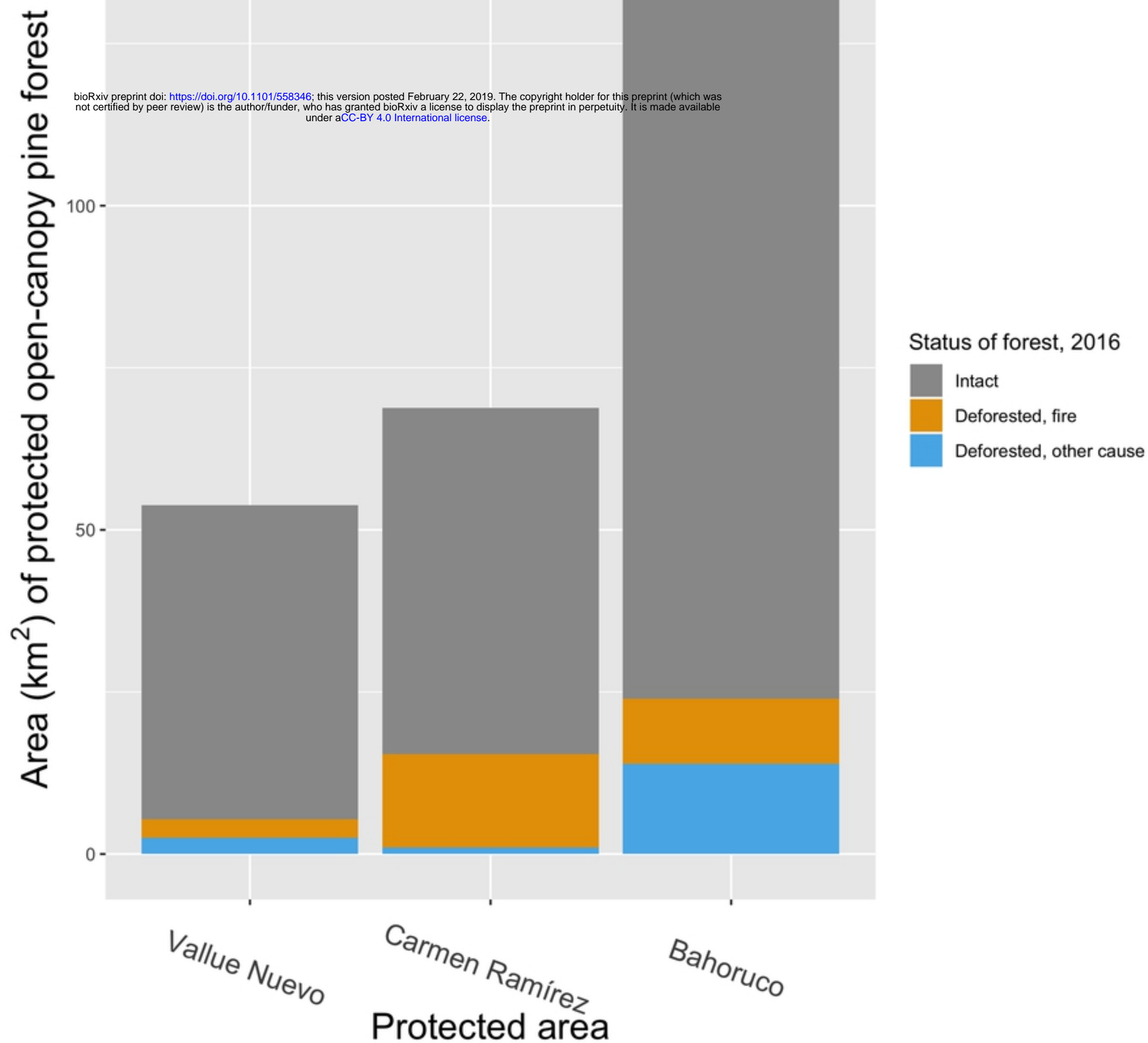


Figure 4

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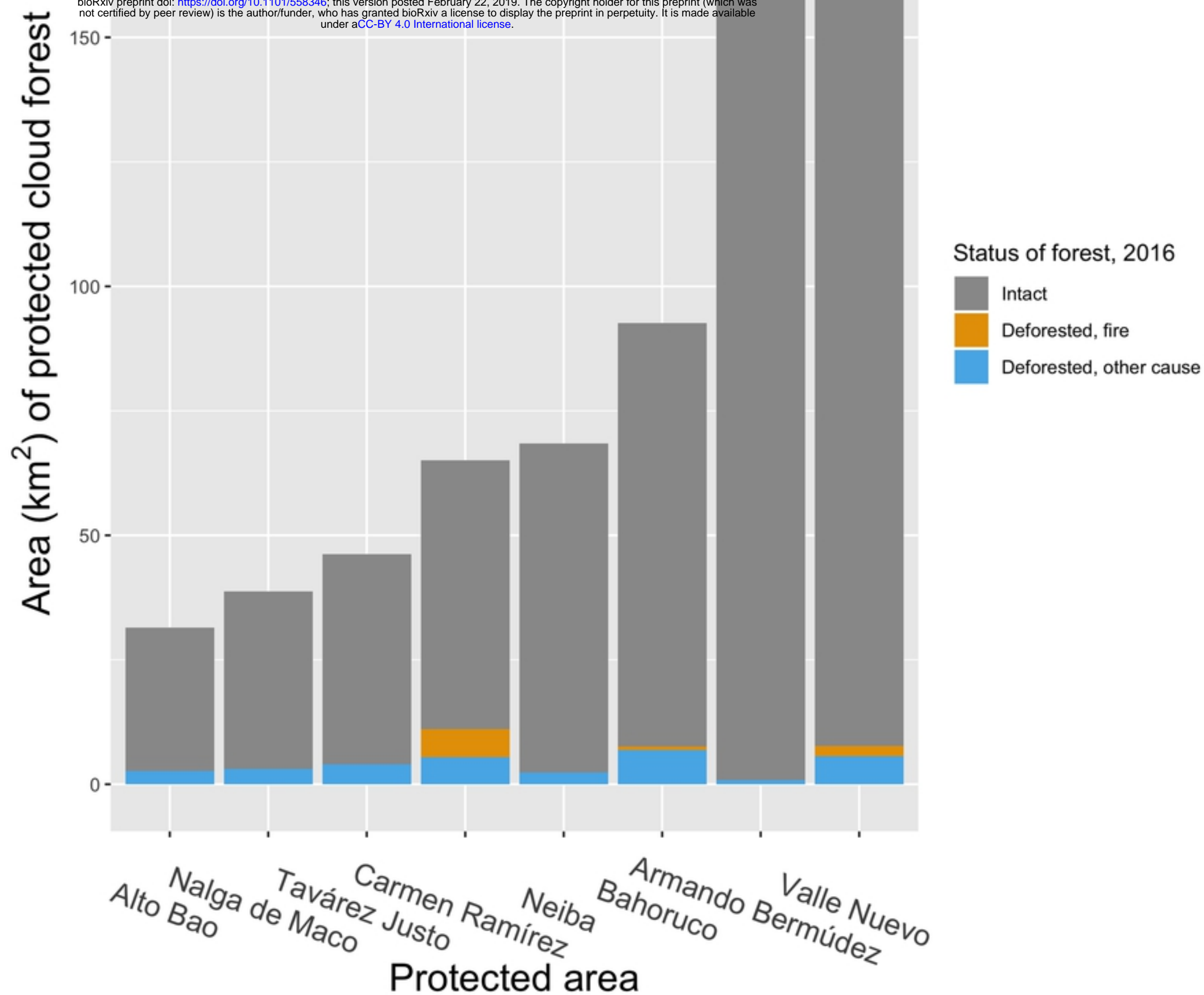


Figure 5

Area (km²) of protected moist broadleaf forest

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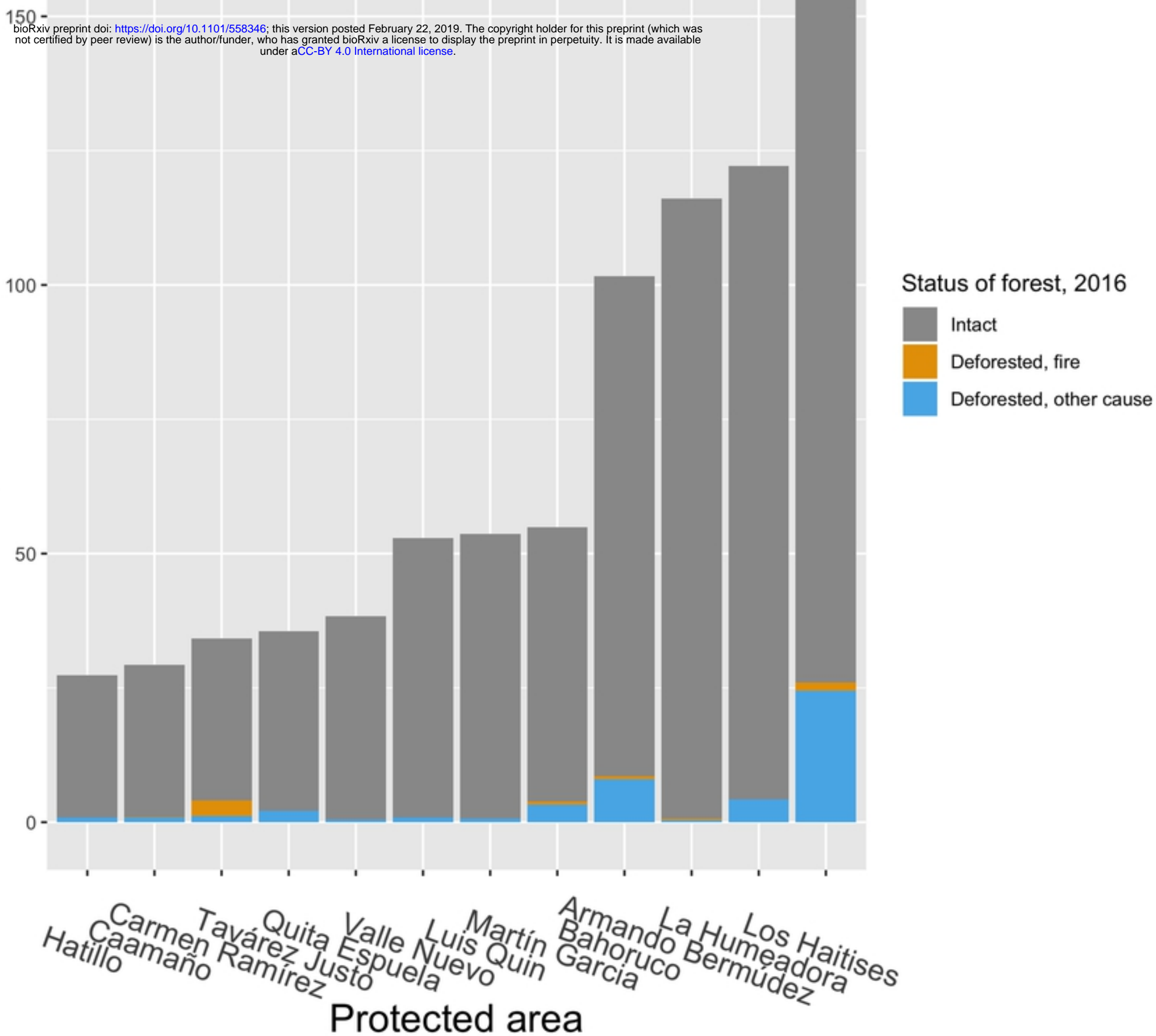


Figure 6

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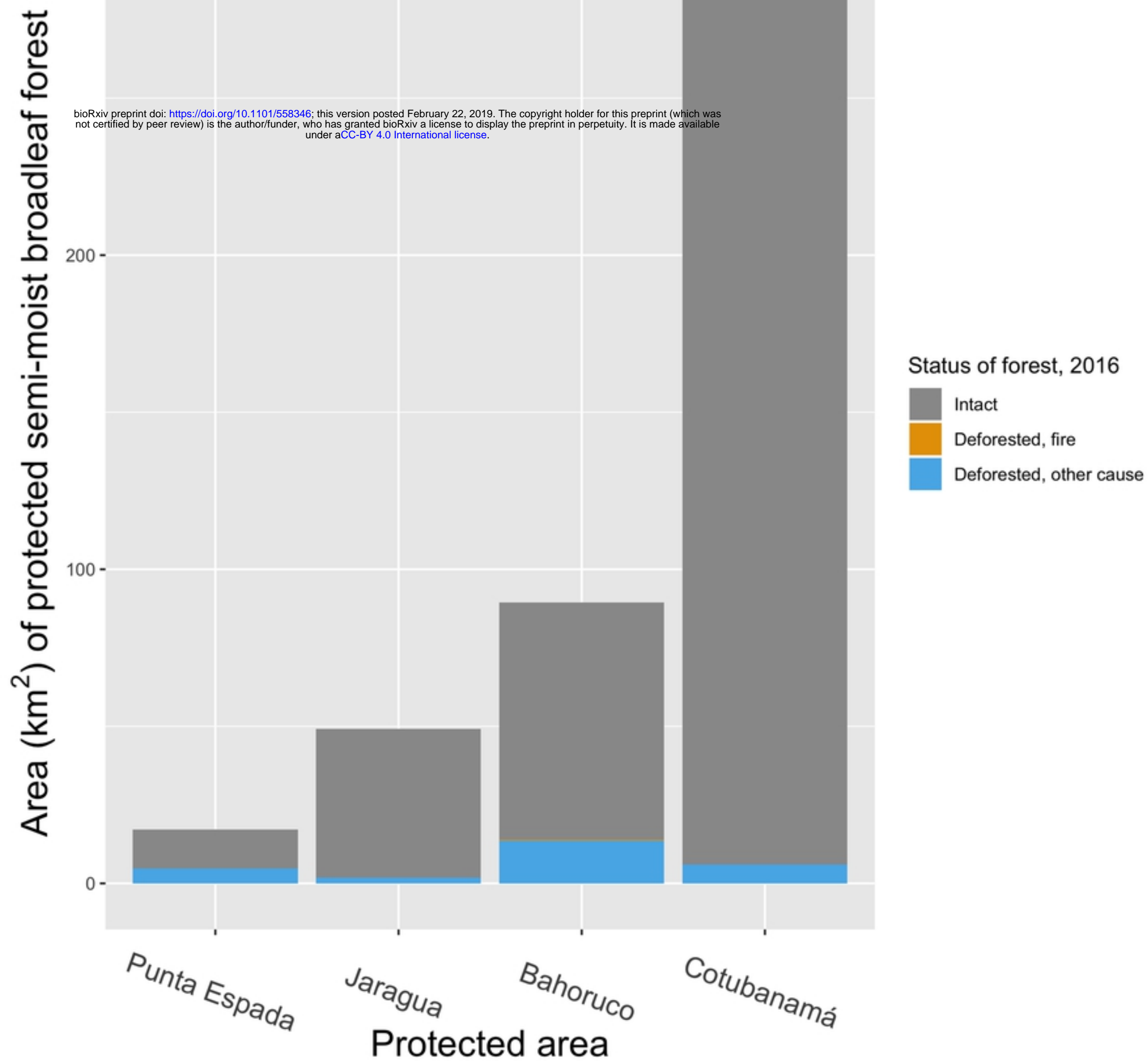


Figure 7

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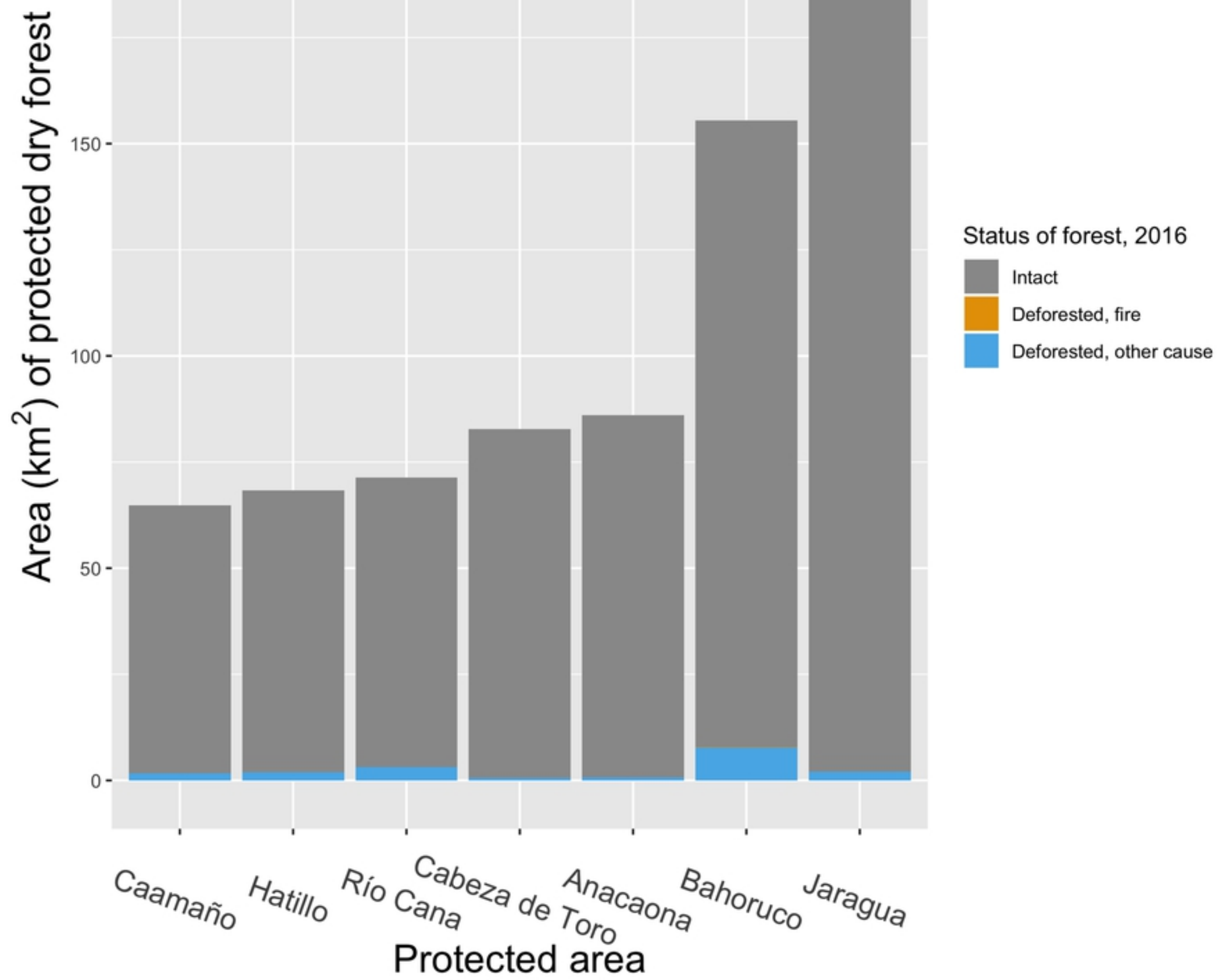


Figure 8