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Isabel Rosa (i.rosa@bangor.ac.uk)
Bangor University https://orcid.org/0000-0001-8257-1963
José Ochoa-Quintero
Humboldt Institute
Elkin Noguera
Humboldt Institute
Edwin Tamayo
Humboldt Institute
Marcelo Pineros
Humboldt Institute

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Scenarios of environmental change in a post-conflict Colombia

Isabel M.D. Rosa[1], Elkin Noguera[2] Edwin Tamayo[2], Marcelo Villa Pineros[2], Jose M. Ochoa-Quintero[2]

[1] School of Natural Sciences, Bangor University, Bangor, Gwynedd, LL57 2DG, United Kingdom

[2] Alexander von Humboldt Institute on Biological Research, Bogotá, Colombia.

Corresponding author: Isabel M.D. Rosa
School of Natural Sciences
Bangor University, Bangor, Gwynedd
LL57 2DG United Kingdom
E-mail i.rosa@bangor.ac.uk
Phone +44(0)1248 383642
ORCID: 0000-0001-8257-1963

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Abstract

Colombia is a notorious biodiversity hotspot that came to the spotlight of conservation upon the signing of the peace agreement in 2016. Here we used a counterfactual approach to forecast by 2036 the impact of deforestation on Colombia's biodiversity and carbon stocks under three scenarios: (1) pre-signing of the peace agreement, (2) post-signing and (3) business-as-usual. We found that if deforestation rates continued at the same pace of post-signing, up to 41,000 km^2 *of forest area may be lost by 2036, whereas pre-signing rates would save nearly 25,000 km*^{2} *(equivalent to the total forest loss observed between 2000 and 2018). Under the pre-signing scenario, between 2018-2036 Colombia would reduce the average impact on the range of forest-specific species by nearly 50% of habitat area relative to 2000-2018, whereas under the post-signing scenario, it would increase by 33%. Moreover, losses of 312-807 Mm*^{3} *of growing stock volume and 267-688 Mt of aboveground biomass were projected by 2036, jeopardizing the country's commitments towards international conservation as well as climate targets. Importantly, we found a mismatch at the department level on biodiversity and biomass losses, which highlight an urgent need to generate coherent policies at a national level aiming to tackle both issues.*

Colombia is recognized as one of the most important hotspots of biodiversity worldwide[1] and unlike many other countries is still largely covered by its natural ecosystems, with more than 50% of its area covered by forests[2]. The civil war that ravaged the country from the 1960s until 2016 has had social, political, economic and environmental consequences[3–7]. The Revolutionary Armed Forces of Colombia—People's Army (FARC, Spanish acronym) was the first armed group with political goals to profit from illegal crops, often cultivated under tree canopies[8]. The paramilitaries, on the other hand, had the support of the main drug traffickers[4] as well as wealthy cattle ranchers forcing population displacement[4]. Such factors are widely recognised drivers of land cover change across tropical forests[9–11]. In a context of violence and economic interests, institutions are less able to take actions to safeguard the environment[12]. Furthermore, as the population is forced to leave, the land can be used for further legal and illegal activities that contribute to deforestation, such as mineral exploitation[12]. The so-called “gunpoint conservation”, i.e. hostile regions where FARC and paramilitaries enforce and maintain forest preservation through the threat of violence[13], was used by armed groups as refuge from air surveillance by government forces[8], to house their headquarters, and for their role in the local hydrology[4].

Such social dynamics have led to important changes in the country’s forest cover. In fact, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, Spanish acronym) reported that from 1990 through 2015, the total amount of forest lost was 52,342 km^2, representing 8% of the forest area in 1990[14,15]. Particularly critical was the twenty-year period between 1990 and 2010 in which the annual deforestation rate increased from 1,300 km^2 between 1990 and 2000 to 3,630 km^2 between 2000 and 2010[16,17].

After three years of negotiations, the Government of Colombia and the FARC signed the peace agreement in La Havana, Cuba[18] in November 2016. In parallel to this process, the Government of Colombia developed the National Reducing Emissions from Deforestation and forest Degradation (REDD+) Strategy that intends to mitigate climate change through reforestation and sustainable forest management[18]. To achieve this goal, the peace accords promise land titles to former combatants in areas historically controlled by the FARC and allocates funding to build roads throughout former FARC territories. As a consequence, a vast area of highly biodiverse forest historically used as coverage from air-assisted detection by authorities is now accessible for extractive industries and agricultural expansion[19], and early signs of increased deforestation are already noticeable with important consequences in terms of carbon emissions and biodiversity loss[20]. Therefore, it is crucial to try and anticipate the environmental impacts of these increased deforestation rates if Colombia is to ever achieve its international commitments under the Paris Agreement (20-30% reduction in carbon emissions by 2030) and consolidate biodiversity as the differential factor on global competitivity based on its natural capital.

Using a counterfactual approach based on a spatially-explicit model[21], we projected deforestation in Colombia up to 2036 under three scenarios, reflecting three different model calibration periods (see Methods). The business-as-usual (BAU) scenario reflects 18 years of deforestation in Colombia (2000-2018), whereas the Low scenario reflects the three years leading to the signing of the peace agreement (2013-2015) and the High scenario reflects the three years post-signing of such agreement (2016-2018). The model was used with a combination of drivers that include the most used predictors of tropical deforestation[20,22,23].

The historical (2000-2018) and future (2018-2036) deforestation maps at 1 km^2 were analysed for the whole country as well as per department to assess which areas are under greater risk of future forest conversion. Additionally, by overlapping these forest maps (historical and future for the three scenarios) with expert-validated freely available species distribution maps for Colombia[24] (Figure S1) as well as maps of aboveground biomass and growing stock volume[25] (Figure S2), we determined the environmental impacts of expected conversions, and compared it with the historical impacts.

Our analyses showed that the main drivers of deforestation were mostly consistently across the three time periods analysed, however, there were important differences to notice. For instance, the location of previous deforestation was an important variable in the BAU and Low scenarios but not in the High scenario, which suggests that deforestation moved to new areas that were previously relatively intact (Table 1). Further, we observed less loss in areas of higher armed conflict, but that effect disappeared in the most recent period, although deforestation seem to take place closer to areas of coca plantations in all periods. As it is typical, roads consistently played an important role in driving deforestation, while elevation, slope and areas of protection as well as indigenous and black communities territories prevent further losses across all time periods in Colombia (Table 1). Importantly, the fact that the strength of the parameters' values for conservation areas (protected areas, African communities and indigenous communities) is reducing, supports current findings that these areas may be losing their effectiveness in acting as deforestation stoppers[26]. Finally, higher parameter values for distance to coca plantations in the most recent scenario (High) relative to the previous three years (Low) supports that the deforestation frontier is moving towards forests located closer to where these plantations are[5,27].

Forest cover in Colombia reduced from 756,894 km^2 in 2000 to 731,353 km^2 in 2018 (Figure 1), i.e. an average annual deforestation rate of 1419 km^2/year (2000-2018). This rate increased sharply in 2016-2018 to 2597 km^2/year, nearly three times higher than in the previous three years (986 km^2/year). Such fluctuations in the deforestation rates resulted in marked differences in the projections by 2036. In detail, under the BAU scenario we project that Colombia could lose a further 25,560 km^2 (± 14 km^2 [standard error, s.e.]) of forests by 2036, compared to 16,402 km^2 (± 12 km^2 s.e.) in the Low scenario and 41,062 km^2 (± 18 km^2 s.e.) in the High scenario (Figure 1). This means that if an effort had been made to keep the rates at the low levels of 2013-2015, Colombia could have saved 2341 km^2 (± 7.4 km^2 s.e.) of forest area by 2018, and could save up to 24,660 km^2 by 2036, an area almost equivalent to what was observed to be lost between 2000 and 2018 (25,541 km^2).

Historically, deforestation in Colombia has varied greatly across departments (Table S1). Over the 18 years analysed, there were 46 km^2 per year of forest being cut down on average per department; with Caquetá, Meta and Antioquia being the departments with the highest annual deforestation rates, respectively 278 km^2/year, 204 km^2/year and 159 km^2/year (Figure 2a). Furthermore, between 2013-2015 and 2016-2018 there was an increase in the annual deforestation rate in all departments of Colombia, from an average 32 km^2/year to 84 km^2/year (Table S1). Such increase was mostly concentrated in Caquetá and Meta where there was a sharp acceleration (509 km^2/year and 356 km^2/year, respectively) but also in Guaviare (289 km^2/year) (Table S1).

The three scenarios resulted in different amounts of forest lost for each department (Figure 2a). We projected that deforestation would mostly continue to occur alongside areas that have previously been deforested (Figure 3). We do however project that the expansion into new territories occurs at a more accelerated pace in the High scenario than in the Low (Figure 3d). At the department level, we found that on average, each department is projected to lose 824 km^2 (or 4.2% of its forests), 529 km^2 (2.9 %) and 1324 km^2 (7.2%) of forest from 2018 through 2036, under the BAU, Low and High scenarios, respectively (Figure 2a). By comparison, in the previous eighteen years, there was an average total loss of 823 km^2 or 4.3% of forest. This means that ensuring the rates at the level of the Low scenario would allow to keep the deforestation rates significantly lower than the previous 18 years whereas the High scenario would increase these by more than 50%. For instance, in terms of absolute area, Caquetá was projected to lose 4918 km^2 of forest from 2018 through 2036 under the High scenario compared to less than half of that under the Low scenario (2150 km^2), perpetuating the trends from the previous years (Table S1). Proportionally, though, other departments emerge as more problematic (Table S1). For example, under the High scenario, and with a projected loss of 1034 km^2 of forest by 2036, Arauca is expected to lose 17% of its 2018 forest cover, Bolivar is projected to lose 16% (2227 km^2) and Sucre 14% (348 km^2).

Such losses are expected to have had (and will continue to have) extensive environmental and ecological impacts on the biodiversity- and carbon-rich forests of Colombia. To assess such impacts, we determined a variety of indicators: loss of aboveground biomass and growing stock volume (Figure 3b and c); loss in biodiversity -

species richness (as a whole), forest-specific species, endemic species and species that are both endemic and forest-specific (Figure 4 a-d), and per species impacts (Figure 5).

We estimated that historically (2000-2018) Colombia has lost 376.42 Mt of aboveground biomass (AGB) and 440.62 M m^3 of growing stock volume (GSV). On average, each department lost 673,560 t/ year (s.e. 194,112 t/year, 3.29% of the value in 2000), and 788,409 m^3/year (s.e. 226,797 m^3/year, 3.27% of the value in 2000). Since Caquetá, Meta and Guaviare were the departments with greatest forest losses, these were also the departments with greater absolute losses of AGB and GSV (Figure 2b and c). Proportionally, however, Meta, Bolivar and Sucre emerge as those departments with highest losses, i.e. 6-7% of the AGB and 6-8% of GSV present in 2000 (Tables S2 and S3).

Under the High scenario, we projected that Colombia may lose up to 807.06 M $m^3$of GSV by 2036, i.e. 4.45% of the remaining GSV in the forests of the country. By contrast in the Low scenario, 312.30 M m^3 would be lost, or 1.72% of the remaining GSV, saving up to 494.76 M m^3 if the rates of deforestation stayed as low as in the 2013-2015 period. Similarly, in terms of AGB, we projected losses between 267.10 and 688.32 Mt by 2036, or between 1.75 and 4.5% of the remaining AGB of the country's forests. The effort to keep rates at the Low level would have saved nearly the same amount as the loss of AGB observed between 2000 and 2018. While in absolute terms these losses are expected to continue in the same departments as previously, i.e. Meta, Guaviare and Caquetá, proportionally, we found that under the High scenario new departments emerge with rapid losses, such as Guainía, Vichada and Valle del Cauca (Tables S2-S3, Figure 2b, c), thus highlighting the need for a coordinated regional policy to prevent further deforestation as to avoid leakages across departments.

Future deforestation will also lead to important impacts on biodiversity[28]. We found that on average, between 2000 and 2018, the number of overall species in each 1 km^2 pixel reduced by 3.06% in Colombia. For forest-specific species, the reduction was from 335 species to 324 (3.28%), whereas the endemic species reduced by 2.78% and forest-specific endemic species by 2.63%. By department, we found that on average 21 species were impacted between 2000-2018, 11 of which were forest-specific (Tables S4-S7). Proportionally, we estimated that departments have lost 3.69% of its biodiversity, 3.81% of the forest-specific species, 2.44% of its endemic as well as forest-specific and endemic species. Unlike the AGB, GSV results, when it comes to biodiversity, the focus is placed on other departments: Meta, Putumayo and Atlántico had the highest proportional losses (Figure 4a-b) of overall and forest-specific species (Tables S4-S5). However, when it comes to endemic species (Figure 4c-d), the highest losses were observed in Atlántico, Bolivar and Santander (Tables S6-S7). Such results reiterate the mismatch between carbon and biodiversity in tropical regions[29], and support the need to use multiple indicators when assessing environmental impacts of forest loss. These different impacts may play a different role in decision making and thus help support more targeted policies towards conservation.

Under the pre-signing scenario, between 2018-2036 Colombia would reduce the average impact on the range of forest-specific species by nearly 50% relative to 2000-2018, whereas under the post-signing scenario it would increase by 33% (1.48% and 3.92% *vs* 2.93%). Moreover, we projected further losses across departments with an average of 12 to 31 species being impacted (Low to High), of which nearly 50% are forest-specific and thus less likely to persist once the trees are removed. By 2036, for each department, this represents an average loss of between 2.5% and 6.3% of the species present in 2018 (Tables S4-S5), with departments such as Arauca, Bolivar e Sucre having the highest proportional losses by 2036 (Figure 4a-b), ranging from 6 to 15% of overall and forest-specific species losses relative to 2018. For the endemic species, the proportional losses are expected to range from an average 1.7% (Low) to 4.6% (High) (Tables S6-S7), with Santander, Sucre and Bolivar being projected to have the highest losses (Figure 4c-d).

While aggregated species indicators may be useful to highlight hotspots of change, species-specific analyses can provide additional information to help design more targeted conservation actions, i.e. to incorporate the ecology of the species and what is known of the behaviour into policy including information about thresholds of species loss[30]. Therefore, our final set of results concern species-specific indicators to highlight species at under greater risk of being impacted by future deforestation in Colombia. On average, 71% of these species' potential distribution (Figure S1) overlapped with forests in 2000, reducing by 3% in 2018. Between 2000 and 2018, each species lost on average 2.6% of their habitat, reaching a maximum of 19% loss in the case of *Alchornea castaneifolia*; *Xiphorhynchus elegans* forest-specific species with highest loss of 18%, and *Ortalis garrula* endemic species with highest loss (-12%). From the three higher IUCN threat categories, we found that the Near Threatened *Egretta rufences* (-11%), the Endangered *Saguinus leucopus* (-7.4%), which is also an endemic species and the Critically Endangered *Crocodylus intermedius* (-3.2%) were the most impacted species in terms of range loss.

Importantly, endemic species are widely impacted (Figure 5), but which ones depend on the scenario. For instance, the critically endangered and endemic species *Lipaugus weberi* would be more impacted than in the past in two out of three scenarios (except Low, Figure 5), whereas the Endangered endemic species *Saguinus leucopus* is projected to be only as impacted as in the past in the BAU scenario (Figure 5c). Such variations are even higher when we analyse impacts at the department level (Table S9). One important limitation is that we did not consider whether the species could survive in highly transformed habitats. Nonetheless, this information is crucial for policy and decision-makers to develop effective measures as there is no one-size-fits-all when it comes to species' conservation. This informs not only on the amount of forest lost, the potential carbon and stock volume losses, the overall species impacted, and the specific species impacts. Such information allows policy makers to assess the trade-offs of allowing deforestation to follow certain scenarios at the department and region levels.

With our analyses we firstly aimed to provide policy- and decision-makers in Colombia a better understanding of the changes in drivers of deforestation (at the national scale) across the three different periods analysed, and then provide a combined estimate of potential future environmental impacts (in terms of species losses, aboveground biomass, and growing stock volume) in Colombia. While some of the drivers did not change over time (e.g. roads), importantly, we demonstrated that conservation areas may be losing their effectiveness in preventing deforestation and that new frontiers are being opened close to areas previously under control of armed groups, a finding supported by recent research[31–33]. An understanding of where deforestation is likely to occur and the drivers leading to such changes is useful for decision making given the current and expected trends of deforestation risking the biodiversity of one of the most important hotspots across the globe. Further, with our department level analyses, we hope to attribute a sense of responsibility not only to the government of Colombia but also to the regional authorities to ensure that they act before it is too late.

While we obviously do not advocate for a ‘gunpoint conservation’ approach, and the current pandemic might also play an important role, it is important to recognise that the years leading to the signing of the agreement were beneficial for the country’s natural resources. Suggesting that formal governance is essential for Colombia to protect its forests[34], since higher state presence and judicial capacity seem to reduce deforestation[35]. Our analyses are in line with previous research that raised concerns about the future of the ecosystems in Colombia in a post-peace agreement era [5,31,33], and support calls for the Colombian government to strengthen environmental research and engage scientists in decision-making processes[36]. As Colombia ratified several international commitments in terms of biodiversity conservation as well as climate change action, highlighting potential consequences of investment in infrastructure, and allowing deforestation to progress without major counter-action, is hopefully important to raise policy- and decision-makers on the need to act now.

Methods

Model Input Data Sources

To analyse forest cover change in Colombia we downloaded the freely available tree cover (0-100%) and tree loss (0-18) dataset from Hansen et al. (2013), version 1.6 (2000-2018). The tree cover dataset was transformed into a binary forest/non-forest map (1/0) using a conservative threshold higher than the forest definition of the Food and Agriculture Organisation (10% tree cover)[37], i.e. a pixel was classified as forest if tree cover was above 50%. The full time series (2000-2018) was then split into three distinct time periods for all subsequent analyses.

As highlighted by Baptiste et al.[5], Aguilar et al.[38] and others, forest cover change and the armed conflict in Colombia have historically been quite interrelated. It has been argued that forests were used to protect coca cultivation, and that areas where the armed conflict was more intense have been protected by the lack of socio-economic development. Therefore, we split the time series into three periods related to the peace agreement signing: *post-signing* corresponding to the last three years (2016-2018) when deforestation rates increased rapidly (High scenario); *pre-signing* (2013-2015) when deforestation rates were at the lowest levels (Low scenario), and the full time series (2000-2018) as a business-as-usual scenario (BAU scenario). These three periods were used to calibrate three different deforestation models, thus assessing the strength and direction of impact of the different drivers across time periods, and then used to project deforestation up until 2036. We then compared the outcomes not just in terms of forest change under each scenario, but also potential impacts on aboveground biomass and local biodiversity.

Alongside the forest maps, we collected a myriad of variables representing the main direct and indirect drivers of forest cover change in Colombia[20,39], and on tropical deforestation more broadly[22]. For instance, Armenteras et al.[20] and Ayram et al.[39] identified some of the ‘traditional’ drivers (roads, population, elevation, slope, etc.), whereas Murad and Pearse[40] as well as Davalos et al.[41] highlighted the role of agriculture (cattle ranching), and others identified more Colombia-specific drivers such as coca cultivation[9,41], illegal mining and oil pipelines[42]. Conversely, protected areas have been found to reduce deforestation[32] although their effectiveness seems to be reducing since the peace agreement, with increased fires taking place inside these areas[33]. As a result of this literature search, we included predictors that reflected accessibility, such as the Euclidean distance to the nearest road (in m), to the nearest trail (in m), to the nearest river (in m), as well as the slope (in degrees) and elevation (in m); predictors related to other socio-economic activities such as soil fertility (low to high), Euclidean distance to extraction wells (in m), and to mining operations (in m), as well as population density (number of people per km^2). Two variables were directly related to the conflict: armed conflict density (number of armed conflict actions per km^2), and Euclidean distance to coca plantation (in m). Finally, three land tenure related variables: protected areas, indigenous areas and African communal lands (all as binary variables, in/out). The data were all freely available upon request from the Alexander von Humboldt Institute in Bogotá, Colombia. All data layers were pre-processed to ensure spatial overlap at 1 km^2 resolution using the MAGNA Colombia coordinate system, and are shared publicly in the author’s GitHub repository (see Supplementary Materials).

Spatially-explicit deforestation model

In this study we used a widely validated spatially-explicit tropical deforestation model[21,29,30,43,44] (code provided in GitHub, see Supplementary Materials) to: (1) understand the fluctuations in the effect of the drivers of deforestation in Colombia in the three different time periods (2000-2018, 2013-2015, and 2016-2018); and (2) project the future rates and location of deforestation using the three models as three different scenarios (Low, BAU and High). In practice, the model projects the cumulative probability of each 1 km^2 pixel changing from forest to non-forest by 2036, and it allows us to understand what is driving deforestation in each of the time periods analysed.

The model is based around $P_{defor,x,t}$, i.e. the probability that pixel x becomes deforested in a set interval of time t. This probability is defined as a logistic function (Eq. 1), so as $k_{x,t}$ goes from minus infinity to plus infinity, $P_{defor,x,t}$ goes from 0 to 1. Simple linear models can then be tested for $k_{x,t}$ as a function of the driver variables affecting location x at time t.

$$Pdefor_{x,t} = \frac{1}{(1 + exp^{-k_{x,t}})} \qquad \text{Eq. (1)}$$

To ensure comparability, each model was initiated for each time period with all variables (representing the drivers of deforestation) described before. Then, using an internal model selection procedure based on maximum likelihood (see Rosa et al.[21] for details) the variables that mostly contributed to explain the rate and patterns of deforestation in Colombia in each time period were identified. Once the 'best' model (the one where the combination of variables led to the highest test likelihood) for each time period was identified, each models' area under the receiver operating characteristic (ROC) curve, a measure of goodness-of-fit of the model, was determined for each time period. All three models showed good fitness to the data, i.e. AUC of 0.89 (BAU), 0.90 (Low) and 0.90 (High).

The calibrated models were then used to project future deforestation by 2036 under each of the three scenarios (Low, BAU and High). In fact, to allow for the uncertainty of the parameter values to be propagated through the projections, we randomly sampled the Gaussian distribution of each parameter for 100 iterations to ensure that each iteration would lead to a slightly different outcome. Further, the model does not impose a rate of change, rather this emerges from the probabilities determined by the model itself, by comparing the probability with a random uniform number for each pixel (in each year) and then selecting that pixel to be deforested if the probability is larger than the random number. The procedure is repeated for the same 100 iterations to allow for quantification of uncertainty posed by the sampling of the posterior distribution of the parameters as well as the random selection procedure. In practice, for each year and each scenario, we produced 100 forest/non-forest maps, as well as an accumulated probability of deforestation map by 2036. The probability maps are the result of combining all iterations into a final probability of each pixel being deforested, i.e. a pixel that was selected 80 times out of 100 to be deforested would have an 80% chance of being deforested by 2036. For a more in-depth description of the modelling approach, see Rosa et al.[21], where the model was originally described.

Estimating impacts on local biodiversity

To assess potential impacts on biodiversity in Colombia (as a country and per department), we overlapped the historical forest maps (2000, 2018) and our projections of deforestation by 2036 with the BioModelos dataset[24] (see Data availability in Supplementary Materials). This dataset contains expert-validated species distribution maps at 1 km^2, and includes 5808 species for Colombia, of which, according to the International Union for Conservation of Nature (IUCN) 2313 are forest-specific, 99 are endemic and 84 are both endemic and forest-specific. These were the four subsets of data that we used in our analyses (Figure S1) for the aggregate analyses, alongside species-specific analyses were also performed.

On average, we found that an individual 1 km^2 pixel contained 908 species, 464 forest-specific species, three endemic species and two species that were simultaneously endemic and forest-specific. Of the forest-specific species in the Biomodelos dataset, four were considered Critically Endangered (CR), two of them endemic, i.e. *Crocodylus intermedius, Hyloxalus abditaurantius, Lipaugus weberi* and *Oophaga histrionica*. The seventeen species classified by IUCN as Endangered (EN) are all forest-specific species, eight of which are endemic. Eighty are Near Threatened (NT), 62 are Vulnerable (V) and 2142 are of Least Concern (LC), with the remainder either Data Deficient or Unavailable. Departments varied greatly in terms of number of species present with Casanare, Caquetá and Meta being the richness in terms of forest-specific species, and Antioquia, Córdoba and Risaralda the richest in terms of endemic forest species (Table S8).

Our analyses focused on observed impacts (2000-2018) as well as projected impacts (2018-2036) under the three scenarios: Low, BAU and High, both for Colombia as a whole and per department (Table S10). In particular, we overlapped the forest maps in 2000, in 2018 and the 100 forest/non-forest maps projected in 2036 under each scenario to estimate the loss in range (in %) of the four groups of species mentioned above (total richness, forest-specific richness, endemic richness and forest and endemic richness), as well as for each individual species (Eqs. 2 and 3). Results for the whole of Colombia and at the department level are provided as an average of the impacts on each group of species (Eq 4., Tables S4-7) as well as the total impact on each species individually (Eq. 5). Finally, the impacts per species were ranked and the top-impacted species per department were also identified (Table S9). By providing species-specific information across two spatial scales we hope to inform more targeted conservation actions.

$$SR_{2000,2018} = Forest_{2000,2018} \, x \, SR_0 \qquad \text{Eq. (2),}$$

$$SR_{2036,s} = \frac{(\sum_i^I Forest_{2036,s} \, x \, SR_0)}{I} \qquad \text{Eq. (3),}$$

where species richness in time t equals the forest map in time t (2000, 2018 or each i of the I = 100 iterations in 2036, for each scenario s) multiplied by the species richness base map (SR_0). The species richness base map can be for all species, forest-specific species, endemic species, forest and endemic species or the individual species range, depending on the analysis being carried out.

To aggregate the results per department or for the whole of Colombia:

$$\overline{SR}_{d,t,s} = \frac{\sum_{n}^{N_d} SR_{n,t,s}}{N_d} \quad \text{Eq. (4),}$$

where, $\overline{SR}_{d,t,s}$ (in number of species) corresponds to the overall species richness, forest-specific species, endemic species, or forest-specific and endemic species; d is the department or Colombia as a whole, and N the total number of pixels (N_d = number of pixels in department d). Repeated for each scenario (s) and each time step (t).

For each individual species, we determined the total range reduction by calculating $SPP_{d,t,s}$, i.e. the species range in time t under scenario s (Eq. 5), and then calculating the % change relative to a previous t (2000 or 2018). For example, to calculate the reduction in range of the species *Saguinus leucopus*, in department d, between 2018 and 2036 under the High scenario, we applied the following equations:

$$SPP\_saguinus_{d,t,s} = \sum_{n}^{N_d} SPP\_saguinus_{n,t,s} \qquad \text{Eq. (5),}$$

$$\%SPP\_saguinus_{d,18-36,HIGH} = \left(\frac{SPP_{saguinus_{d,2036,HIGH}} - SPP_{saguinus_{d,2018}}}{SPP_{saguinus_{d,2018}}} \right) x\ 100 \quad \text{Eq. (6).}$$

The same logic was applied for all other species, all other departments, and all other time steps under consideration in our analyses. These temporal ratios were also determined for the groups of species.

Estimating impacts on aboveground biomass and growing stock volume

To assess potential impacts on aboveground biomass (AGB in t/ha) as well as growing stock volume (GSV in m^3/ha) in the whole of Colombia as well as per department, we used the data provided by Santoro et al.[25] (see Data availability in Supplementary Materials). As per the FAO definition, adopted by the authors, GSV represents the “volume of all living trees more than 10 cm in diameter at breast height measured over bark from ground or stump height to a top stem diameter of 0 cm, excluding smaller branches, twigs, foliage, flowers, seeds, stump and roots”; whereas AGB is “the mass, expressed as oven-dry weight of the woody parts (stem, bark, branches and twigs) of all living trees excluding stump and roots”. In detail, we downloaded the two 40° x 40° tiles that covered the whole of Colombia (N40W100 and N00W100), and processed the data to only include values within the boundaries of the country (Figure S2). We downloaded the data for 2010 as well as the error estimates on both AGB and GSV as provided by Santoro et al.[25]. These latter datasets were used to allow for uncertainty to be propagated in the analysis.

Afterwards, we followed a similar approach as the one described above for the biodiversity datasets, i.e. we overlapped the forest maps in 2000, in 2018 and the 100 forest/non-forest maps projected in 2036 under each scenario with the AGB, GSV and respective error maps (Eqs. 7-8). We then calculated the total AGB and GSV per pixel and aggregated these values to the whole of Colombia as well as per department using a simple sum (the same for the error maps) as stated in Eq. 9. Relative % changes in AGB/GSV over time were then determined for each scenario and each department in a similar fashion as described above in the biodiversity analyses. Although we found that AGB and GSV were unsurprisingly highly correlated (Pearson’s correlation [r] = 0.99, $p < 0.001$), we still chose to present both results as they provide estimates that might be relevant for different policy and decision makers.

$$AGB_{2000,2018} = Forest_{2000,2018} \; x \; AGB_0 \quad \text{Eq. (7),}$$

$$AGB_{2036,s} = \frac{(\sum_i^I Forest_{2036,s}\ x\ AGB_0)}{I} \qquad \text{Eq. (8),}$$

where AGB in time t equals the forest map in time t (2000, 2018 or each i of the I = 100 iterations in 2036, for each scenario s) multiplied by the AGB base map (AGB_0). To then aggregate for the whole of Colombia or per department d:

$$AGB_{d,t,s} = \sum_n^{N_d} AGB_{n,t,s}\ x\ 100 \qquad \text{Eq. (9),}$$

where $AGB_{d,t,s}$ is the total aboveground biomass (tonnes) in each department or Colombia as a whole (d) for each time step t (2000, 2018, and 2036), under each scenario s (observed, Low, BAU and High). The same procedure was adopted for total GSV (m^3), as well as for the error maps for both AGB (tonnes) and GSV (m^3). N_d is the number of pixels in each department d.

On average, we found that an individual 1 km^2 forested pixel in 2000 contained 137.91 t/ha of aboveground biomass (76.13 t/ha error) and 163.37 m^3/ha of growing stock volume (85.76 m^3/ha error). The average AGB and GSV in Colombia were reduced by 2.40% and 2.37%, respectively, by 2018, with strong variations across departments (Tables S2 and S3). Finally, it is important to notice that when correlating AGB (and GSV) values with species richness, we observed that pixels with higher AGB (and GSV) also had more species in them, although this was a weak positive correlation ($r = 0.17$ for AGB and $r = 0.19$ for GSV, p-value < 0.001), which strengthen slightly with forest-specific richness data ($r = 0.24$ for AGB and $r = 0.25$ for GSV, p-value < 0.001). Interestingly, pixels with higher endemism, overall or of forest-specific species, seem to have less AGB and GSV ($r = -0.09$ for AGB and $r = -0.08$ for GSV, p-value < 0.001, for all endemic species; and $r = -0.10$ for AGB and $r = -0.09$ for GSV, p-value < 0.001, for forest-specific endemic species).

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Author contributions

IMDR and JMOQ designed the analysis and IMDR developed the model and run the analyses. ED prepared the datasets and helped with data analysis. EK prepared the species data and helped with analysis. MVP revised code. All authors contributed to the writing.

Tables

Table 1 – Model calibration results for best model under each scenario (BAU: 2000-2018, Low: 2013-2015 and High: 2016-2018). Posterior distribution mean and 95% confidence interval used for the model projections. Model goodness of fit shown inside round brackets next to the scenario name (Area under the ROC curve).

	BAU (0.89)		**Low (0.90)**		**High (0.90)**	
Parameter	*mean*	*± 95% C.I.*	*mean*	*± 95% C.I.*	*mean*	*± 95% C.I.*
Intercept	-1.92	0.58	-3.74	0.16	-2.41	0.24
Previous deforestation	1.96	1.47	0.64	0.37	-	-
Distance to all roads	-1.5×10^{-5}	1.1×10^{-5}	-3.9×10^{-5}	5.5×10^{-6}	-6.4×10^{-5}	1.3×10^{-5}
Distance to type 1 roads	-	-	-	-	-	-
Distance to rivers	-	-	-	-	-	-
Elevation	-7.8×10^{-4}	1.6×10^{-5}	-8.8×10^{-4}	2.0×10^{-4}	-9.3×10^{-4}	9.2×10^{-5}
Distance to mining	-	-	-	-	-	-
Slope	-	-	-0.03	0.01	-0.02	0.008
Distance to trails	-	-	-	-	-	-
Armed actions density	1.6×10^{-5}	2.9×10^{-4}	4.1×10^{-4}	3.9×10^{-4}	-	-
Distance to coca plantations	-3.0×10^{-5}	3.5×10^{-6}	-1.2×10^{-5}	3.5×10^{-6}	-1.3×10^{-5}	1.1×10^{-5}
Population density	-	-	-	-	-	-
Distance to Extraction Wells	-	-	-	-	-	-
Protected Areas	-0.59	0.25	-0.99	0.32	-0.54	0.15
African communities	-1.42	0.38	-1.90	0.10	-1.18	0.21
Indigenous communities	-1.31	0.18	-1.23	0.26	-1.24	0.18

Figures

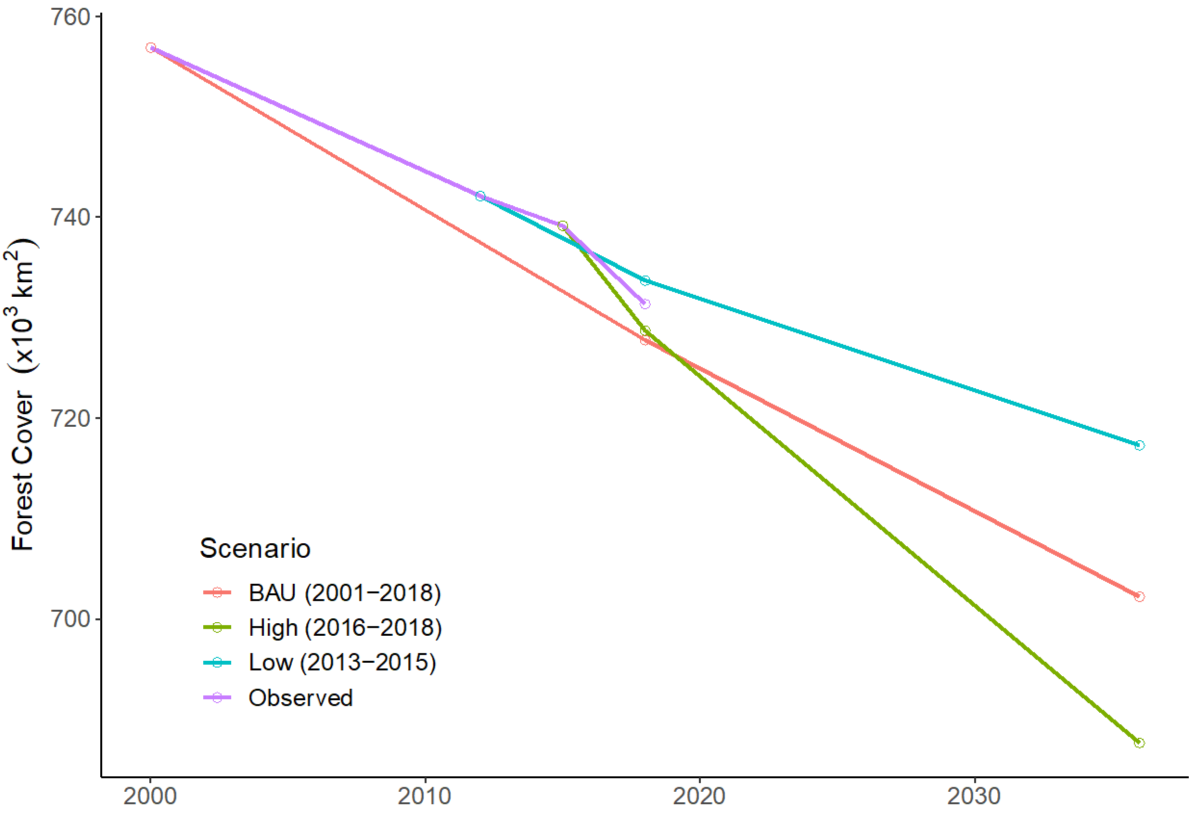

Figure 1 – Forest cover loss from 2000 through 2036 under three scenarios. Error bars represent 95% confidence interval (100 iterations of the model).

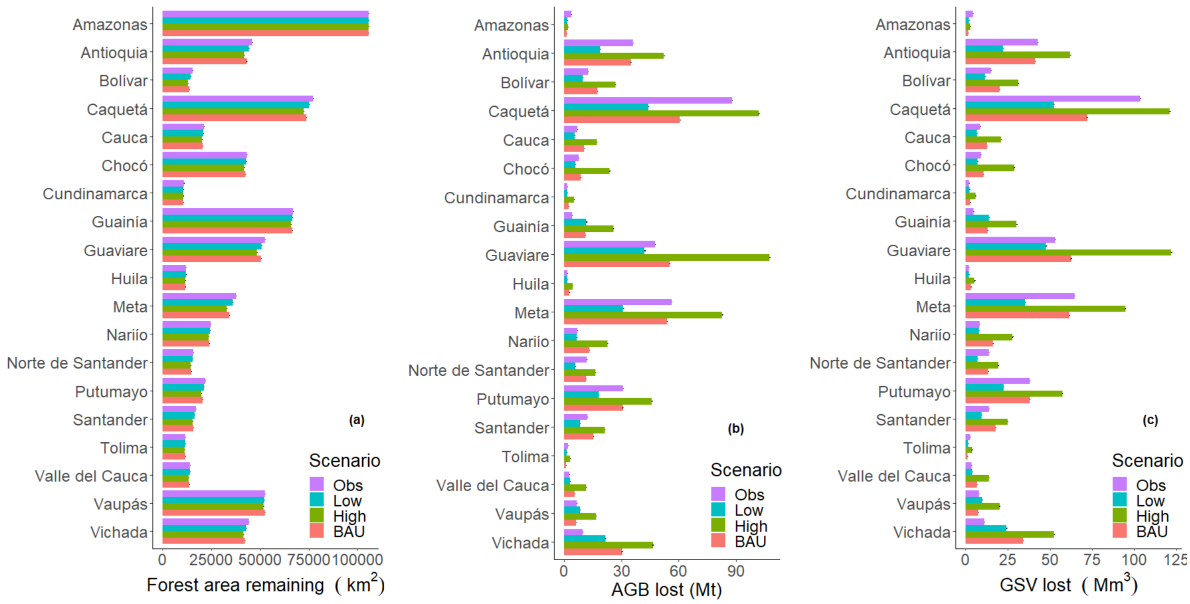

Figure 2 – (a) Forest area in 2018 (Obs) and remaining forest by 2036 under the three scenarios (BAU, Low and High), per department in Colombia. Aboveground biomass (AGB) (b) and growing stock volume (GSV) (c) lost between 2001-2018 (Obs), under the same three scenarios, per department in Colombia. Error bars represent 95% confidence interval (100 iterations of the model). Showing only departments with at least 10.000 km^2 of forest area in 2018 to improve readability (all departments in Tables S2-S4).

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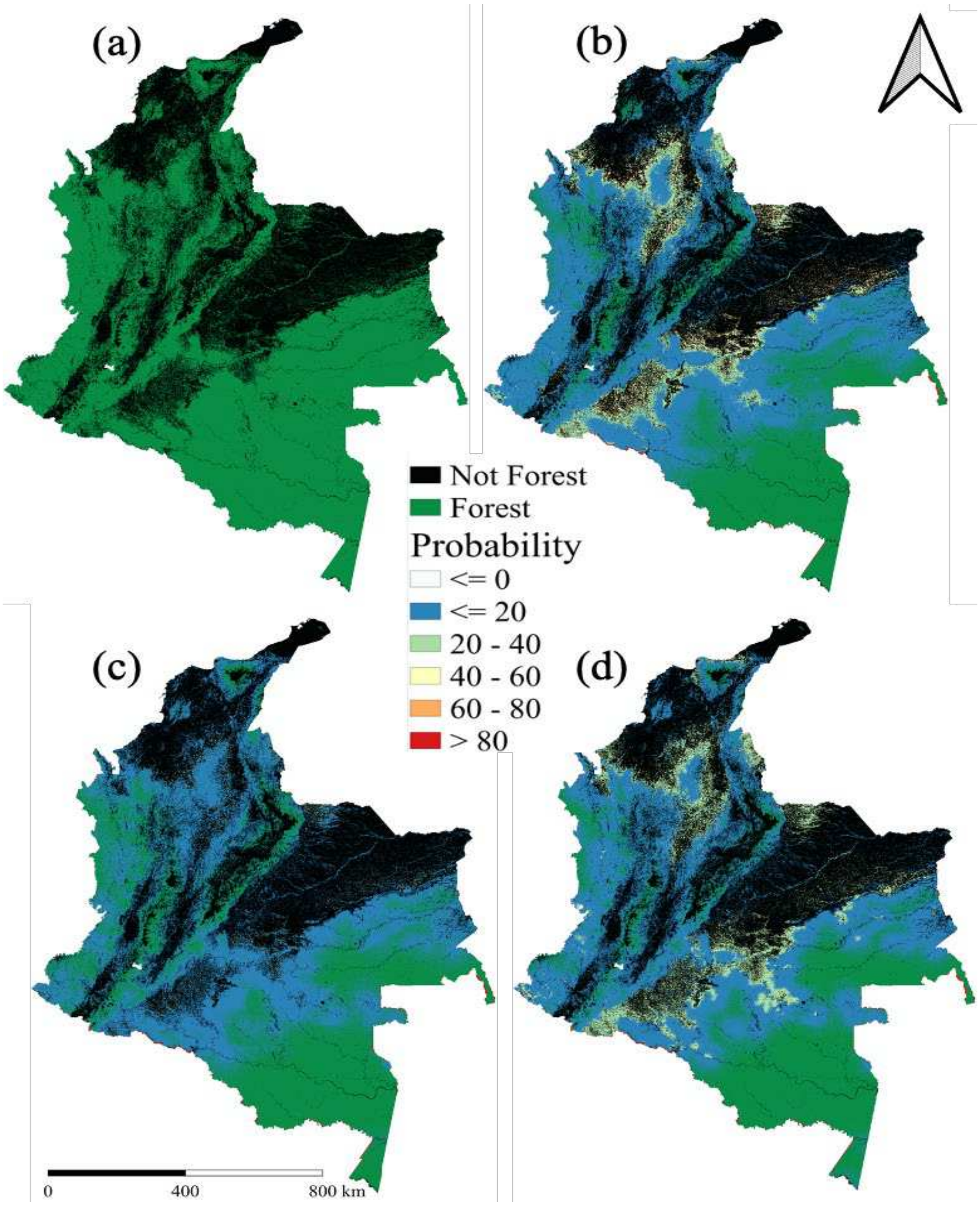

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595 **Figure 3 –** Observed forest cover (a) in 2018, and projected probability of loss of forest by

596 2036 under the three scenarios (b) BAU, (c) Low, and (d) High.

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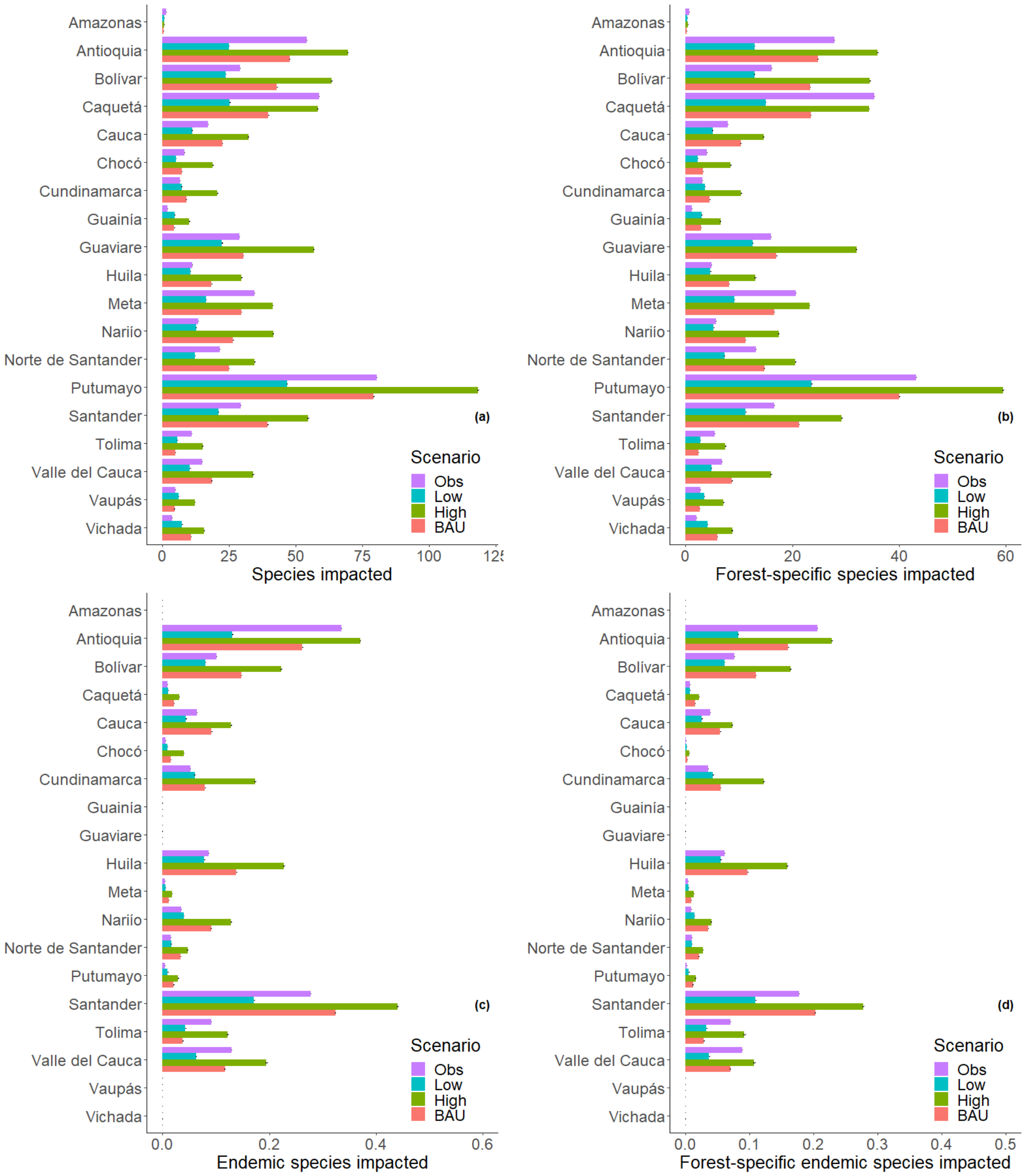

Figure 4 – Observed (2001-2018) and projected (2018-2036) average impact on the number of (a) all species, (b) forest-specific species, (c) endemic species and (d) forest-specific endemic species, per department in Colombia, under three different scenarios (Obs, High, Low and BAU). Error bars represent 95% confidence interval (100 iterations of the model). Showing only departments with at least 10.000 km^2 of forest area in 2018 to improve readability (all departments in Tables S5-S8).

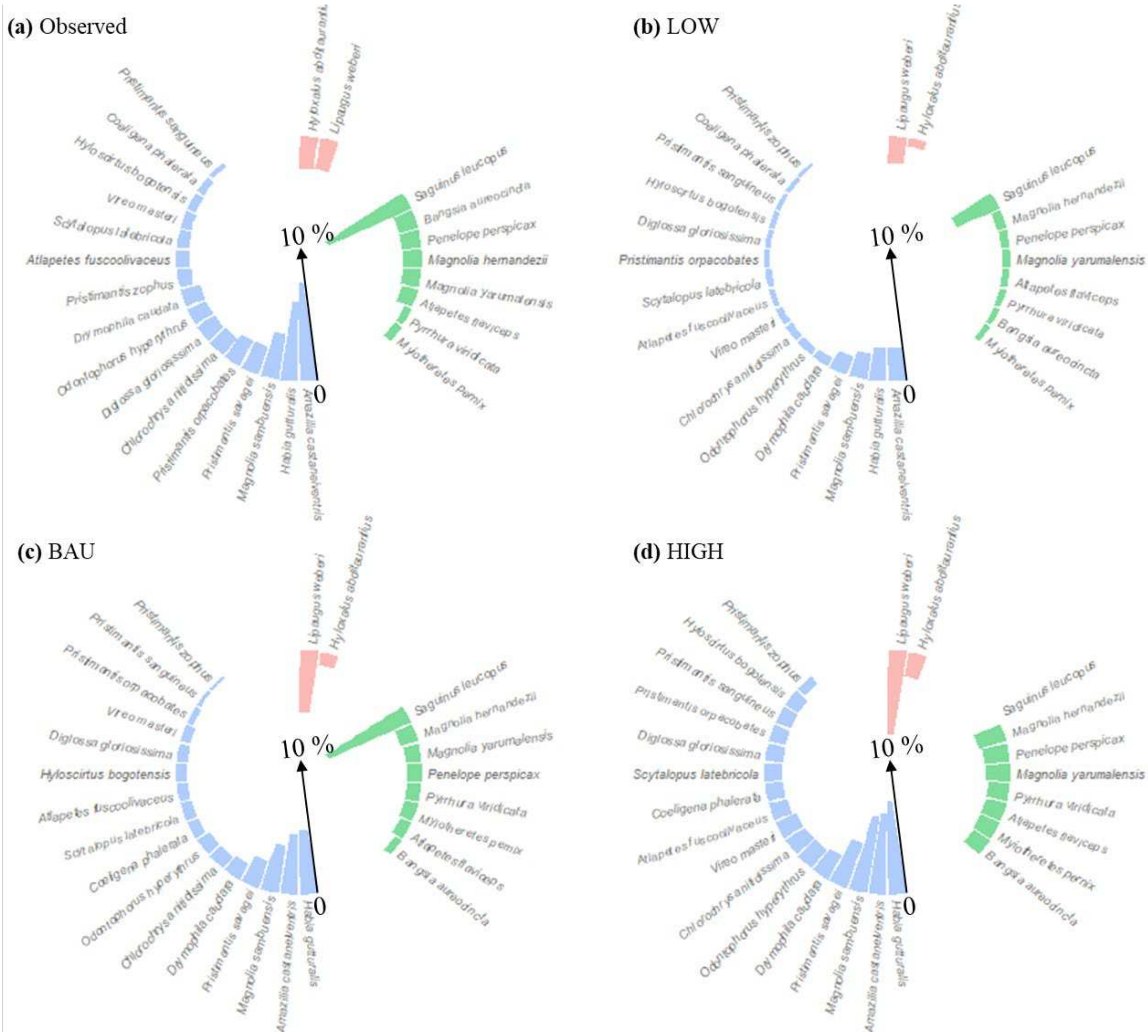

Figure 5 – Impact on the overall range (- %, loss of range) in Colombia, on Near Threatened (blue), Endangered (green), and Critically Endangered (red) endemic species (a) observed between 2000 and 2018; and projected between 2018-2036 under the (b) Low, (c) BAU and (d) High scenarios. For all other species, please see Supplementary File “Colombia_Species_ScenariosImpacts.csv”.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ColombiaSpeciesScenariosImpacts.csv
- ColombiaperDepartmentSpeciesScenariosImpacts.csv
- manuscriptSM.docx