Spatial scenario of tropical deforestation and carbon emissions for the 21st century

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Tropical forests are disappearing at an alarming rate due to human activities. Here, we provide spatial models of deforestation in 92 countries covering all the tropical moist forests in the world. Our results question the global effectiveness of protected areas in decreasing deforestation and allow reinterpreting the impact of roads on deforestation in terms of both accessibility and forest fragmentation. Using our models, we derive high-resolution pantropical maps of the deforestation risk and future forest cover for the 21st century under a “business-as-usual” scenario based on the deforestation rates observed in the 2010s. Under this scenario, 42% (39–56%) of tropical moist forests are expected to disappear during the course of the 21st century, and many tropical countries will have lost all their forests by 2100. The remaining forests in 2100 will be highly fragmented and located in remote places. We also show that future deforestation will likely concern forests with higher carbon stocks, and hence that carbon emissions from tropical deforestation are expected to increase (up to 0.583–0.628 Pg/yr in 2100). Combined with the decreasing carbon absorption (down to 0.312 Pg/yr in 2100) due to the decrease in forest cover, tropical moist forests will likely become a strong net carbon source in the 21st century.

While models and scenarios of carbon dioxide emission and climate change have been developed for several years by the Intergovernmental Panel on Climate Change (IPCC 2014) and are now widely used by the scientific community and known to the general public, equivalent models and scenarios for land-use change and biodiversity at the global scale are still relatively scarce (Pereira et al. 2020). Moreover, baseline scenarios of deforestation and associated carbon dioxide emission are necessary for implementing REDD+ (Reducing Emissions from Deforestation and forest Degradation) activities in the framework of the Paris Agreement on climate change (Goetz et al. 2015). Spatialized forest cover change scenarios are crucial because both forest carbon stocks (Avitabile et al. 2016, Baccini et al. 2017) and biodiversity (Kremen et al. 2008, Mittermeier et al. 2011) vary considerably in space at fine scale. Non-spatial scenarios of forest cover change (FAO 2020) cannot be used to forecast associated carbon emissions and change in biodiversity accurately, or for systematic conservation planning at the local scale. Spatial forecasts of forest cover change are based on spatial statistical models, which enable the estimation of a probability of change in space as a function of a set of spatial predictors (Rosa et al. 2014). In addition to forecasts, statistical models can be used to identify the main drivers of deforestation and quantify their relative effects. For example, models can be used to assess the impact of roads on the risk of deforestation (Laurance et al. 2014) and the effectiveness of protected areas in reducing deforestation (Andam et al. 2008, Wolf et al. 2021).

Few authors have attempted to provide spatialized forest cover change scenarios in the tropics at large spatial scales. The most significant studies to date have focused on modelling and forecasting forest cover change at the scale of the Amazonian basin (Soares-Filho et al. 2006, Swann et al. 2015, Aguiar et al. 2016). In this study, we present a spatial model to forecast the effects of deforestation and forest regeneration on carbon emissions and biodiversity at the global scale. Our results show that deforestation will likely occur in areas with high human pressure and low carbon stocks, and that the remaining forests will be highly fragmented and located in remote areas. Future deforestation will likely happen in forests with higher carbon stocks. In the absence of change in the deforestation rates, increase in carbon emissions from deforestation and decrease in carbon absorption due to reduction of forest cover will make tropical forests a major carbon source in the 21st century.
paper, we used high-resolution spatial data to model and forecast deforestation at the pantropical scale. This was made possible by the recent availability of pantropical spatial datasets of forest cover change (Vancutsem et al. 2021) and of global spatial datasets of explanatory factors related to deforestation at the required resolution (World Database on Protected Areas, SRTM Digital Elevation Database, and OpenStreetMap). We combine these extensive datasets in a spatial statistical model to test the effectiveness of protected areas in reducing deforestation and assess the impact of roads on the risk of deforestation at the pantropical scale. Assuming a business-as-usual scenario, we derive high-resolution maps of deforestation risk and future forest cover over the 21st century in the humid tropics. We also estimate the carbon emissions associated with projected deforestation and conduct an uncertainty analysis.

Scenario of deforestation by 2100

Using the study by Vancutsem et al. (2021) as a reference, we estimate that around 6.4 Mha (4.5–8.3 Mha) of tropical moist forest have been disappearing each year during the last decade (2010–2020), which corresponds to an annual area of 64,000 km², about the size of Greece or West Virginia. We show here that under a business-as-usual scenario of deforestation, 48% (39–56%) of the world's tropical moist forests will have disappeared over the course of the 21st century (Fig. 1 and Table 1). The percentage of lands covered by tropical moist forests would then decrease from 8.5% (1259 Mha) in 2000 to 4.7% (656 Mha) in 2100. We observed marked differences in the percentage of forest cover loss at continental and country scales (Fig. 2 and Table 1). In Southeast Asia, where the forest area remaining in 2020 is estimated at 248 Mha and the area deforested each year is estimated at 2.0 Mha/yr, the percentage of forest cover loss over the 21st century would reach 67% (52–79%). In Africa, where the annual deforestation rate is lower (1.9 Mha/yr), this percentage would be 53% (45–60%). In Latin America, where the annual deforestation rate is the highest (2.5 Mha/yr), but where the remaining tropical moist forest in 2020 is also much larger than in Southeast Asia and Africa (621 Mha), this percentage would be 38% (31–45%). Under a business-as-usual scenario of deforestation, three-quarters of the tropical moist forests that remained in 2000 will have disappeared around years 2120, 2160, and 2220 in Southeast Asia, Africa, and Latin America, respectively, with an average uncertainty of ±45 years (Fig. 2 and Table 1).

At the country scale, we predict that 41 countries (16 in Latin America, 21 in Africa, and four in Southeast Asia) out of the 92 we studied, plus 14 states in Brazil and one region in India, will lose all their tropical forests by 2100 (Fig. 1). Among these countries or regions, 19 countries (six in America, ten in Africa, and three in Asia), three states in Brazil, and one region in India had more than one million hectares of forest in 2000, thus underlining the

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Fig. 1. Pantropical map of the predicted change in forest cover. Maps show the predicted change in tropical moist forest cover in the three continents (America, Africa, and Asia) for the period 2020–2100 under a business-as-usual scenario of deforestation. The horizontal black line represents the Equator. Study area boundaries are represented by dark grey lines. For the deforestation projections, we assumed no diffusion of the deforestation between countries. Forest areas in red are predicted to be deforested in the period 2020–2100, while forest areas in green are likely to still exist in 2100. Several countries are expected to lose all their tropical moist forests by 2100 (including Nicaragua and Mexico in Central America, Madagascar and Ghana in Africa, and Laos and Vietnam in Asia). We predict progressive fragmentation of the remaining forest in the future, with an increasing number of isolated forest patches of smaller size (e.g., Pará state in Brazil, the Democratic Republic of the Congo, and Indonesia). These maps make it possible to identify both future hotspots of deforestation and forest refuge areas (e.g., concentrated in the heart of the Amazon, West Central Africa, and Papua New Guinea). An interactive map is available at https://forestatrisk.cirad.fr/maps.html.
We provide past and predicted forest cover for the three continents and for the three countries with the highest forest cover in 2010 for each continent (Brazil in America, the DRC in Africa, and Indonesia in Asia). Past forest cover areas (in thousand hectares, Kha) refers to their status on January 1st 2000, 2010, and 2020 ("fc2000", "fc2010", and "fc2020", respectively). The mean annual deforested area d (Kha/yr) for the last decade from January 1st 2010 to January 1st 2020 with the corresponding mean annual deforestation rate p (%/yr). Projected forest cover areas are given for the years 2050 and 2100 ("fc2050" and "fc2100"). Projections are based on the remaining forest cover in 2020 ("fc2020") and the projected mean annual deforested area (d) assuming a business-as-usual scenario of deforestation. Column "los21" indicates the projected percentage of forest cover loss during the 21st century (2100 vs. 2000). Column "yr75" indicates the year at which 75% of the forest cover that remained in 2000 will have disappeared.

### Table 1. Past and predicted changes in forest cover

<table>
<thead>
<tr>
<th>Countries</th>
<th>fc2000 (Kha)</th>
<th>fc2010 (Kha)</th>
<th>fc2020 (Kha)</th>
<th>d (Kha/yr)</th>
<th>p (%/yr)</th>
<th>fc2050 (Kha)</th>
<th>fc2100 (Kha)</th>
<th>loss21 (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>374,282</td>
<td>348,650</td>
<td>334,948</td>
<td>1,370</td>
<td>0.4</td>
<td>293,844</td>
<td>225,336</td>
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<td>DRC</td>
<td>131,298</td>
<td>125,605</td>
<td>118,283</td>
<td>732</td>
<td>0.6</td>
<td>96,318</td>
<td>59,711</td>
<td>55</td>
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<td>Indonesia</td>
<td>139,358</td>
<td>126,473</td>
<td>117,072</td>
<td>940</td>
<td>0.8</td>
<td>88,876</td>
<td>41,883</td>
<td>70</td>
</tr>
<tr>
<td>America</td>
<td>687,339</td>
<td>646,685</td>
<td>621,229</td>
<td>2,545</td>
<td>0.4</td>
<td>544,869</td>
<td>427,790</td>
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<tr>
<td>Africa</td>
<td>274,993</td>
<td>258,401</td>
<td>239,681</td>
<td>1,871</td>
<td>0.7</td>
<td>188,403</td>
<td>129,045</td>
<td>53</td>
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<tr>
<td>Asia</td>
<td>297,090</td>
<td>268,058</td>
<td>248,035</td>
<td>2,002</td>
<td>0.8</td>
<td>188,558</td>
<td>98,922</td>
<td>67</td>
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<tr>
<td>All cont.</td>
<td>1,259,422</td>
<td>1,173,144</td>
<td>1,108,945</td>
<td>6,418</td>
<td>0.6</td>
<td>921,830</td>
<td>655,757</td>
<td>48</td>
</tr>
</tbody>
</table>

Fig. 2. Projected forest cover loss per continent. Points represent the observed percentage of forest cover loss (in comparison with the year 2000) for the years 2000 (0%), 2010, and 2020, for America, Africa, and Asia. Lines represent the projected percentage of forest cover loss (in comparison with the year 2000) from year 2020 to 2400 per continent. For the deforestation projections, we assumed no diffusion of the deforestation between countries. Under this assumption, deforestation at the continent scale is rapidly decreasing (dashed lines) once large countries (Brazil for America, DRC for Africa, and Indonesia for Asia) have lost all their forests (ca. 2260, 2180, and 2140, respectively, see SI Appendix, Table S16). The horizontal black line indicates a loss of 75% of the forest cover. Under a business-as-usual scenario, this would happen ca. 2120, 2160, and 2220 for Asia, Africa, and America, respectively. The confidence envelopes around the mean are obtained using the lower and upper bounds of the confidence intervals of the mean annual deforested areas for all study areas.

As tropical forests shelter a large proportion of terrestrial biodiversity and carbon stocks on land, future tropical deforestation is expected to have strong negative impacts on both biodiversity and climate. The impact of projected deforestation on carbon emissions is discussed below, but rigorous assessment of the impact of projected deforestation on biodiversity is beyond the scope of this study. Such an impact analysis would require accurate species distribution and biodiversity maps including a large number of species representative of the biodiversity in the tropics. Such maps are not available to date (Pimm et al. 2014). Nonetheless, as a rough estimate, if we consider only endemic species (Mittermeier et al. 2011) in the six biodiversity hotspots where almost all the tropical forest is predicted to disappear by 2100, and assume that most of these species depend on tropical moist forests, deforestation would lead to the extinction of 29,140 species of plants and 4,576 species of vertebrates (including birds, reptiles, amphibians, freshwater fishes, and mammals) which cannot be found anywhere else on Earth (SI Appendix, Table S18).
Carbon emissions under a business-as-usual scenario of deforestation

Here we estimate the aboveground carbon emissions associated with deforestation projected for 2020–2110 under a business-as-usual deforestation scenario. When computing carbon emissions associated with projected deforestation, we assume that the carbon stocks of existing forests will remain stable in the future. Under a business-as-usual scenario of deforestation (i.e., constant annual deforested area), the change in predicted annual carbon emissions is only attributable to the location of the future deforestation (Fig. 1 and SI Appendix, Fig. S11) and to the spatial distribution of forest carbon stocks (SI Appendix, Fig. S12).

We used three aboveground biomass maps to assess carbon emissions associated with deforestation of tropical moist forests. Using the WHRC map (Zarin et al. 2016), for which carbon stocks are less variable in space than for the two other maps (SI Appendix, Fig. S12), annual carbon emissions should remain almost constant throughout the 21st century at about 0.600 Pg/yr (SI Appendix, Fig. S13). In contrast, both the ESA CCI (Santoro et al. 2021) and the WUR (Avitabile et al. 2016) maps suggest a substantial increase in carbon emissions, from 0.432 Pg/yr in 2010–2020 with the ESA CCI map (or 0.467 Pg/yr with the WUR map) to 0.590 Pg/yr in 2090–2100 (or 0.628 Pg/yr), which corresponds to a 27% (or 35%) increase in annual carbon emissions (Fig. 4 and SI Appendix, Fig. S13). Using either the ESA CCI or WUR maps, an increase is predicted for all three continents.

The predicted increase in annual carbon emissions is explained by the fact that forest areas which will be deforested in the future have higher carbon stocks. Several studies have shown that elevation is an important variable in determining forest carbon stocks (Saatchi et al. 2011, Vieilledent et al. 2016, Cuni Sanchez et al. 2021). Forest carbon stocks are expected to be optimal at mid-elevation (Vieilledent et al. 2016) due to higher orographic precipitation at this elevation and because the climatic stress associated with winds and temperature is lower at mid-elevation than at high elevation. Here, we show that low-elevation areas have been more deforested than high-elevation areas (SI Appendix, Tables S4, S5). This is explained by the fact that low-elevation areas are more accessible to human populations and by the fact that arable lands are concentrated at low elevation, where the terrain slope is usually lower and the soil is more productive (Geist and Lambin 2002). Consequently, the predicted increase in carbon emissions can be explained by the deforestation moving towards higher elevation areas where forest carbon stocks are higher. Moreover, remote forest areas less disturbed by human activities in the past have accumulated large quantities of carbon (Dargie et al. 2017, Brinck et al. 2017). The progressive deforestation of more intact forests also explains the predicted increase in carbon emissions.

A decrease in annual carbon emissions is also predicted starting from ca. 2070 for Southeast Asia. At pantropical scale, a similar decrease is predicted from ca. 2070 when using the WHRC biomass map and from ca. 2090 when using the ESA CCI or WUR biomass maps (Fig. 4 and SI Appendix, Fig. S13). This decrease can be explained partly by the lower carbon stocks of future deforested areas (driven by the environment, such as lower carbon stocks at very high elevation) and partly by a decrease in the total deforested area at the continental and global scale, as countries progressively lose all their forest. In Southeast Asia, we expect that four countries which currently account for a significant proportion of the annual defor-
Biomass map: ESA CCI (Santoro et al. 2021)

Fig. 4. Annual carbon emissions associated with projected deforestation. Mean annual carbon emissions (Pg/yr) are estimated for ten-year intervals from 2010–2020 to 2100–2110. The dots represent the observed mean annual carbon emissions (based on past deforestation maps) in 2010–2020, for the three continents (America, Africa, and Asia), and the three continents combined. Lines represent the projected mean annual carbon emissions based on projected forest cover change maps from 2020–2030 to 2010–2110 per continent, and for all continents together. The confidence envelopes around the mean are obtained using the lower and upper bounds of the confidence intervals of the mean annual deforested areas for all study areas. The results shown here were obtained using the ESA CCI aboveground biomass map version 3. See SI Appendix, Fig. S13 for comparison with results obtained with other aboveground biomass maps.

Another consequence of tropical forest cover loss on the global carbon cycle is that the ability of tropical forests to uptake carbon from the atmosphere through photosynthesis and tree growth will decrease in the future. Requena Suarez et al. (2019) provide annual rates of aboveground net biomass change for old-growth tropical rainforests equal to +1.0, +1.3 and +0.7 Mg/ha yr for America, Africa, and Asia, respectively. Using these rates and our maps of future forest cover, we estimate that the amount of carbon absorbed annually by tropical moist forests will drop by 47% (38–55%) during the 21st century, from 0.589 Pg/yr in 2000 to 0.312 Pg/yr (0.267–0.363 Pg/yr) in 2100. Because carbon sequestration by tropical forests will not compensate for carbon emissions from tropical deforestation (0.583–0.628 Pg/yr in 2090–2100, range derived from the three biomass maps), tropical forests will likely act as an increasing net carbon source under a business-as-usual scenario, thus reinforcing climate change in the future.

Questioning the global effectiveness of protected areas at reducing deforestation

Here we show that protected areas significantly reduce the risk of deforestation in 70 study areas out of 119 (59% of the study areas). These 70 study areas accounted for 88% of the tropical moist forest in 2010 (SI Appendix, Table S6). Although this result shows a statistically significant effect of protected areas on the risk of deforestation in most of the study areas, the effectiveness of protected areas at reducing tropical deforestation is less evident. First, the magnitude of the effect is relatively low. On average, we found that protected areas reduce the risk of deforestation by 34% (Figs. 3, 5 and SI Appendix, Table S5). In a recent global study, Wolf et al. (2021) estimated that deforestation was 41% lower inside protected areas, a value higher than our estimate which is restricted to tropical moist forests. This means that protected areas do not prevent deforestation (deforestation does not stop at the boundaries of the protected areas) and that the risk of deforestation is only reduced to some extent within protected areas. Second, our study shows that the effect of protected areas is very variable from one region to another (SI Appendix, Table S6). For 18 countries or regions with a forest cover greater than 1 Mha in 2010, the effect of protected areas in reducing deforestation was not significant. Some of these countries or regions, such as the Amapa state in Brazil, Gabon, or Papua New Guinea, have very low historical deforestation rates (< 0.10% in 2010–2020) so that it seems complicated to reduce further the deforestation with a protected area network. But for some other countries or regions such as the Tocantins state in Brazil, Cuba, Nicaragua, Ethiopia, Ivory Coast or Nigeria, which have high historical deforestation rates (> 1% in 2010–2020), protected areas are ineffective at reducing deforestation on average. Moreover, when considering countries or regions with a forest cover greater than 1 Mha in 2010 where protected areas significantly reduce the risk of deforestation, the decrease in the risk of deforestation within protected areas varies considerably (standard deviation = 18.72%) from 2% (for the Bahia state in Brazil) to 82% (for Malaysia).

Like other studies reporting the effect of protected areas on deforestation (Andam et al. 2008, Wolf et al. 2021, Yang et al. 2021), our study shows that protected areas are effective on average in displacing deforestation outside protected areas in tropical countries, but not necessarily that protected areas play a role in reducing the deforestation intensity per se. Indeed, the factors that drive the intensity of deforestation at the country scale are more socio-economic or political, such as the level of economic development, which determines people’s livelihood and the link between people and deforestation (Geist and Lambin 2002), the size of the population (Barnes 1990), or the environmental policy (Soares-Filho et al. 2014). In tropical countries with weak governance (where environmental law enforcement is low) and with a low level of development (where the pressure on forests is high), it is very unlikely that protected areas will remain forested. Under a business-as-usual deforestation scenario, we assume that the deforestation intensity will remain constant over time. When all forests outside protected areas will have disappeared, deforestation is expected to occur inside protected areas (Fig. 1). In this scenario, protected areas are efficient at protecting forest areas of high and unique biodiversity in the medium term, i.e., forests will be concentrated in protected areas, where the probability of deforestation is lower. In the long term, under a business-as-usual scenario, forests will completely disappear from protected areas (Fig. 1). This phenomenon is already clearly visible in countries or states where deforestation is advanced, such as in Rondonia state (Brazil) in South America (Ribeiro et al. 2005), Ivory Coast (Sangne et al. 2015) or Madagascar (Vieilledent et al. 2020) in Africa, or Cambodia (Davis et al. 2015) in Southeast Asia. In these countries, several forested protected areas have been entirely deforested (e.g., the Haut-Sassandra protected forest in Ivory Coast, or the PK-32 Ranobe protected area in Madagascar) or severely deforested (e.g., the Beng Per wildlife sanctuary in Cambodia).

Vieilledent et al.
Despite the uncertainty surrounding the mean annual deforested area for each country (SI Appendix, Figs. S14–S15, and Table S20), the consequences of a business-as-usual deforestation scenario on the loss of biodiversity and carbon emissions by 2100 remain clear and alarming (Figs. 2, 4 and SI Appendix, Data S1, S2). Moreover, given the current global context, the business-as-usual deforestation scenario can be considered as conservative. For example, we do not account for the effect of future population growth (Raftery et al. 2017), which will likely have a major impact on deforestation, particularly in Africa, where a large part of the population depends on slash-and-burn agriculture for their livelihood (Barnes 1990, Vieilledent et al. 2020). Nor do we account for the increasing demand for agricultural commodities from the tropics, such as palm oil, beef and soybeans, which will likely lead to a significant increase in deforestation (Karstensen et al. 2013, Strona et al. 2018). Our projections using high estimates of the annual deforested area for each study area, corresponding to a total deforestation of 8.3 Mha/yr at the pantropical scale, give an indication on the consequences of a 30% increase in the annual deforested area in the future. This would lead to a 56% loss of tropical moist forest cover over the 21st century and the percentage of lands covered by tropical moist forests would then drop to 3.7% (554 Mha) in 2100 (SI Appendix, Fig. S15). This would also lead to a faster decrease in carbon absorption by tropical forests down to 0.267 Pg/yr in 2100, and a faster increase in carbon emissions up to 0.749–0.793 Pg/yr (Fig. 4 and SI Appendix, Fig. S13), turning tropical moist forests into an even bigger net carbon source.

Although conservation strategies, such as protected areas, can help save some time in the fight against deforestation (being efficient at displacing deforestation toward areas of lower biodiversity or carbon stocks), it is extremely urgent to find political and socioeconomic solutions that are effective at curbing deforestation in the long term. Several initiatives involving actors from the political and economic worlds have already been taken to this end, without having so far led to a significant decrease in deforestation rates in the tropics (Vancutsem et al. 2021). Such initiatives include recent national or multinational strategies against imported deforestation (Bager et al. 2021), certification schemes for private companies providing agricultural commodities such as the Roundtable on Sustainable Palm Oil (Cazzolla Gatti and Velichevskaya 2020), or the REDD+ mechanism (Goetz et al. 2015). The outcomes of our study could facilitate the concrete implementation of these initiatives on the ground and help increase their effectiveness. In particular, our deforestation probability map can be used to monitor areas having a high risk of being deforested. Our projections by country can also be used as reference scenarios of deforestation and carbon emissions which are necessary for implementing REDD+ at a wide scale on the basis of a common methodology. Doing so, we hope to contribute to the fight against deforestation and that our map of tropical forest cover in 2100 never comes true.

Materials and Methods

We present below a summary of the materials and methods used in this study. A detailed description can be find in the SI Appendix, Materials and Methods.

Study-areas and data.

We modelled the spatial deforestation process for 119 study-areas representing 92 countries in the three tropical continents (America, Africa, and Asia), see SI Appendix, Fig. S1. Study-areas cover all the tropical moist forest in the world, at the exception of some islands (eg. Sao Tome and Principe or Wallis-and-Futuna). For each study-area, we derived past forest cover change maps on two periods of time: January 1st 2000–January 1st 2010, and January 1st 2010–January 1st 2020, from the annual forest cover change product by Vancutsem et al. (2021) at 30 m resolution (SI Appendix, Fig. S2 and Table S1). For the forest definition, we only considered natural old-growth tropical moist forests, disregarding plantations and regrowths. We included degraded forests (not yet deforested) in the forest definition. To explain the observed deforestation in the period 2010–2020, we considered a set of spatial explanatory variables (SI Appendix, Fig. S3–S6) describing: topography (altitude and slope, 90 m resolution), accessibility (distances to the nearest road, town, and river, 150 m resolution), forest landscape (distance to forest edge, 30 m resolution),

![Figure 5: Effects of protected areas, roads, and distance to forest edge on the spatial probability of deforestation.](https://example.com/figure5.png)

**Disentangling the effect of roads and distance to forest edge on the deforestation risk**

Here we find that a greater distance to the road significantly reduces the risk of deforestation in 61 study areas out of 119 (51% of the study areas). These 61 study areas accounted for 90% of the tropical moist forest in 2010 (SI Appendix, Table S7). On average, a distance of 10 km from a road reduces the risk of deforestation by 14% (Figs. 3, 5 and SI Appendix, Tables S5, S9). This said, opening a road in the forest leads to creating two forest edges and computing a distance from a forest pixel to the nearest road implies the existence of a distance to the forest edge. When studying the impact of roads on deforestation, it is thus impossible to neglect the impact of the distance to forest edge on the risk of deforestation.

Here, we find that the distance to the forest edge is the most important variable in determining the risk of deforestation (SI Appendix, Table S5), in agreement with the results of other studies showing the impact of forest fragmentation on the risk of deforestation in the tropics (Hansen et al. 2020). We estimate that, on average, a distance of 1 km from the forest edge reduces the risk of deforestation by 91%, and a distance of 10 km reduces the risk of deforestation by almost 100% (Figs. 3, 5 and SI Appendix, Tables S5, S9).

Consequently, building new roads in non-forest areas but close to existing forest edges would significantly increase forest accessibility and the risk of deforestation in the nearby forest. This negative impact would be even more significant if new roads were opened in the heart of forest areas. In addition to the direct deforestation associated with road building in the forest (Kleinschroth and Healey 2017), this would involve creating new forest edges and dramatically increase deforestation probability in the area concerned. While road networks are expanding rapidly worldwide, notably in remote areas in tropical countries (Laurance et al. 2014), our results underline the importance of conserving large roadless and unfragmented forest areas.

**Uncertainty and alternative deforestation scenarios**

Despite the uncertainty surrounding the mean annual deforested area for each country (SI Appendix, Figs. S14–S15, and Table S20),
deforestation history (distance to past deforestation, 30 m resolution), and land conservation status (presence of a protected area, 30 m resolution).

This paper is based on data from the pan-tropical land cover change database, which covers the 132 tropical countries and 21 million km² of land (Soille 2003), including original and 30 m resolution forest cover change map (Soille 2003, see SI Appendix, Table S2).

Sampling. For each study-area, we built a large dataset from a sample of forest cover change observations in 2010–2020. We performed a stratified balanced sampling between deforested and non-deforested pixels in the period 2010–2020. Pixels in each category were sampled randomly (SI Appendix, Fig. S7). The number of sampled observations in each study-areas was a function of the forest area in 2010. Datasets included between 2,398 (for Sint Maarten island in America) and 100,000 (for study-areas with high forest cover change and associated carbon emissions: an average prediction considering the mean annual deforested area, and two additional predictions considering the lower and upper bound estimates of the mean annual deforested area per study area (SI Appendix, Figs. S14–S15, and Data S1, S2).

Software. To perform the analyses, we used the forestrisk Python package (Vieilledent 2021) which has been specifically developed to model and forecast deforestation at high resolution on large spatial scales (SI Appendix, Materials and Methods).

Model performance. We compared the performance of the iCAR model at predicting the spatial probability of deforestation with three other statistical models: a null model, a simple generalized linear model (equivalent to a simple linear regression), and a spatial random effects model. These two last models have been commonly used for deforestation modelling (SI Appendix, Materials and Methods). Using a cross-validation procedure, we showed that the Random Forest model overfit the data and was less performant at predicting the probability of deforestation at new sites than the iCAR model. The iCAR model had better predictive performance than the other three statistical models (SI Appendix, Tables S10–S13). The iCAR model increased the explained deviance from 39.3 to 53.3% in average compared to the simple generalized linear model. This shows that spatial patterns of deforestation are strongly linked to the spatial variability of the explanatory variables already included in the model (such as population density, local environmental law enforcement, etc.). Spatial random effects were assumed spatially autorecorrelated through an intrinsic conditional autoregressive (iCAR) model (SI Appendix, Eq. S1). Variable selection for each study area was performed using a backward elimination procedure and parameter inference was done in a hierarchical Bayesian framework (SI Appendix, Tables S4–S9).

Deforestation risk and future forest cover. Using rasters of explanatory variables at their original resolution, and the fitted iCAR model for each study-area including estimated spatial random effects (SI Appendix, Fig. S9), we computed the spatial probability of deforestation at 30 m resolution for the year 2020 for each study-area (SI Appendix, Fig. S10). For each study-area, we also estimated the mean annual deforested area (ha/yr) for the period 2010–2020 from the past forest cover change map (SI Appendix, Tables S14–S15). Using the mean annual deforested area in combination with land cover change and associated carbon emissions: an average prediction considering the mean annual deforested area, and two additional predictions considering the lower and upper bound estimates of the mean annual deforested area per study area (SI Appendix, Figs. S14–S15, and Data S1, S2).

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