Forest refuge areas and carbon emissions from tropical deforestation in 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 models confirm the effectiveness of protected areas in displacing deforestation and the negative impact of roads and landscape fragmentation on forest conservation in the tropics. 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. Although under this scenario, large areas of tropical moist forest should remain in the heart of the Amazon, in the Congo Basin, and in New Guinea in 2100, 48% (39–56%) of all forest cover is expected to disappear during the course of the 21st century, and many countries will have lost all their forests by 2100. The remaining forests will be highly fragmented and located in remote places. As future deforestation will concern forests with higher aboveground carbon stocks, annual carbon emissions associated with tropical deforestation are expected to increase by +0.161 Pg/yr (+35%) between the 2010s and the 2090s.

biodiversity | deforestation | tropical forests | CO_2 emissions | scenarios

Tropical forests are at the heart of concerns when it comes to climate change and biodiversity loss, which both pose unprecedented threats to human civilization (Cardinale et al. 2012, IPCC 2014). Commonly called the "Jewels of the Earth", tropical forests shelter 30 million species of plants and animals, representing half of the Earth's wildlife and at least two-thirds of its plant species (Gibson et al. 2011, Wilson et al. 2012). Through carbon sequestration, they play an important role in the global carbon cycle and regulate the global climate (Baccini et al. 2017). Intact tropical forest ecosystems also prevent outbreaks of zoonoses and reduce the risk of pandemics (Tollefson 2020). At local scale, tropical forests regulate the regional climate (Dickinson and Kennedy 1992), cooling the atmosphere (Ellison et al. 2017), and facilitate access to water (Ellison et al. 2017, Zhang and Wei 2021). They also protect against erosion and flooding (Bradshaw et al. 2007). Close to 1.6 billion people (a quarter of the world's population) rely on forest resources for their livelihoods (FAO 2020). Despite the many ecosystem services they provide, tropical forests are disappearing at an alarming rate (Hansen et al. 2013, Achard et al. 2014, FAO 2020, Vancutsem et al. 2021), mostly because of human activities (Geist and Lambin 2002, Curtis et al. 2018). Past studies have estimated that about 10 Mha of tropical forest (including moist and dry forests) are currently disappearing each year (FAO 2020). At this rate, will there still be any tropical forests left at the end of the 21st century, if so, where will they be concentrated, and what will be the consequences of tropical deforestation on climate and biodiversity in the future?

Forecasting forest cover change is paramount as it allows us to foresee the consequences of deforestation (in terms of carbon emissions, biodiversity loss, or water supply) under various technological, political, and socio-economic scenarios, and to inform decision makers accordingly (Clark et al. 2001). The "business-as-usual" scenario is of particular interest as it makes it possible to predict the likely future in the absence of change in deforestation rates, and if necessary, to alert decision-makers to an essential change of course to avoid any potential environmental disaster. 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 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 to 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 at 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 largest studies to date have focused on modelling and forecasting forest cover change at the scale of the Amazonian basin (Soares-Filho et

Significance Statement

Under a "business-as-usual" scenario of deforestation (i.e. projecting the 2010–2020 deforestation rates at the country level in the future), three quarters of the tropical moist forests that existed in 2000 will have disappeared around years 2120, 2160, and 2220 in Southeast Asia, Africa, and Latin America, respectively. By 2100, 41 tropical countries, plus 14 states in Brazil and one region in India, will lose all their tropical forests. Remaining forests will be highly fragmented and concentrated in remote areas (far from roads and towns), preferentially in protected areas, and at high elevations. Future deforestation will concern forests with higher carbon stocks. In the absence of change in the deforestation rates, annual carbon emissions associated with tropical deforestation will increase from 0.467 Pg/yr in the 2010s to 0.628 Pg/yr in the 2090s (+35%), making tropical forests a major carbon source in the 21st century.

Author contributions: GV and FA conceived the study; CV provided the forest cover change data; GV performed analysis and wrote the original draft; all authors reviewed and edited the final manuscript.

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Data deposition: Raw data and products of the study are available on the ForestAtRisk website accompanying the present publication. Code is available on GitHub and is permanently archived in the Cirad Dataverse.

Supporting Information available on the ForestAtRisk website.

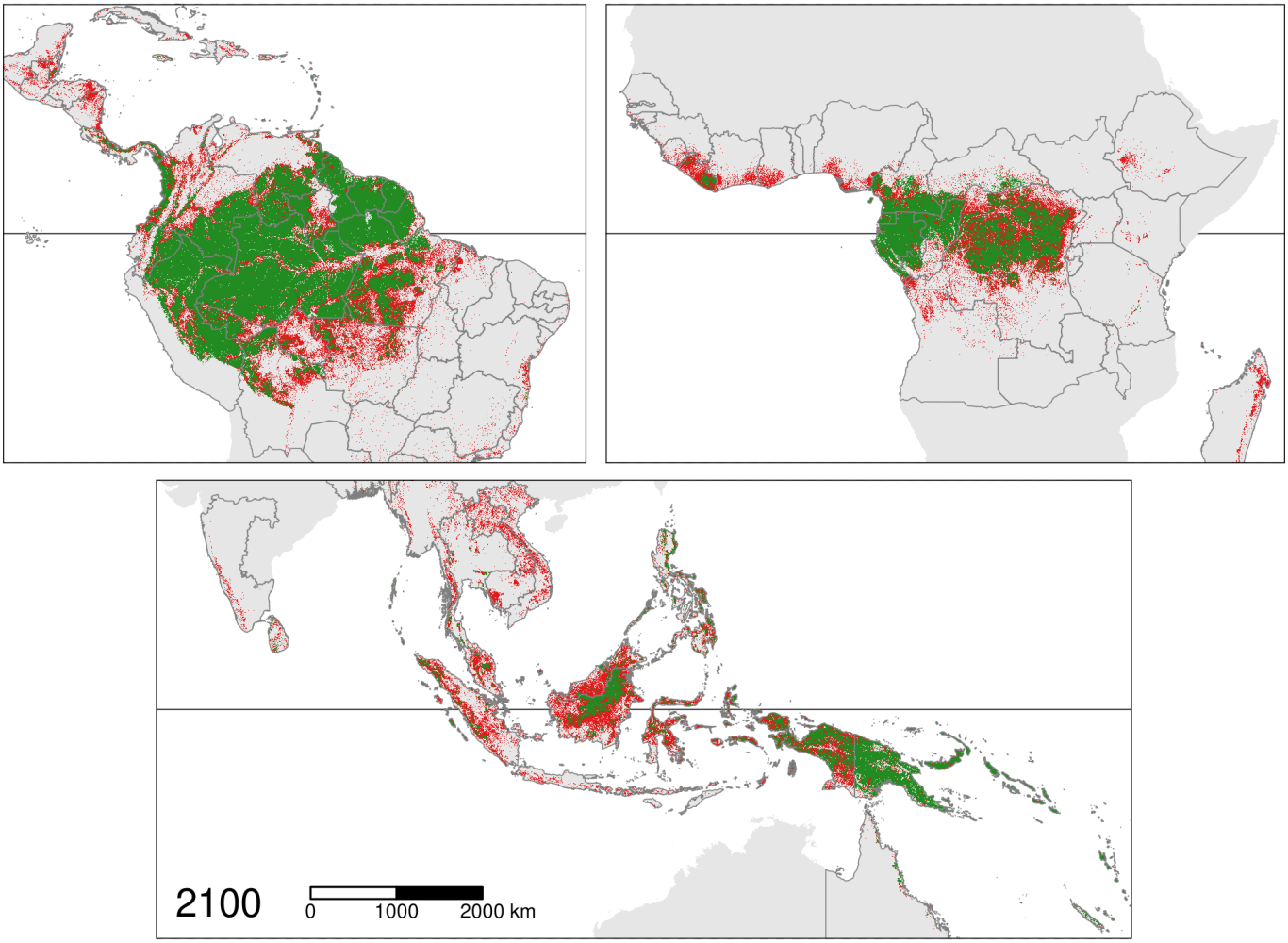

Fig. 1. Pantropical map of the predicted change in forest cover. Maps show the predicted change in tropical moist forest cover in the three continents (America, Africa, and Asia) for the period 2020–2100 under a business-as-usual scenario of deforestation. The horizontal black line represents the Equator. The boundaries of the study area 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 on the three continents 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.

al. 2006, Swann et al. 2015, Aguiar et al. 2016). In this paper, we model and forecast deforestation at the pantropical scale using high-resolution spatial data. 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 at reducing deforestation and to 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.

Remaining tropical moist forests in 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 over the last decade (2010–2020). This corresponds to an area of 64,000 km^2, about the size of Greece or West Virginia, which is deforested each year. We show here that under a business-as-usual scenario of deforestation, 48% (39–56%) of the world's tropical moist forest will have disappeared over the course of the 21st century (Fig. 1 and Table 1). The percentage of emerge lands covered by tropical moist forest would then decrease from 8.5% (1259 Mha) in 2000 to 4.7% (554 Mha) in 2100. We observed marked differences in the percentage of forest cover loss at the 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 deforested area is lower (1.9 Mha/yr), this percentage would be 53% (45–60%). In Latin America, where the annual deforested area is higher (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 existed 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

Table 1. Past and predicted changes in forest cover

Regions	fc2000 (Kha)	fc2010 (Kha)	fc2020 (Kha)	d (Kha/yr)	p (%/yr)	fc2050 (Kha)	fc2100 (Kha)	loss21 (%)	yr75
Countries									
Brazil	374,282	348,650	334,948	1,370	0.4	293,844	225,336	40	2204
DRC	131,298	125,605	118,283	732	0.6	96,318	59,711	55	2134
Indonesia	139,358	126,473	117,072	940	0.8	88,876	41,883	70	2111
Continents									
America	687,339	646,685	621,229	2,545	0.4	544,869	427,790	38	2220
Africa	274,993	258,401	239,681	1,871	0.7	188,403	129,045	53	2163
Asia	297,090	268,058	248,035	2,002	0.8	188,558	98,922	67	2117
All cont.	1,259,422	1,173,144	1,108,945	6,418	0.6	921,830	655,757	48	2192

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). We provide the mean annual deforested area d (Kha/yr) for the last ten-year period from January 1st 2010 to January 1st 2020, and 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 forest cover in 2020 ("fc2020") and the mean annual deforested area (d) assuming a business-as-usual scenario of deforestation. Column "loss21" indicates the projected percentage of forest cover loss during the 21st century (2100 vs. 2000). We estimate the year ("yr75") at which 75% of the forest cover in 2000 will have disappeared.

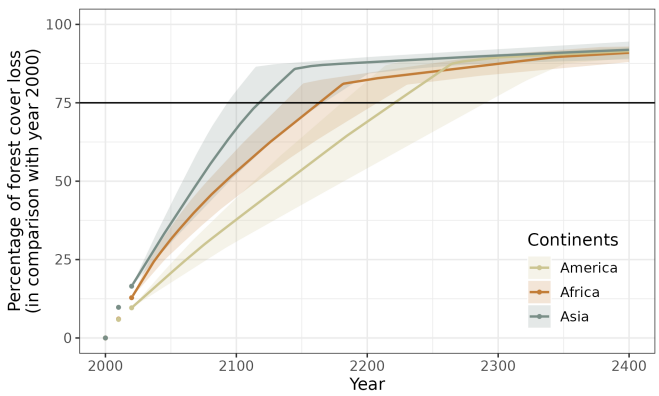

Fig. 2. Projected percentage of forest cover loss per continent. Points represent the observed percentage of forest cover loss (in comparison with the year 2000) for the years 2000 (0%), 2010, and 2020, for the three continents: America, Africa, and Asia. Lines represent the projected percentage of forest 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. As a consequence, when large countries with high annual deforested areas (Brazil for America, DRC for Africa, and Indonesia for Asia) have no more forest (in 2264, 2181, and 2144, respectively, see *SI Appendix*, Table S16), deforestation at the continent scale is rapidly decreasing. The horizontal black line indicates a loss of 75% of the forest cover in comparison with the year 2000. Under a business-as-usual scenario, this should happen in 2117, 2163, 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.

in Asia), three states in Brazil, and one region in India had more than one million hectares of forest in 2000, thus underlining the fact that the complete loss of tropical moist forest before 2100 will not only occur in countries with a low forest cover at the beginning of the century. It can also be noticed that these countries include most of the countries of Central America (Guatemala, Honduras, Mexico, Nicaragua), Western (Ghana, Guinea, Ivory Coast, Nigeria, Sierra Leone) and Eastern (Ethiopia, Kenya, Madagascar) Africa, and continental Southeast Asia (Cambodia, Laos, Vietnam, Indian Western Ghats). These regions include almost all tropical forests located within six biodiversity hotspots identified by Mittermeier et al. (2011): Mesoamerica, Guinean Forests of West Africa, the Horn of Africa, Madagascar and Indian Ocean Islands, Indo-Burma, Western Ghats and Sri Lanka (Fig. 1).

Using a spatial statistical modelling approach (see *SI Appendix*, Materials and Methods, Figs. S1–S9, and Tables S1–S13), we obtain high resolution (30 m) pantropical maps of the deforestation risk (Fig. 3 and *SI Appendix*, Fig. S10) and project forest cover for the 21st century in the humid tropics under a business-as-usual scenario (Fig. 1 and *SI Appendix*, Fig. S11, and Tables S14–S17). Three large "blocks" of relatively intact tropical moist forest will remain in 2100 (Fig. 1). One forest block will be located in Latin America and will include the upper part of the Amazonian basin (including the Peruvian, Ecuadorian, Colombian and Venezuelan Amazonia) and the Guiana Shield (Guyana, Suriname, and French Guiana). The second block will be located in the western part of the Congo basin and will include forests in Gabon, Equatorial Guinea, Cameroon, the Central African Republic, and the Republic of Congo. The third block will be located in Melanesia and will include forests in Papua New Guinea, Solomon Islands, and Vanuatu.

Apart from these three large and relatively intact forest blocks, the tropical moist forest remaining in 2100 will be highly fragmented (Fig. 1). In Latin America, highly fragmented forests will be found in the Brazilian states of the Amazonian deforestation arc (Acre, Rondonia, Mato Grosso, Para, Amapa) and in the Roraima state in the northern Amazonia. In Africa, forests in the Democratic Republic of the Congo (DRC) will also be highly fragmented (*SI Appendix*, Fig. S11) and will be completely separated from the large forest block located in the western part of the Congo basin (Fig. 1). In Southeast Asia, small patches of heavily fragmented forests will remain in Thailand, Indonesia, and the Philippines (Fig. 1). The remaining forests will be concentrated in remote areas (far from roads and towns), preferentially in protected areas, and at high elevations (Figs. 1, 3 and *SI Appendix*, Tables S4–S9). For example, the remaining forests of Borneo will be concentrated in the Betung Kerihun and Kayan Mentarang National Parks.

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).

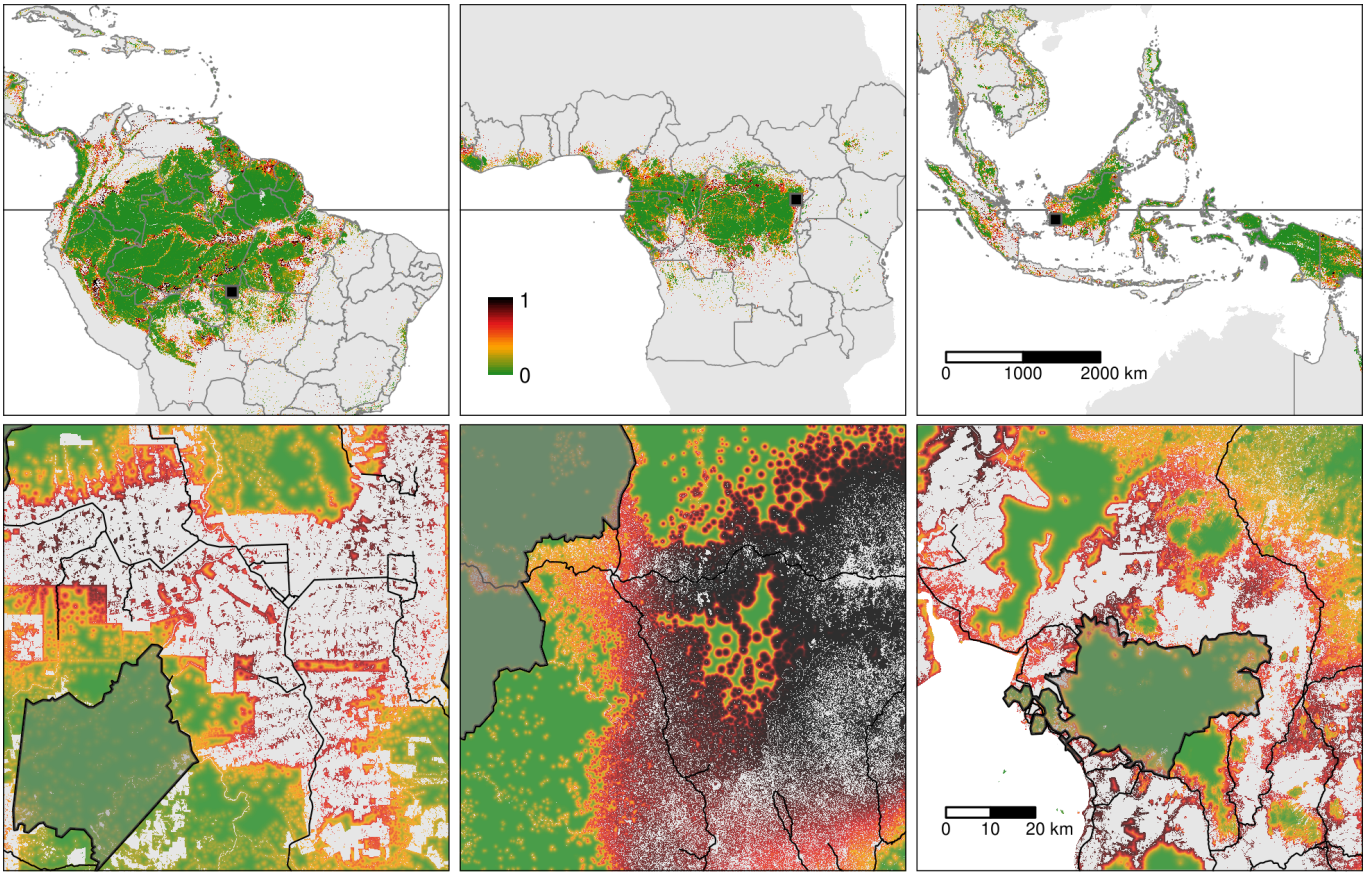

Fig. 3. Pantropical map of the risk of deforestation. *Upper panels*: Maps of the spatial probability of deforestation at 30 m resolution for the three continents. Maps of the spatial probability of deforestation at the level of the study area were aggregated at the pantropical level. The horizontal black line represents the Equator. The boundaries of the study area are represented by dark grey lines. Coloured pixels represent forest pixels for the year 2020. Inside each study area, forest areas in dark red have a higher risk of deforestation than forest areas in green. *Lower panels*: Detailed maps for three 100 × 100 km regions (black squares in the upper panels) in the Mato Grosso state (Brazil), the Albertine Rift mountains (the Democratic Republic of the Congo), and the West Kalimantan region (Borneo Indonesian part). Deforestation probability is lower inside protected areas (black shaded polygons) and increases when the forest is located at a distance closer to roads (dark grey lines) and forest edge. An interactive map of the spatial probability of deforestation is available at https://forestatrisk.cirad.fr/maps.html.

Carbon emissions under a business-as-usual scenario of deforestation

Here we estimate the aboveground carbon emissions associated with deforestation projected for the period 2020–2110 under a business-as-usual scenario of deforestation. 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 find that annual carbon emissions associated with deforestation of tropical moist forests will increase from 0.467 Pg/yr in 2010–2020 to 0.628 Pg/yr in 2090–2100, which corresponds to a 35% increase (Fig. 4 and *SI Appendix*, Table S19). This increase in annual carbon emissions is predicted for all three continents. A decrease in annual carbon emissions is then predicted starting from the period 2070–2080 for Southeast Asia and the period 2090–2100 at pantropical scale (Fig. 4).

The predicted increase in annual carbon emissions is explained by the fact that the forests 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, Cuní 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 are 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 fact that deforestation will move towards higher elevation areas where forest carbon stocks are higher. Moreover, remote forest areas that have been 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.

The decrease in carbon emissions predicted from the period 2070–2080 for Southeast Asia, and from the period 2090–2100 at pantropical scale, can be associated with a decrease in carbon stocks of deforested areas (in association with environmental factors, such as lower carbon stocks at very high elevation) or a decrease in the total deforested area at the continental and global scale, as countries progressively lose all their forest. In Southeast Asia, four countries will lose all their forest between 2070 and 2110 (*SI Appendix*, Table S16). These countries (which include Laos, Myanmar, and Vietnam) account for a significant proportion (20%) of the annual deforested area in Southeast Asia (407,498 ha/yr out of 2,001,803 ha/yr, see *SI Appendix*, Tables S14, S15). This largely explains the predicted decrease in carbon emissions in Southeast Asia from 2070 on.

Our estimates of 0.467 Pg/yr (0.194, 0.167, and 0.105 Pg/yr for Latin America, Southeast Asia, and Africa, respectively) of aboveground carbon emissions due to tropical deforestation for the period 2010–2020 are consistent with those of previous studies (Harris

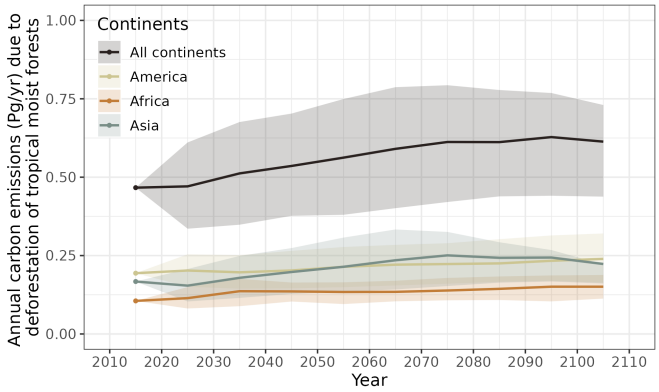

Fig. 4. Aboveground carbon emissions associated with projected deforestation. This figure shows the changes in annual carbon emissions (Pg/yr) associated with the predicted deforestation of tropical moist forests. Mean annual carbon emissions are computed for ten-year intervals from 2010–2020 to 2100–2110. The dots represent the observed mean annual carbon emissions (based on past deforestation maps) for the period 2010–2020, for the three continents (America, Africa, and Asia), and for the three continents combined. Lines represent the projected mean annual carbon emissions based on projected forest cover change maps from 2020–2030 to 2100–2110 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. Annual carbon emissions at the pantropical scale are predicted to increase from 0.467 Pg/yr in 2010–2020 to 0.628 Pg/yr in 2090–2100, representing a 35% increase (+0.161 Pg/yr).

et al. 2012, Achard et al. 2014, Baccini et al. 2017). For the period 2000–2014, previous studies estimated 0.81–0.88 Pg/yr of carbon emissions associated with deforestation considering both moist and dry tropical forests (representing an estimated area of 1575–1790 Mha in 2000 in these studies), while our study only focuses on tropical *moist* forests (estimated at 1259 Mha in 2000). Because of the projected 35% increase in carbon emissions associated with tropical deforestation under a business-as-usual scenario, tropical forests will act as an increasing net carbon source (Baccini et al. 2017), thus reinforcing climate change in the future.

These results demonstrate the importance of spatial predictions of deforestation to forecast carbon emissions associated with future deforestation. Using mean annual forest cover change estimates per country and forest type (such as those provided by the Forest Resource Assessment report, FAO 2020) and mean forest carbon stocks per continent and forest type (such as the emission factors provided by the Intergovernmental Panel on Climate Change, IPCC 2019), it is not possible to predict future trends in carbon emissions associated with deforestation. Under a business-as-usual scenario of deforestation, projected carbon emissions will result from the combination of the spatial variation in forest carbon stocks and the location of the future deforestation.

Effectiveness of protected areas at displacing deforestation

Forested protected areas are usually located in areas of high or unique biodiversity, in a non-random way. They are also usually found in remote places with less human disturbances and reduced accessibility, i.e. far from roads or cities, and usually at higher elevation (*SI Appendix*, Fig. S6), because low-lying arable lands have already been preempted for agriculture (Geist and Lambin 2002). As a consequence, it is often difficult to unravel the effect of protected areas from other correlated variables, for example distance to the nearest road, city, or elevation (Andam et al. 2008). The multivariate logistic regression model we use makes it possible to disentangle the effect of each explanatory variable in the spatial deforestation process. Moreover, the spatial random effects included in our model (see Methods and *SI Appendix*, Fig. S8, S9) correct the potential bias in the protected area effect that could be associated with other unmeasured confounding variables, such as population density (Andam et al. 2008).

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). On average, protected areas reduce the risk of deforestation by 40% (Figs. 3, 5 and *SI Appendix*, Table S5). This result clearly demonstrates the efficiency of protected areas at reducing the spatial risk of deforestation in the tropics. In a recent global study, Wolf et al. (2021) found that protected areas reduced deforestation rates by 41%, close to the 40% we find here by focusing on tropical moist forests. Most of the previous studies have assessed the effect of protected areas at reducing deforestation in particular countries or regions (Bruner 2001, Andam et al. 2008) or at efficiently protecting a particular group of species (Cazalis et al. 2020). Studies at the global scale (Wolf et al. 2021, Yang et al. 2021) were at 1 km resolution and used spatial matching methods and tree cover loss data (Hansen et al. 2013). Our pantropical approach is based on more accurate forest cover change maps in the humid tropics, in particular in Africa (Vancutsem et al. 2021), and accounts for fine scale deforestation factors acting at a much smaller distance than the distance imposed by a 1 km resolution (see the effect of the distance to forest edge discussed below). Moreover, contrary to most spatial matching methods (Andam et al. 2008, Schleicher et al. 2019), the statistical model we use allows us to account for any potential confounding variables which might skew the estimated effect of protected areas.

Like other studies reporting the effect of protected areas on deforestation, our study demonstrates that protected areas are effective at *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 forest is high), it is very unlikely that protected areas will remain forested. Under a business-as-usual scenario of deforestation, we assume that the deforestation intensity will remain constant over time. When all the forest outside the protected areas is deforested, 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 should completely disappear from protected areas while deforestation continues (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).

Impact of roads and distance to forest edge on the deforestation risk

Here we find that a longer 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

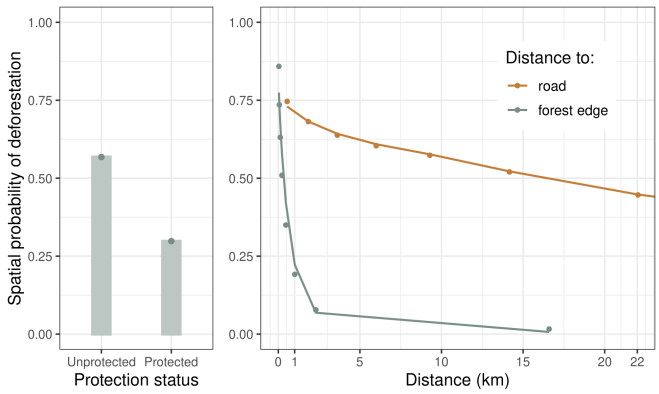

Fig. 5. Effects of protected areas, roads, and distance to forest edge on the spatial probability of deforestation. For this figure, we used a representative dataset at the pantropical scale where the number of observations for each study area was proportional to its forest cover in 2010. We sampled 798,859 observations from the original dataset. *Left*: The dots represent the observed mean probability of deforestation in each forest protection class, either protected or unprotected. Bars represent the mean of the predicted probabilities of deforestation obtained from the deforestation model for all observations in each class. *Right*: The dots represent the local mean probability of deforestation for each bin of 10 percentiles for the distance. Lines represent the mean of the predicted probabilities of deforestation obtained from the deforestation model for all observations in each bin. Note that for distance to forest edge, the first dot accounts for three bins while for distance to road, bins for a distance > 23 km are not shown. For both left and right panels, confidence intervals for predictions were to small to be represented because of the high number of observations per class and bin.

road in the forest leads to the creation of 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 effect of roads on deforestation, it is thus impossible to neglect the effect 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 the risk of deforestation in the nearby forest. This negative impact would be even greater if new roads are 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 would 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. S13, S14, 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 we examine here appears to be rather conservative. For example, we do not account for the effect of future population growth (Raftery et al. 2012), which will likely have a major effect 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 soybean, 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 to a much faster increase in carbon emissions, up to 0.793 Pg/yr in the 2070s, corresponding to a +70% increase in annual carbon emissions compared to the 2010s (Fig. 4). The percentage of emerge lands covered by tropical moist forests would then drop to 3.7% (554 Mha) in 2100 (*SI Appendix*, Fig. S14).

Although some 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 socio-economic solutions that are efficient at curbing deforestation in the long term. Several initiatives involving actors from the political and economical world 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 results and products 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 could be used to monitor areas identified as having a high risk of being deforested. Our projections by country could also be used as reference scenarios of deforestation and associated 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 projected in 2100 will never become a reality.

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 on 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 nearest road, town, and river, 150 m resolution), forest landscape (distance to forest edge, 30 m resolution), deforestation history (distance to past deforestation, 30 m resolution), and land conservation status (presence of a protected area, 30 m resolution). This set of variables were selected on an a priori knowledge of the spatial deforestation process in the tropics (*SI Appendix*, Materials and Methods). Data for explanatory variables were extracted from extensive global datasets (World Database on Protected Areas, SRTM Digital Elevation Database, and OpenStreetMap) and had a resolution close to the original resolution of the forest cover change map (30 m, see *SI Appendix*, Table S2).

Sampling. For each study-area, we built a large dataset from a sample of forest cover change observations in the period 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 such as the Amazonas state in Brazil, Peru, DRC, and Indonesia) observations. The global data-set included a total of 3,186,698 observations: 1,601,810 of non-deforested pixels and 1,584,888 of deforested pixels, corresponding to areas of 144,163 ha and 142,647 ha, respectively (*SI Appendix*, Table S3).

Statistical model. Using sampled observations of forest cover change in the period 2010–2020, we modelled the spatial probability of deforestation as a function of the explanatory variables using a logistic regression (*SI Appendix*, Eq. S1). To account for the residual spatial variation in the deforestation process, we included additional spatial random effects for the cells of a 10 × 10 km spatial grid covering each study-area (*SI Appendix*, Fig. S8). Spatial random effects account for unmeasured or unmeasurable variables that explain a part of the residual spatial variation in the deforestation process which is not explained by the fixed spatial explanatory variables already included in the model (such as local population density, local environmental law enforcement, etc.). Spatial random effects were assumed spatially autocorrelated 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).

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 logistic regression without spatial random effects), and a Random Forest 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 overfitted 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 three other statistical models (*SI Appendix*, Tables S10–S13). The iCAR model increased the explained deviance from 39.3 to 53.3% in average in comparison with the simple generalized linear model. This shows that environmental explanatory variables alone explain a relative small part of the spatial deforestation process, and that including spatial random effects to account for unexplained residual spatial variability strongly improves model's fit (+14.0% of deviance explained in average) and model predictive performance (+7.4% for the TSS for example). Same results were obtained when comparing accuracy indices between models at the continental scale.

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 (in 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 the spatial probability of deforestation map, we forecasted the forest cover change on the period 2020–2110 with a time step of 10 years, assuming a "business-as-usual" scenario of deforestation (*SI Appendix*, Fig. S11 and Tables S16–S17). The business-as-usual scenario makes the assumption of an absence of change in both the deforestation intensity and the spatial deforestation probability in the future.

Impacts on biodiversity loss and carbon emissions. We estimated the number of endemic plant and vertebrate species committed to extinction because of the complete loss of tropical forest by 2100 in 6 biodiversity hotspots (*SI Appendix*, Table S18). We estimated the carbon emissions associated with past deforestation (2010–2020) and projected deforestation (2030–2110) using Avitabile's (2016) pantropical 1 km resolution aboveground dry biomass map (*SI Appendix*, Fig. S12 and Table S19). We used the IPCC default carbon fraction of 0.47 (McGroddy et al. 2004) to convert biomass to carbon stocks. We assumed no change of the forest carbon stocks in the future. We estimated average annual carbon emissions for ten-year periods from 2010 to 2110. Under a "business-as-usual" scenario of deforestation, the change in mean annual carbon emissions in the future is only attributable to the spatial variation of the forest carbon stocks and to the location of future deforestation.

Uncertainty and alternative scenarios. To account for the uncertainty around the mean annual deforested area in our predictions, we computed the 95% confidence interval of the annual deforested area for each study area considering the deforestation observations in the period 2010–2020 (*SI Appendix*, Table S20). We thus obtained three different predictions of the 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. S13–S14, and Data S1, S2).

Software. To perform the analyses, we used the `forestatrisk` 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).

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