

# Spatial forecasting of forest cover change in the humid tropics over the 21<sup>st</sup> century



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# Plan

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## 1 Introduction

- Context
- Objectives
- Approach

## 2 Methods

- Models
- Spatial variables
- Forecast

## 3 Results

- Forest refuge areas
- Carbon emissions
- Effects of PA and roads

## 4 Discussion

- Uncertainty analysis
- Alternative scenarios
- Other perspectives

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# Tropical deforestation

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SCIENCE ADVANCES | RESEARCH ARTICLE

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ENVIRONMENTAL STUDIES

## Long-term (1990–2019) monitoring of forest cover changes in the humid tropics

C. Vancutsem<sup>1\*</sup>, F. Achard<sup>1</sup>, J.-F. Pekel<sup>1</sup>, G. Vieilledent<sup>1,2,3,4</sup>, S. Carboni<sup>5</sup>, D. Simonetti<sup>1</sup>, J. Gallego<sup>1</sup>, L. E.O. C. Aragão<sup>6</sup>, R. Nasi<sup>7</sup>

Vancutsem et al. 2021, *Science Advances*, doi : [10.1126/sciadv.abe1603](https://doi.org/10.1126/sciadv.abe1603)

- Tropical Moist Forest (TMF)
- 1990–2019 : Annual deforestation, degradation, regeneration

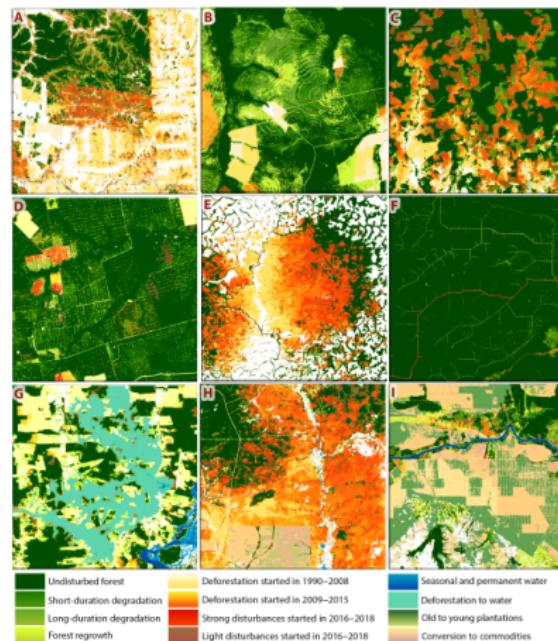
# Tropical deforestation

- Full Landsat archive (1982–2019), 30m pixel, time-series analysis
- Classification tree based on expert knowledge
- Tropical deforestation was underestimated (-33% in 2000–2012, Hansen et al. 2013)
- Maps and data : <https://forobs.jrc.ec.europa.eu/TMF/>



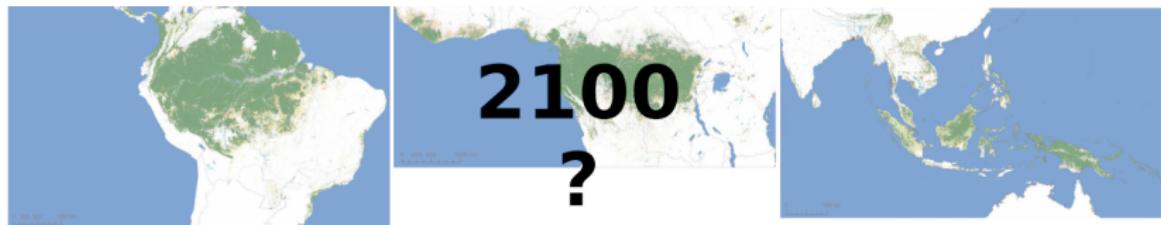
# Tropical deforestation

- Precise enough to visually identify the causes of deforestation (logging, fires, agriculture)



# Forecasting deforestation

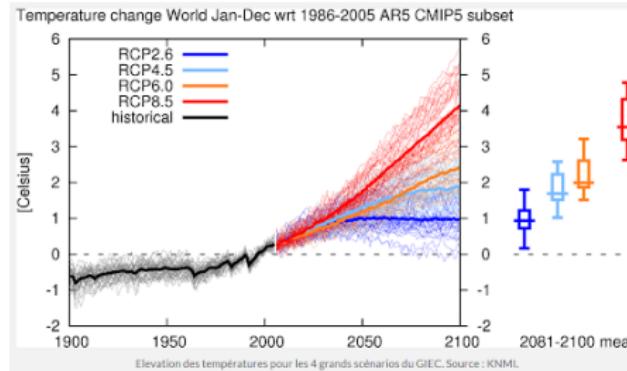
- About 7 Mha of tropical moist forest are disappearing each year (size of Ireland)
- At this rate, will tropical forests still exist in 2100 ?
- If yes, where will they be located ?
- What will be the consequences of future deforestation on biodiversity and carbon emissions ?



# Forecasting deforestation

Why is it a timely question ?

- **Alert** decision makers
- Carbon emissions scenarios ( $\rightarrow$  IPCC)
- Biodiversity scenarios ( $\rightarrow$  IPBES)
- Local scale : systematic conservation planning (protected area network, REDD+)
- Modelling  $\rightarrow$  main spatial drivers of deforestation

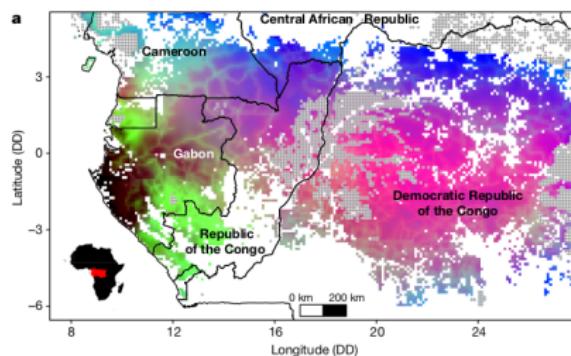


**IPCC scenarios**

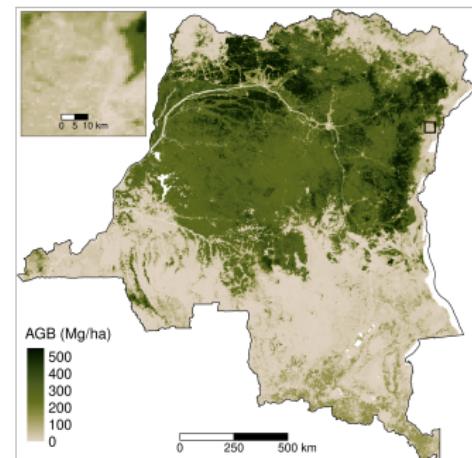
# Forecasting deforestation spatially

Why is **spatial** forecasting important ?

Because both biodiversity and carbon stocks vary strongly in space.



**Community map**  
(Réjou-Méchain 2021)



**AGB map in DRC**

# Approach

- i. Consider tropical moist forest in **92** countries (119 study areas)
- ii. Estimate the current deforestation rate and uncertainty in each country
- iii. Model the spatial risk of deforestation from environmental factors
- iv. Forecast the deforestation assuming a business-as-usual scenario
- v. Consequences in terms of biodiversity and carbon emissions



The 119 study areas in the 3 continents

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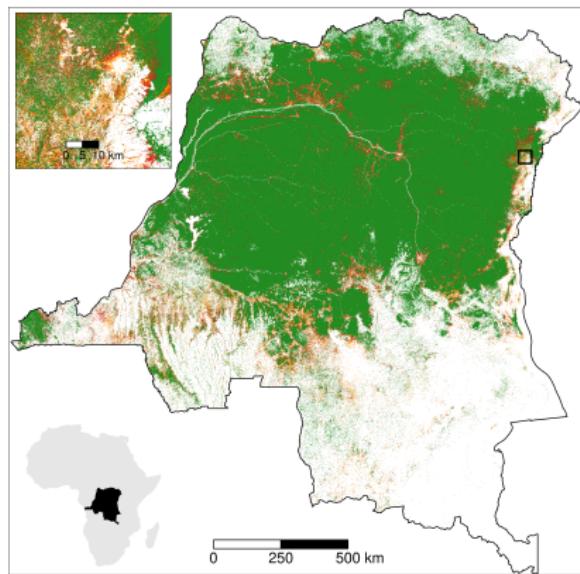
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## Modelling the intensity of deforestation

- 10 values of annual deforested area (ha/yr) in 2010–2020 per country
  - (Brazil : per state, India : per region)
  - Mean deforestation rate (ha/yr) in 2010–2020 per country
  - Uncertainty around the mean (95% confidence interval)



## Past deforestation 2000–2010–2020 in DRC

# Modelling the intensity of deforestation

| Country – study area | fc2010<br>(Kha) | fc2020<br>(Kha) | d<br>(ha/yr) | d'<br>(ha/yr) | d''<br>(ha/yr) |
|----------------------|-----------------|-----------------|--------------|---------------|----------------|
| <b>America</b>       |                 |                 |              |               |                |
| Antigua and B.       | 4               | 3               | 55           | 24            | 87             |
| Bahamas              | 122             | 103             | 2,044        | 1,013         | 3,075          |
| Barbados             | 4               | 3               | 73           | 21            | 125            |
| Belize               | 1,337           | 1,206           | 12,735       | 7,865         | 17,605         |
| Bolivia              | 30,657          | 28,671          | 203,506      | 127,518       | 279,493        |
| Brazil – Acre        | 13,292          | 12,824          | 48,076       | 41,217        | 54,936         |
| Brazil – Alagoas     | 100             | 89              | 1,196        | 730           | 1,663          |
| Brazil – Amapa       | 11,589          | 11,457          | 14,934       | 11,766        | 18,101         |
| Brazil – Amazonas    | 146,956         | 145,361         | 164,083      | 117,648       | 210,518        |

## Examples of mean deforestation rate with uncertainty

# Modelling the spatial risk of deforestation

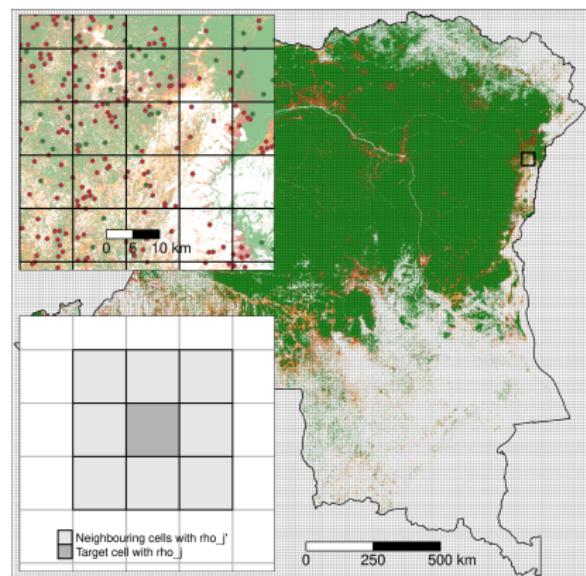
## A logistic regression model with iCAR process

$$y_i \sim \text{Bernoulli}(\theta_i)$$

$$\text{logit}(\theta_i) = \alpha + X_i\beta + \rho_{j(i)}$$

$$\rho_{j(i)} \sim \mathcal{N}ormal\left(\sum_{j'} \rho_{j'}/n_j, V_\rho/n_j\right)$$

(NB : We compared this model with a simple GLM and a Random Forest model using a cross-validation procedure)



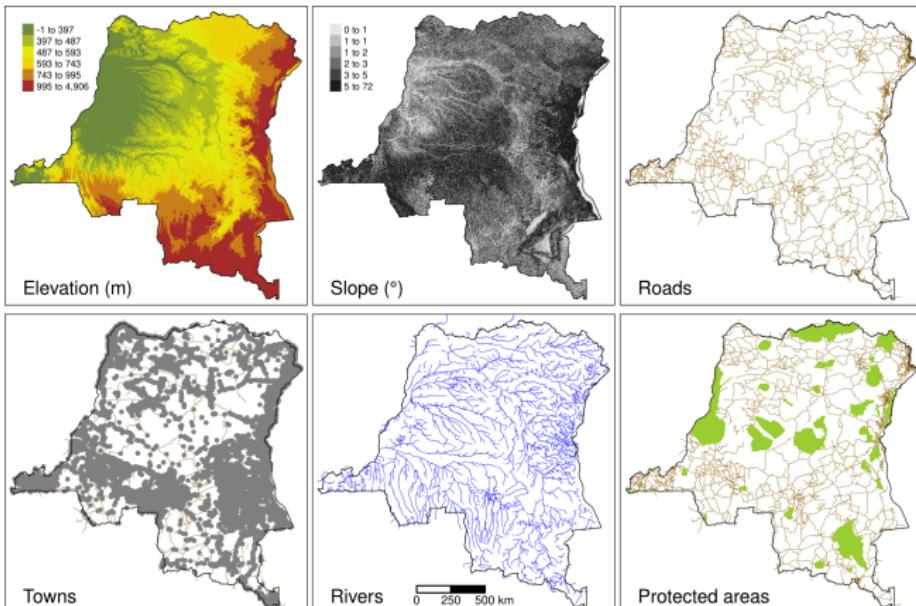
## Square grid of 10km cells over DRC

# Spatial variables

## ● Height explanatory variables

| Product                             | Source                   | Variable derived                     | Unit        | Resolution (m) | Date       |
|-------------------------------------|--------------------------|--------------------------------------|-------------|----------------|------------|
| Forest maps<br>(2000-2010-<br>2020) | Vancutsem et<br>al. 2021 | distance to<br>forest edge           | m           | 30             | –          |
|                                     |                          | distance to<br>past<br>deforestation | m           | 30             | –          |
| Digital<br>Elevation<br>Model       | SRTM v4.1<br>CSI-CGIAR   | elevation                            | m           | 90             | –          |
| Highways                            | OSM-<br>Geofabrik        | slope<br>distance to<br>road         | degree<br>m | 90<br>150      | –          |
| Places                              |                          | distance to<br>town                  | m           | 150            | March 2021 |
| Waterways                           |                          | distance to<br>river                 | m           | 150            | March 2021 |
| Protected<br>areas                  | WDPA                     | presence of<br>protected area        | –           | 30             | March 2021 |

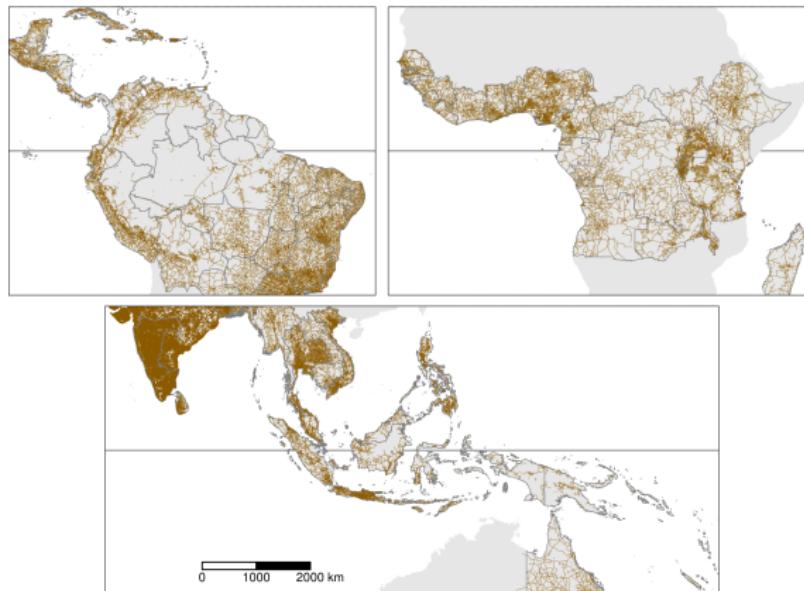
# Spatial variables



**Spatial explanatory variables in DRC**

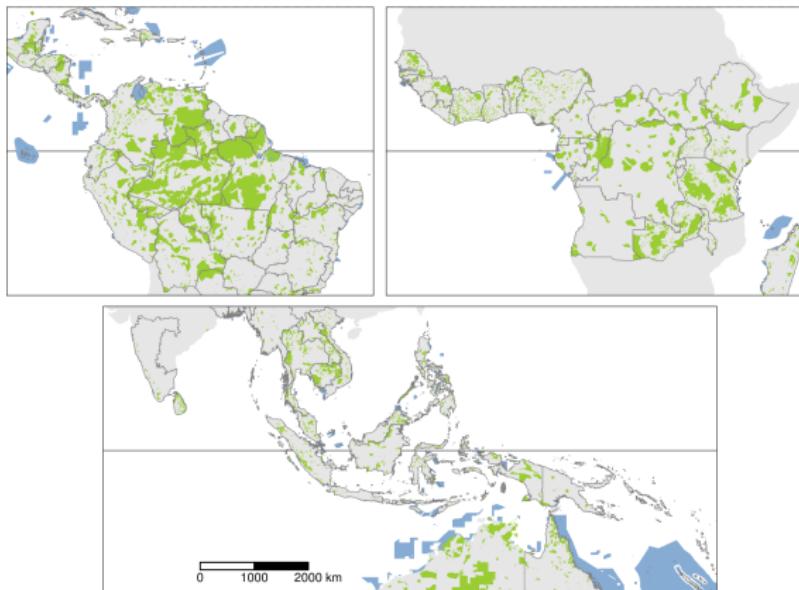
# Roads

- OpenStreetMap (OSM)
- “motorway”, “trunk”, “primary”, “secondary” and “tertiary” roads
- 3.6 million roads from OSM



# Protected areas

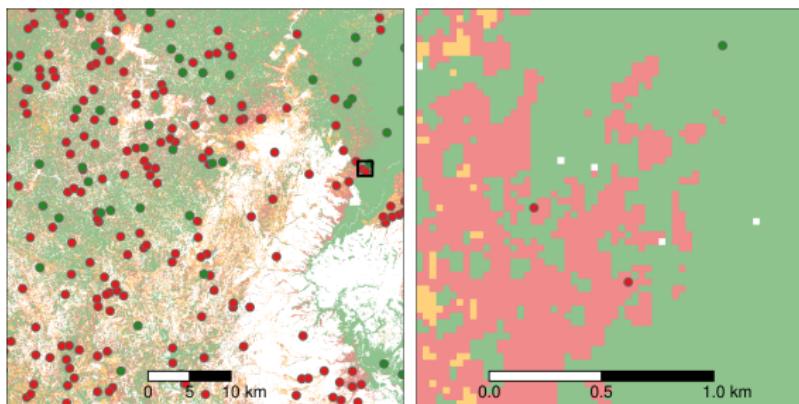
- PA status : “Designated”, “Inscribed”, “Established”, or “Proposed” before 1<sup>st</sup> January 2010
- 85,000 protected areas from WDPA



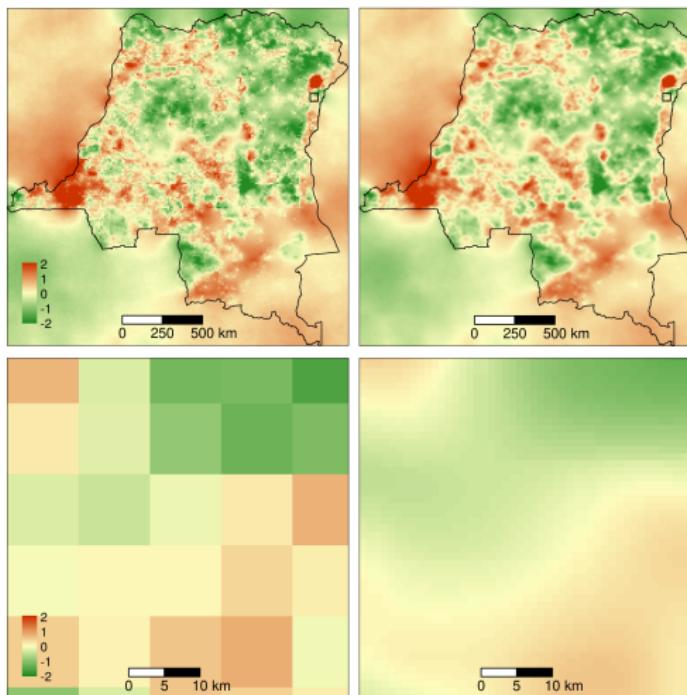
# Sampling

One word on sampling :

- Stratified sampling between deforested/non-deforested pixels in 2010–2020
- Total number of points proportional to the forest cover in 2010 (from 20,000 to 100,000 points per study area)
- Huge data-set of 3.2 M forest pixels (~288 Kha of forest)



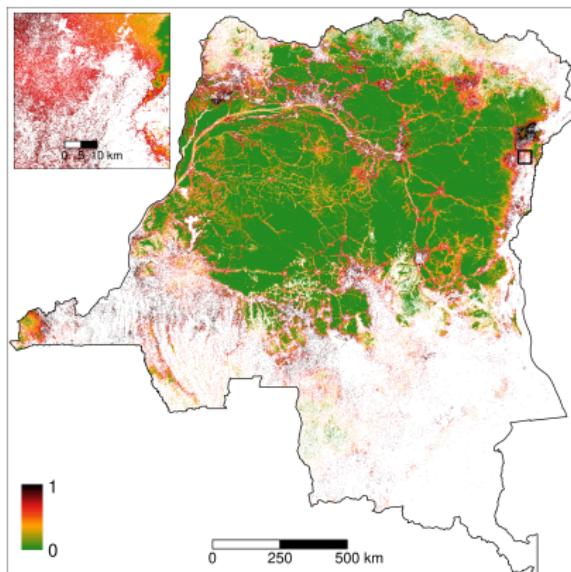
# Spatial random effects



**Interpolation of spatial random effects at 1km in DRC**

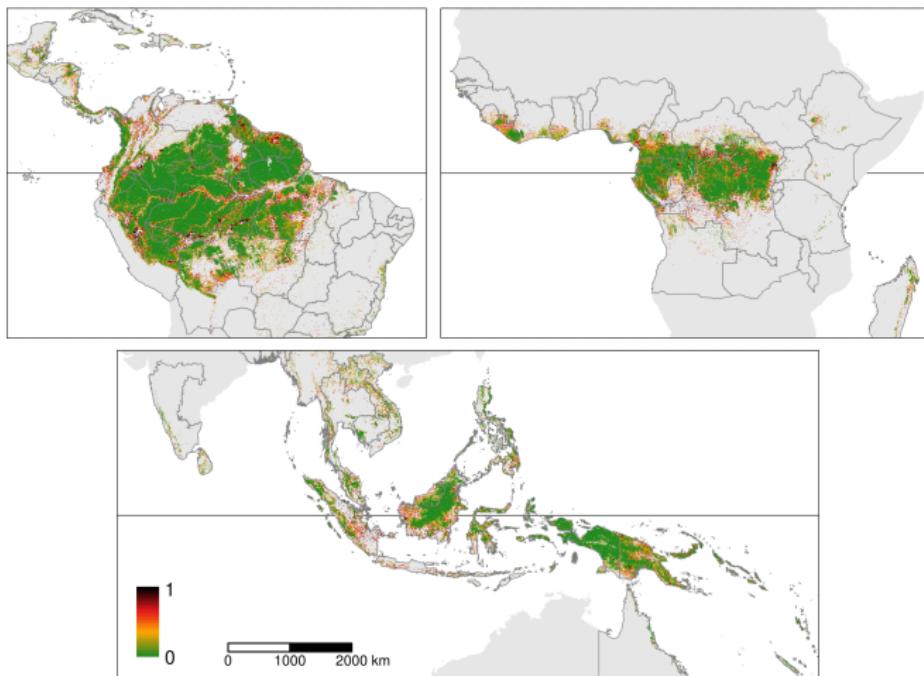
# Spatial probability of deforestation

We use the fitted model to compute the spatial probability of deforestation.



**Relative spatial probability of deforestation in DRC for the year 2020**

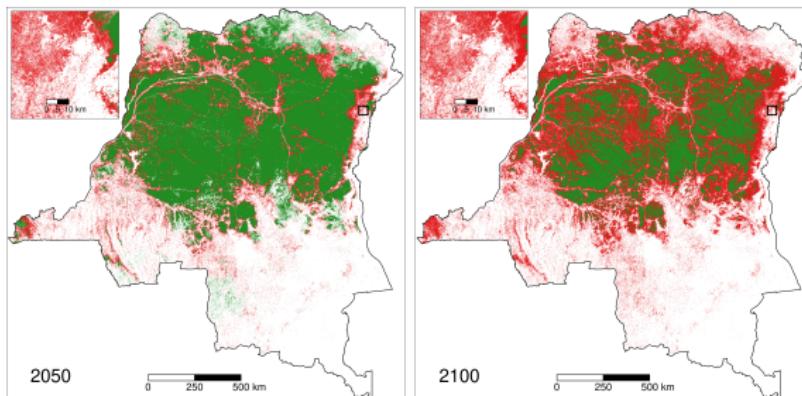
# Spatial probability of deforestation



**Pantropical map of the spatial probability of deforestation**  
<https://forestatrisk.cirad.fr/maps.html>

# Future forest cover

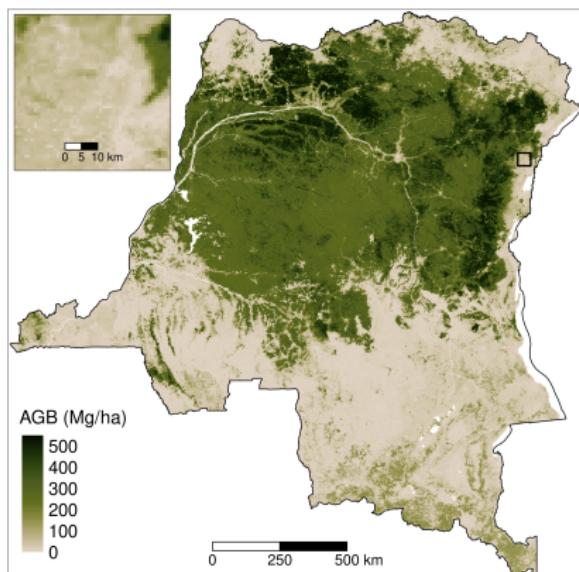
- Total deforested area  $D$  (ha) in a given period of time  $Y$  (yr) :  
$$D = d \times Y$$
, with  $d$  the annual deforested area (ha/yr).
- Number of pixels to be deforested :  $n = D/0.09$ , 0.09 ha being the pixel area.
- The  $n$  pixels with the highest deforestation probabilities are considered deforested in that period of time.



Projected deforestation in 2020–2050 and 2020–2100 in DRC

# Future carbon emissions

- Projected deforestation for years 2030, 2040, ..., 2100.
- We combine the maps of the projected deforestation with the (2000–2010) forest carbon map by Avitabile 2016 GCB (1km resolution).



Aboveground biomass in DRC

# Software

- forestatrisk Python package
- Process large rasters by blocks
- Several statistical models : iCAR, GLM, RF, etc.
- Set of functions for sampling, modelling, forecasting, validating

## forestatrisk Python package

python 2 | 3 pypi v1.0 PyPkg passing licence GPLv3 DOI 10.5281/zenodo.996337 JOSS 10.21105/joss.02975



Website : <https://ecology.ghislainv.fr/forestatrisk>  
Article : Vieilledent 2021, JOSS, doi : 10.21105/joss.02975

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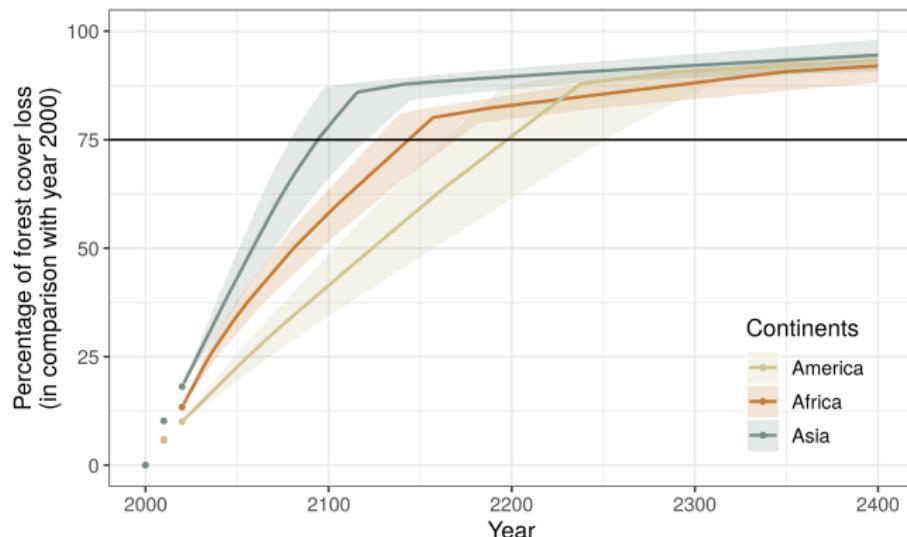
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# Tropical forest cover loss

75% of the tropical forest existing in 2000 will be lost in 2100, 2150, and 2200 in Asia, Africa, and America, respectively.



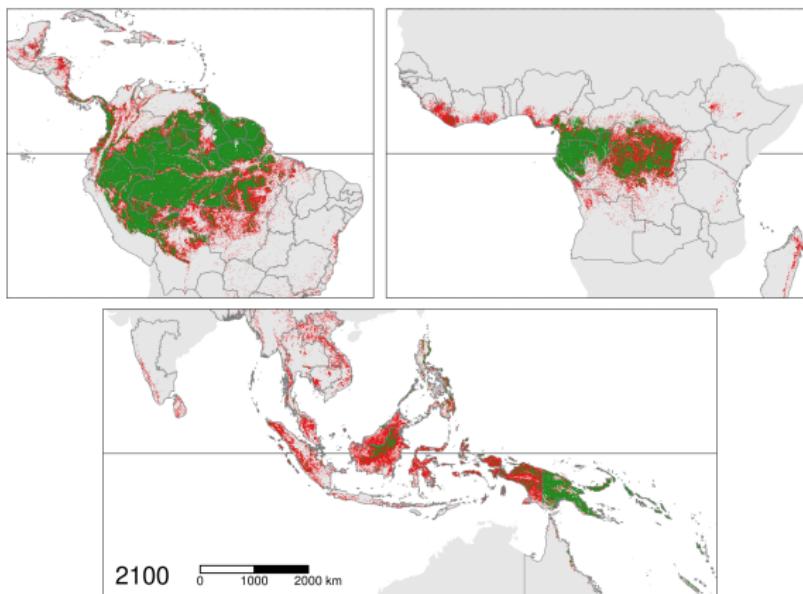
# Tropical forest cover loss

- 20 countries, 5 states in Brazil, and 1 region in India (having > 1 Mha of forest in 2020) will lose all their tropical forest by 2100.
- No more tropical forests in 6 biodiversity hotspots (extinction of 29,140 endemic species of plants and 4,576 species of vertebrates).

| Regions           | fc2000<br>(Kha) | fc2010<br>(Kha) | fc2020<br>(Kha) | d<br>(Kha/yr) | p<br>(%/yr) | fc2050<br>(Kha) | fc2100<br>(Kha) | loss21<br>(%) | yr75 |
|-------------------|-----------------|-----------------|-----------------|---------------|-------------|-----------------|-----------------|---------------|------|
| <b>Countries</b>  |                 |                 |                 |               |             |                 |                 |               |      |
| Brazil            | 375,893         | 349,784         | 334,982         | 1,537         | 0.4         | 288,862         | 211,996         | 44            | 2183 |
| DRC               | 131,621         | 126,164         | 117,812         | 860           | 0.7         | 92,007          | 48,999          | 63            | 2114 |
| Indonesia         | 141,262         | 127,699         | 116,317         | 1,215         | 1.0         | 79,853          | 19,078          | 86            | 2087 |
| <b>Continents</b> |                 |                 |                 |               |             |                 |                 |               |      |
| America           | 690,358         | 648,928         | 621,160         | 2,893         | 0.5         | 534,552         | 404,344         | 41            | 2197 |
| Africa            | 275,745         | 259,667         | 238,791         | 2,176         | 0.9         | 180,848         | 115,591         | 58            | 2143 |
| Asia              | 301,412         | 270,679         | 246,894         | 2,533         | 1.0         | 171,417         | 66,034          | 78            | 2094 |
| All cont.         | 1,267,515       | 1,179,273       | 1,106,845       | 7,602         | 0.7         | 886,816         | 585,968         | 54            | 2171 |

# Pantropical map of the future forest cover

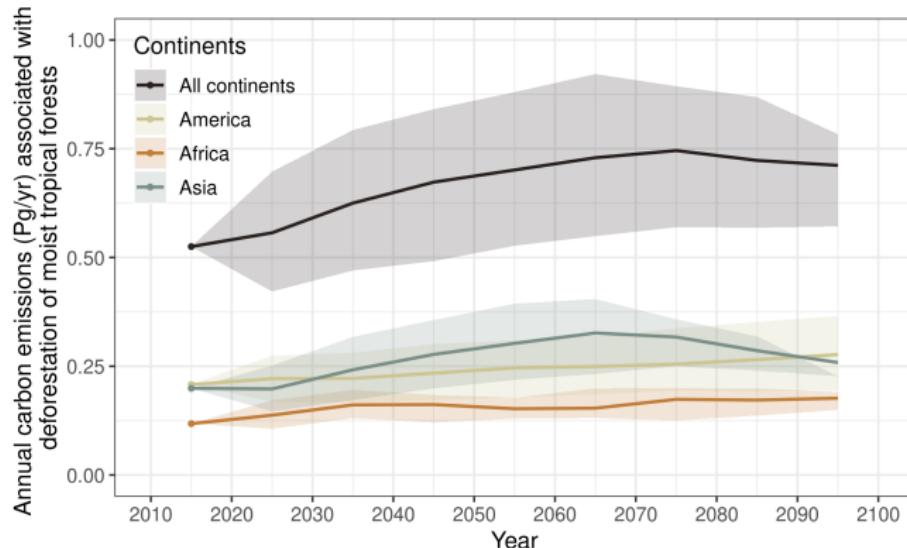
Tropical forests in 2100 will be (i) highly fragmented, (ii) concentrated in remote areas (far from roads and towns), pref. in protected areas, and at high elevations.



**Pantropical map of future forest cover in 2100**  
<https://forestrisk.cirad.fr/maps.html>

# Carbon emissions

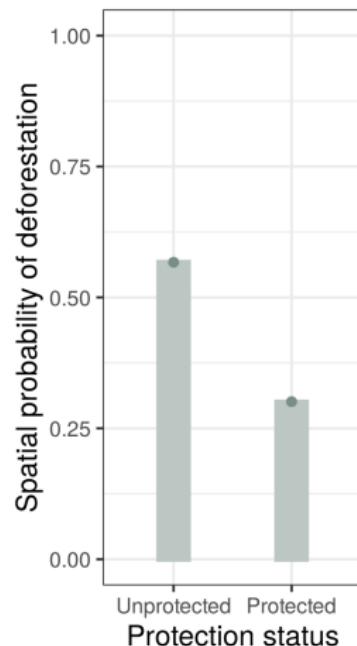
- Future deforestation will impact forests with higher carbon stocks
- Annual carbon emissions will increase from 0.525 Pg/yr in 2010–2020 to 0.746 Pg/yr in 2070–2080 (42% increase)



## Carbon emissions from future deforestation

# Protected area effect

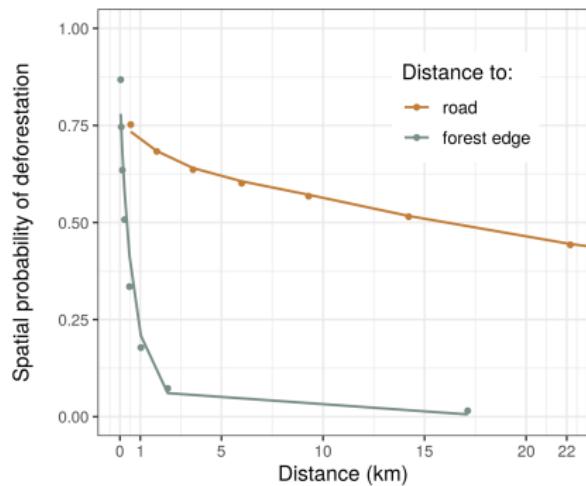
- Significant PA effect in 74 study areas out of 119 (88% of the TMF in 2010).
- PA reduce the risk of deforestation by 40%.



**Effect of PA on the deforestation risk**

# Road effect

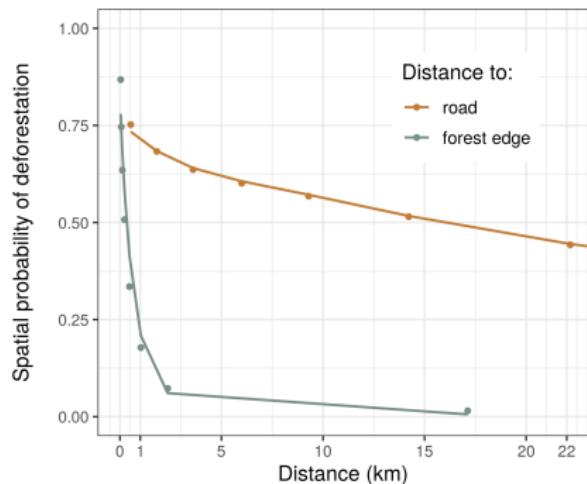
- Significant road effect in 59 study areas out of 119 (90% of the TMF in 2010).
- At 10km from a road, the risk of deforestation decreases by 13%.



**Effects of roads and forest edge on the deforestation risk**

# Forest edge effect

- Road effect must be interpreted together with forest edge effect.
- At 1km from the forest edge, the risk of deforestation decreases by 93%.



**Effects of roads and forest edge on the deforestation risk**

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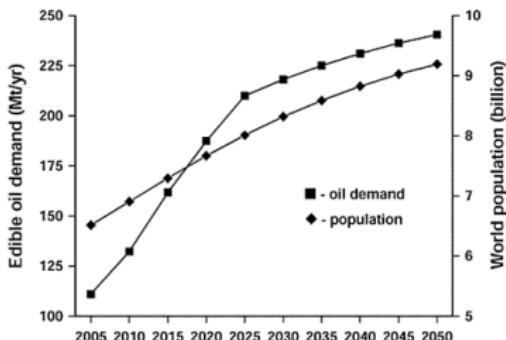
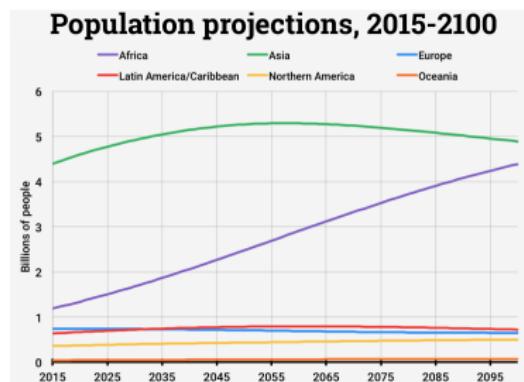
# Uncertainty analysis

- Despite uncertainty, results are clear and alarming.
- “Business-as-usual” scenario  $\neq$  what **will** happen in the future.
- “Business-as-usual” scenario = in the absence of any change.
- The objective is to alert and create a momentum for change.
- Nonetheless, rather optimistic scenario.



# Alternative scenarios : demography and demand

- Demography : in Africa, a large part of the population depends on slash-and-burn agriculture for their livelihood.
- Increasing demand for agricultural commodities : e.g., palm oil, Corley et al. 2009



## Other perspectives

- Models can be refined locally (e.g., Ivory-Coast, Madagascar, New-Caledonia) with more information on the context.
- Very rough estimates of biodiversity loss : need for world biodiversity maps.
- (Fragmentation study, regeneration potential, etc.)



Mining activity in New-Caledonia



... Thank you for attention ...  
<https://forestatrisk.cirad.fr>



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