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1 ForestAtRisk: A Python package for modelling and 2 forecasting deforestation in the tropics

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7 Summary

8 The ForestAtRisk Python package can be used to model the spatial probability of deforestation and predict future forest cover in the tropics. The spatial data used to model deforestation comes from georeferenced raster files which can be very large (several gigabytes). The functions available in the ForestAtRisk package process large rasters by blocks of data, making calculations fast and efficient. This allows deforestation to be modeled over large geographic areas (eg. at the country scale) and at high resolution (eg. ≤ 30 m). The ForestAtRisk package offers the possibility of using a logistic regression with auto-correlated spatial random effects to model the deforestation process. The spatial random effects make it possible to structure the residual spatial variability in the deforestation process which is not explained by the variables of the model and is often very large. In addition to providing new features, the ForestAtRisk Python package is open source (GPLv3 license), cross-platform and scriptable (via Python), user-friendly (functions provided with full documentation and examples), and easily extendable (with statistical models for example). The Python package ForestAtRisk was recently used to model deforestation and predict future forest cover by 2100 across the humid tropics.

23 Statement of Need

24 Commonly called the “Jewels of the Earth,” tropical forests shelter 30 million species of
25 plants and animals representing half of the Earth’s wildlife and at least two-thirds of its plant
26 species ([Gibson et al., 2011](#)). Through photosynthesis and carbon sequestration, they play an
27 important role in the global carbon cycle, and in regulating the global climate ([Baccini et al.,
28 2017](#)). Despite the many ecosystem services they provide, tropical forests are disappearing at
29 an alarming rate ([Keenan et al., 2015](#); [Vancutsem et al., 2020](#)), mostly because of human
30 activities. Currently, around 8 Mha (twice the size of Switzerland) of tropical forest are
31 disappearing each year ([Keenan et al., 2015](#)). Spatial modelling of the deforestation allows
32 identifying the main factors determining the spatial risk of deforestation and quantifying their
33 relative effects. Forecasting forest cover change is paramount as it allows anticipating the
34 consequences of deforestation (in terms of carbon emissions or biodiversity loss) under various
35 technological, political and socio-economic scenarios, and informs decision makers accordingly
36 ([Clark et al., 2001](#)). Because both biodiversity and carbon vary greatly in space ([Allnutt et al.,
37 2008](#); [Baccini et al., 2017](#)), it is necessary to provide spatial forecasts of forest cover change to
38 properly quantify biodiversity loss and carbon emissions associated with future deforestation.

39 The ForestAtRisk Python package we present here can be used to model the tropical
40 deforestation spatially, predict the spatial risk of deforestation, and forecast the future forest

41 cover in the tropics (Figure 1). Several other software allow modelling and forecasting forest
42 cover change (Mas et al., 2014). Most famous land cover change software include *Dinamica-*
43 *EGO* (Soares-Filho et al., 2002), *Land Change Modeller* (Eastman & Toledano, 2017), and
44 *CLUE* (Verburg & Overmars, 2009). Despite the many functionalities they provide, these
45 software are not open source and might not all be cross-platform, scriptable, and completely
46 user-friendly. Moreover, the statistical approaches they propose to model the land cover
47 change do not allow to take into account the residual spatial variability in the deforestation
48 process which is not explained by the model's variables, and which is often very large. The
49 more recent sophisticated algorithms they use (genetic algorithms, artificial neural networks,
50 or machine learning algorithms) might also have the tendency to overfit the data (Mas et al.,
51 2014). Finally, the possibility to use these software on large spatial scales (eg. at the country,
52 or continental scale) with high resolution data (eg. ≤ 30 m) have not yet been demonstrated
53 (but see Soares-Filho et al. (2006) for a study in the Amazon at 1 km resolution). The
54 *ForestAtRisk* Python package aims at filling some of these gaps and enlarging the range of
55 software available to model and forecast tropical deforestation.

56 Main functionalities

57 A set of functions for modelling and forecasting deforestation

58 The *ForestAtRisk* Python package includes functions to (i) compute the forest cover change
59 raster and the rasters of explanatory variables for a given country from several global datasets
60 (such as OpenStreetMap or the SRTM Digital Elevation Database v4.1 for example) (ii)
61 sample efficiently the forest cover change observations and retrieve the information on spatial
62 explanatory variables for each observation, (iii) estimate the parameters of various statistical
63 deforestation models, (iv) predict the spatial probability of deforestation, (v) forecast the
64 likely forest cover in the future, (vi) validate the models and the projected maps of forest
65 cover change, (vii) estimate the carbon emissions associated to future deforestation, and
66 (viii) plot the results. The *ForestAtRisk* package includes a hierarchical Bayesian logistic
67 regression model with autocorrelated spatial random effects which is well suited for modelling
68 deforestation (see below). But any statistical model class with a `.predict()` method can
69 potentially be used together with the function `forestatrisk.predict_raster()` to predict
70 the spatial risk of deforestation. This allows a wide variety of additional statistical models
71 from other Python packages to be used, such as *scikit-learn* (Pedregosa et al., 2011) for
72 example, for deforestation modeling and forecasting.

73 Ability to process large raster data

74 Data for forest cover change and spatial explanatory variables are commonly available as
75 georeferenced raster data. Raster data consists of rows and columns of cells (or pixels), with
76 each cell storing a single value. The resolution of the raster dataset is its pixel width in ground
77 units. Depending on the number of pixels (which is a function of the raster's geographical
78 extent and resolution), raster files might occupy a space of several gigabytes on the hard
79 drive. Processing such large rasters in memory can be prohibitively intensive. Functions in
80 the *ForestAtRisk* package process large rasters by blocks of pixels representing subsets of
81 the raster data. This makes computation efficient, with low memory usage. Reading and
82 writing subsets of raster data is done by using two methods from the GDAL Python bindings
83 (GDAL/OGR contributors, 2020): `gdal.Dataset.ReadAsArray()` and `gdal.Band.Write`
84 `Array()`. Numerical computations on arrays are performed with the NumPy Python module
85 whose core is mostly made of optimized and compiled C code which runs fast (Harris et al.,
86 2020). This allows the *ForestAtRisk* Python package to model and forecast forest cover
87 change on large spatial scales (eg. at the country or continental scale) using high resolution

88 data (eg. ≤ 30 m), even on personal computers with average performance hardware. For
89 example, the ForestAtRisk Python package has been used on a personal computer to model
90 and forecast the forest cover change at 30 m resolution for the Democratic Republic of the
91 Congo (total area of 2,345 million km²), processing large raster files of 71,205 × 70,280 cells
92 without issues.

93 Statistical model with autocorrelated spatial random effects

94 The ForestAtRisk Python package includes a method called `forestatrisk.model_binomi`
95 `al_iCAR()` to estimate the parameters of a logistic regression model including auto-correlated
96 spatial random effects. The model considers the random variable y_i which takes value 1 if a
97 forest pixel i is deforested in a given period of time, and 0 if it is not. The model assumes
98 that y_i follows a Bernoulli distribution of parameter θ_i (Equation 1). θ_i represents the spatial
99 relative probability of deforestation for pixel i and is linked, through a logit function, to a
100 linear combination of the explanatory variables $X_i\beta$, where X_i is the vector of explanatory
101 variables for pixel i , and β is the vector of effects $[\beta_1, \dots, \beta_n]$ associated to the n variables.
102 The model can include or not an intercept α . To account for the residual spatial variation in
103 the deforestation process, the model includes additional random effects $\rho_{j(i)}$ for the cells of
104 a spatial grid covering the study-area. The spatial grid resolution has to be chosen in order
105 to have a reasonable balance between a good representation of the spatial variability and a
106 limited number of parameters to estimate. Each observation i is associated to one spatial
107 cell $j(i)$. Random effects ρ_j are assumed to be spatially autocorrelated through an intrinsic
108 conditional autoregressive (iCAR) model (Besag et al., 1991). In an iCAR model, the random
109 effect ρ_j associated to cell j depends on the values of the random effects $\rho_{j'}$ associated to
110 neighbouring cells j' . The variance of the spatial random effects ρ_j is denoted V_ρ . The
111 number of neighbouring cells for cell j , which might vary, is denoted n_j . Spatial random
112 effects ρ_j account for unmeasured or unmeasurable variables (Clark, 2005) which explain a
113 part of the residual spatial variation in the deforestation process that is not explained by the
114 fixed spatial explanatory variables (X_i). Parameter inference is done in a hierarchical Bayesian
115 framework. The `far.model_binomial_iCAR()` method calls an adaptive Metropolis-within-
116 Gibbs algorithm (Rosenthal, 2011) written in C for maximum computation speed.

$$\begin{aligned} y_i &\sim \text{Bernoulli}(\theta_i) \\ \text{logit}(\theta_i) &= \alpha + X_i\beta + \rho_{j(i)} \\ \rho_{j(i)} &\sim \text{Normal}\left(\sum_{j'} \rho_{j'} / n_j, V_\rho / n_j\right) \end{aligned} \quad (1)$$

117 Applications and perspectives

118 The Python package ForestAtRisk was recently used to model the spatial probability of
119 deforestation and predict the forest cover change by 2100 across the humid tropics (<https://forestatrisk.cirad.fr/tropics>). Future package developments will focus on expanding docu-
120 mentation, case studies, statistical models and validation tools. We are convinced that the
121 “ForestAtRisk” package could be of great help in obtaining estimates of carbon emissions
122 and biodiversity loss under various scenarios of deforestation in the tropics. Such scenarios
123 should help decision-makers take initiatives to tackle climate change and the biodiversity cri-
124 sis. The results from the ForestAtRisk package could contribute to future IPCC and IPBES
125 reports (IPBES, 2019; IPCC, 2014) or help implement the REDD+ mechanism of the Paris
126 Agreement.
127

128 **Figures**

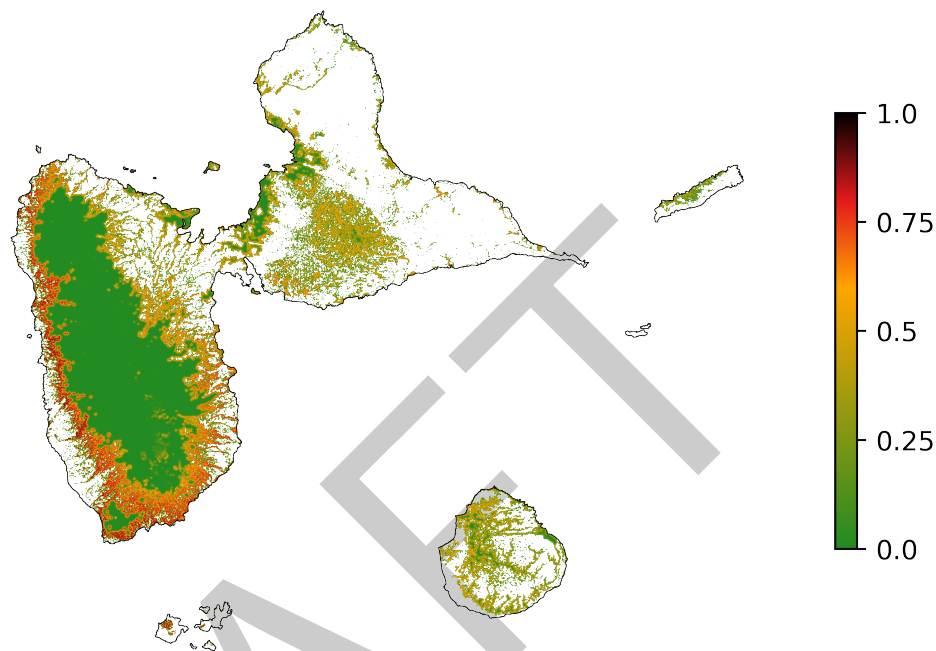


Figure 1: Map of the spatial probability of deforestation in the Guadeloupe archipelago. This map has been produced with the `ForestAtRisk` Python package. Colored pixels represent the extent of the natural old-growth tropical moist forest in 2020. The original map has a 30 m resolution. A relative spatial probability of deforestation was computed for each forest pixel. Probability of deforestation is a function of several explanatory variables describing: topography (altitude and slope), accessibility (distances to nearest road, town, and river), forest landscape (distance to forest edge), deforestation history (distance to past deforestation), and land conservation status (presence of a protected area). This map can be reproduced following the Get Started tutorial at <https://ecology.ghislainv.fr/forestatrisk>.

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