Country-scale mapping of individual forest and non-forest trees and shrubs in Africa - the example of Rwanda

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Goal:

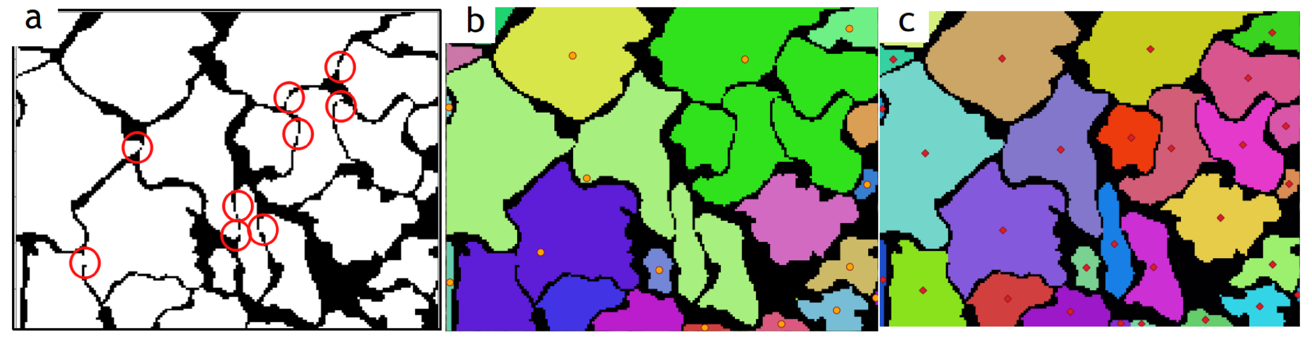
- We use publicly available VHR aerial photographs from 2008 and deep learning techniques to map individual tree crowns and related carbon stock at country scale, both inside and outside forests

Study Area, Data, and Methods

- **Rwanda** covers an area of 26,338 km² and is located in East Africa. The country is a signatory to and regularly reports on the implementation progress of the global major climate mitigation initiatives, and has committed to have 80% of the total land restored by 2030
- We use 0.25 m resolution **aerial photographs,** captured in June-August 2008 and 2009. The photographs are RGB, and stored under 8bits
- We use **environmental data:** mean annual rainfall, temperature, DEM for elevation, and land cover to assess relationship between tree density, and crown size and bio-climatic factors, and stratify the results according to relevant land cover classes.
- With 97,574 hand-labelled tree crowns and 103 bounding boxes, we use a deep learning model with a modified UNet architecture to detect and map individual tree crowns
- We use existing allometric equations for biomass and C stock estimation both inside and outside forests, at individual tree level.
- We apply image morphological operations at post-processing stage to split clumped trees in closed canopies

Separating clumped trees in closed canopies

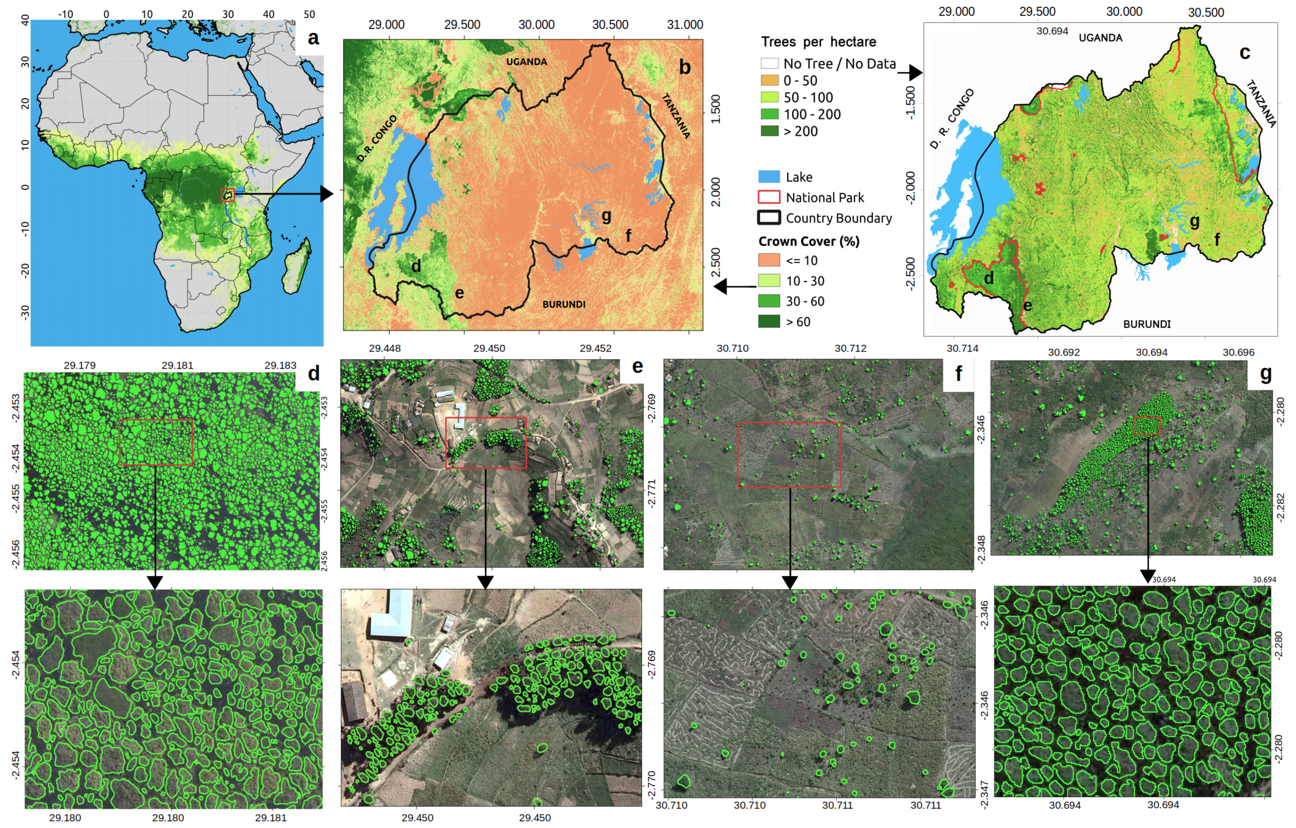
- Trees in closed canopies in natural dense forests are predicted as clumped crowns. We have developed and implemented an approach to separate clumped crowns, with an assumption of symmetry in crown shape. The algorithm finds crown centers, then relabels the image based on weighted distance to these centers.



- **a,** Sample clumped tree crowns after predictions by deep learning; **b,** centroids of predicted clumped crowns. **c**, separated crowns after post-processing, with new centroids corresponding to separated tree crown

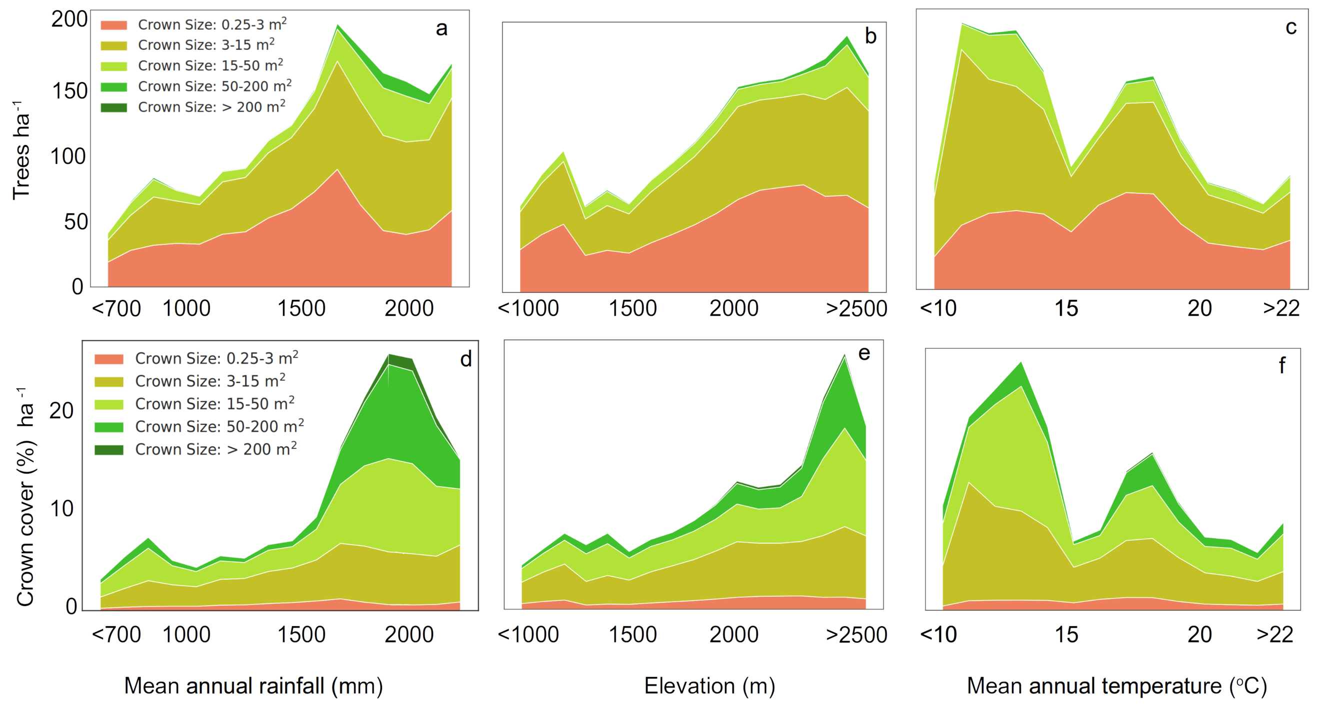
Individual tree mapping and C stock estimation at country scale

- We have mapped 243,687,070 trees with a crown size above 0.25 m², of which 57.7% are found outside forests.
- Visual examples on the mapping of individual trees inside and outside forest in Rwanda:



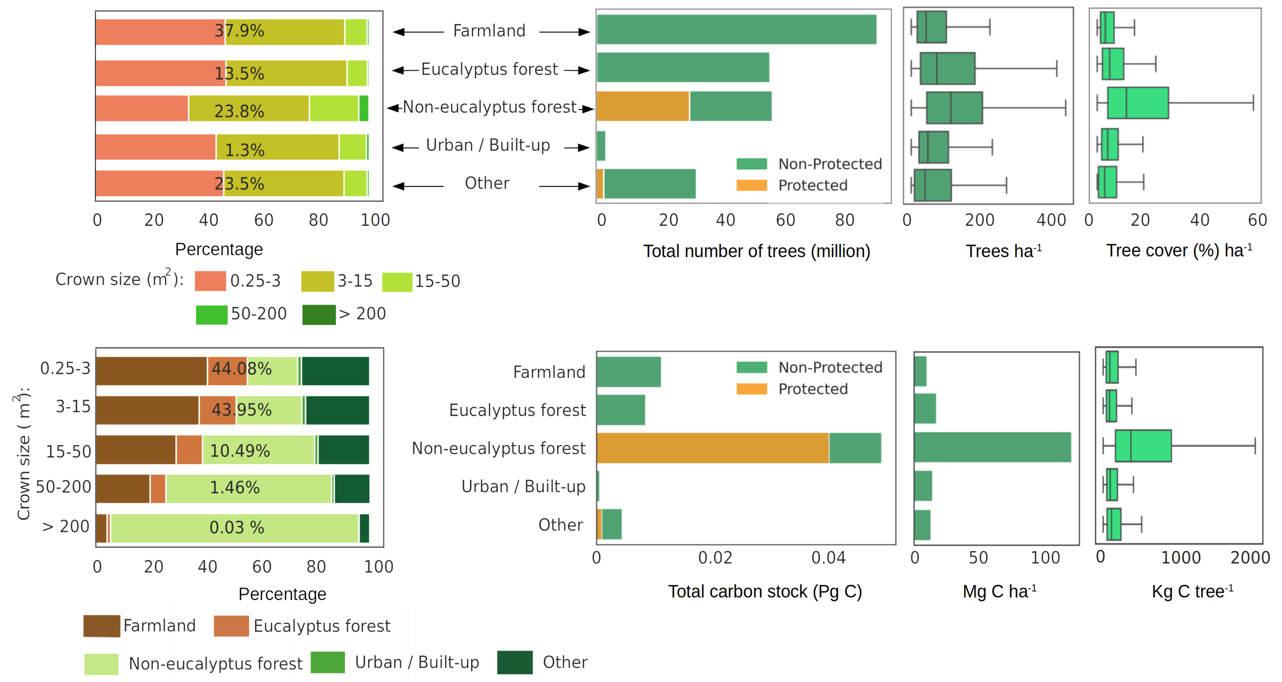
- **a**, Tree cover from a previously published global tree cover map using Landsat data (Hansen et al., 2013) in Africa, and **b**, in Rwanda. **c**, Country-wide tree density estimated by deep learning from 0.25 m aerial photos from 2008 (L: Lowlands, M: Midlands, H: Highlands). **d-g**, Examples of individual tree mapping in **d**, a rainforest; **e**, *Eucalyptus* tree plantations; **f**, farmlands; and **g**, forest plantations.

- Bio-climatic factors influence contribution of different classes of tree density and crown sizes to their overall coverage:

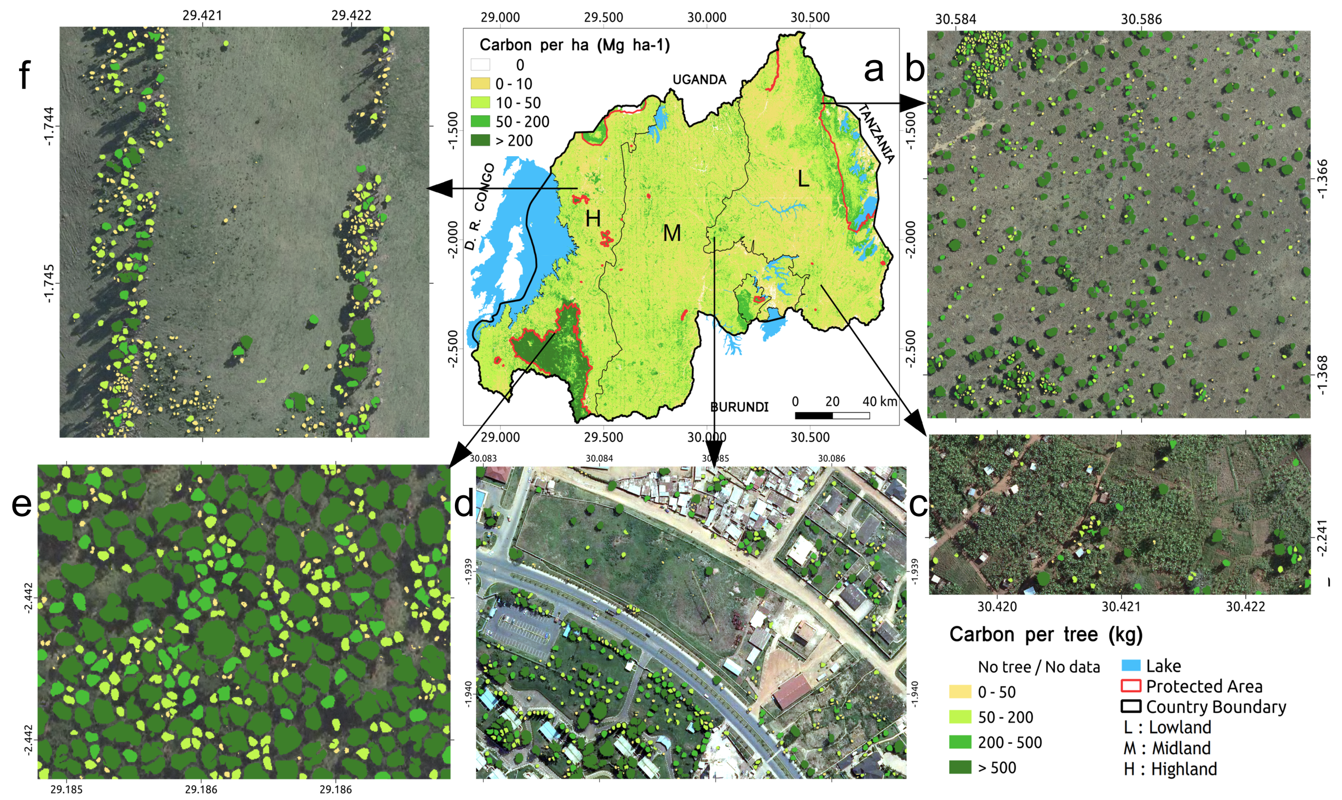


- Variation of different crown sizes and their contribution to the total tree density along gradients of **a**, rainfall, **b**, temperature, and **c**, elevation. **d**, **e**, f, same as a, b, c, but for the mean crown cover.

- We show a dominance of trees with small crown sizes between 0.25 m² and 3 m² covering 44.1% of the mapped trees, followed by crown sizes between 3 m² and 15 m² covering about 43.9% of the total trees, in 5 strata: Farmland, *Eucalyptus* plantations, non-*eucalyptus* plantations, urban areas, and other.



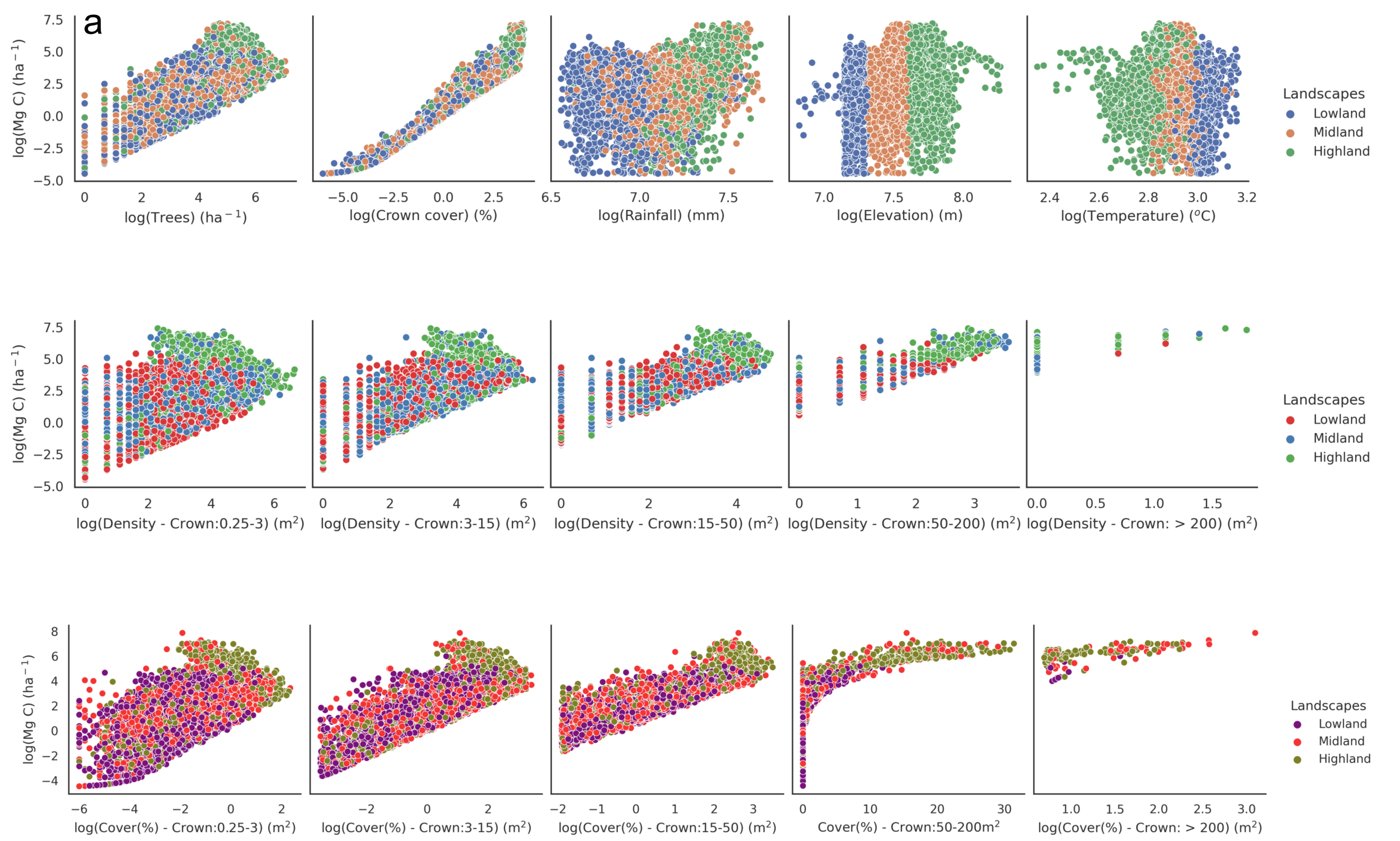
- The 2 crown size ranges highly dominate farmlands and *Eucalyptus* plantations.
- The largest crown sizes (> 200 m²) rare and mainly found in non-*Eucalyptus* forests, where natural forests under protection are found.
- 20% of the total above-ground C stock is found outside forests, and majority of the remaining 80% is found in protected areas
- Our approach makes it possible to have individual-tree based C sock assessment:



- **a**, Spatial distribution of the estimated C stock in Rwanda. **b-f**, Example of estimated C stock per tree in **b**, wooded savanna, **c**, banana-dominated farmland, **d**, urban area - Kigali city, **e**, in rainforest in Nyungwe National Park, **f**, in tree plantations within grazing land.

Tree density, cover and bio-climatic factors

- We have observed an empirical relationship between carbon density, tree density and crown cover.
- The relationship indicates that C stocks significantly increase more with both increase in density and cover of large trees, compared to an increase in small trees:



- The carbon stock's strong relationship with, **a**, tree density and **b**, crown cover.
- No strong relationship between C stock and **c**, rainfall, **d**, elevation, and **e**, temperature.
- The density of small trees appear to have less influence on the C stock (**f**, **g**,) compared to the big trees (**h**,**i**,**j**).
- Crown cover from small trees has less contribution to the C stock (**k**, **l**) compared to the big trees (**m**, **n**,**o**)

Highlights:

- We use deep learning and 0.25 m resolution aerial photographs to map the crown size and carbon stock of 243.7 million individual trees in Rwanda, East Africa
- We map individual trees in all landscapes: farmlands, tree plantations, rainforest, savanna, urban areas, and others.
- More than half (57.7%) of the mapped trees are located outside forests
- Non-forest trees contain about 20% of the country's total above-ground C stock, and majority of the remaining 80% is found in protected areas
- Our approach helps the reporting schemes to not require specific definition related to tree cover, since any custom stratification can be seamlessly applied, given the available individual tree map. This is expected to eliminate discrepancies in tree cover reporting by countries, due to the use of different definitions

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Project description. The current study is conducted under the project on trees outside forests (www.treesoutsideforests.com), which combines machine learning, remote sensing and geography to discover unprecedented knowledge at the level of individual trees