

Supplementary Information

Trees on smallholder farms and forest restoration are critical for Rwanda to achieve net zero emissions

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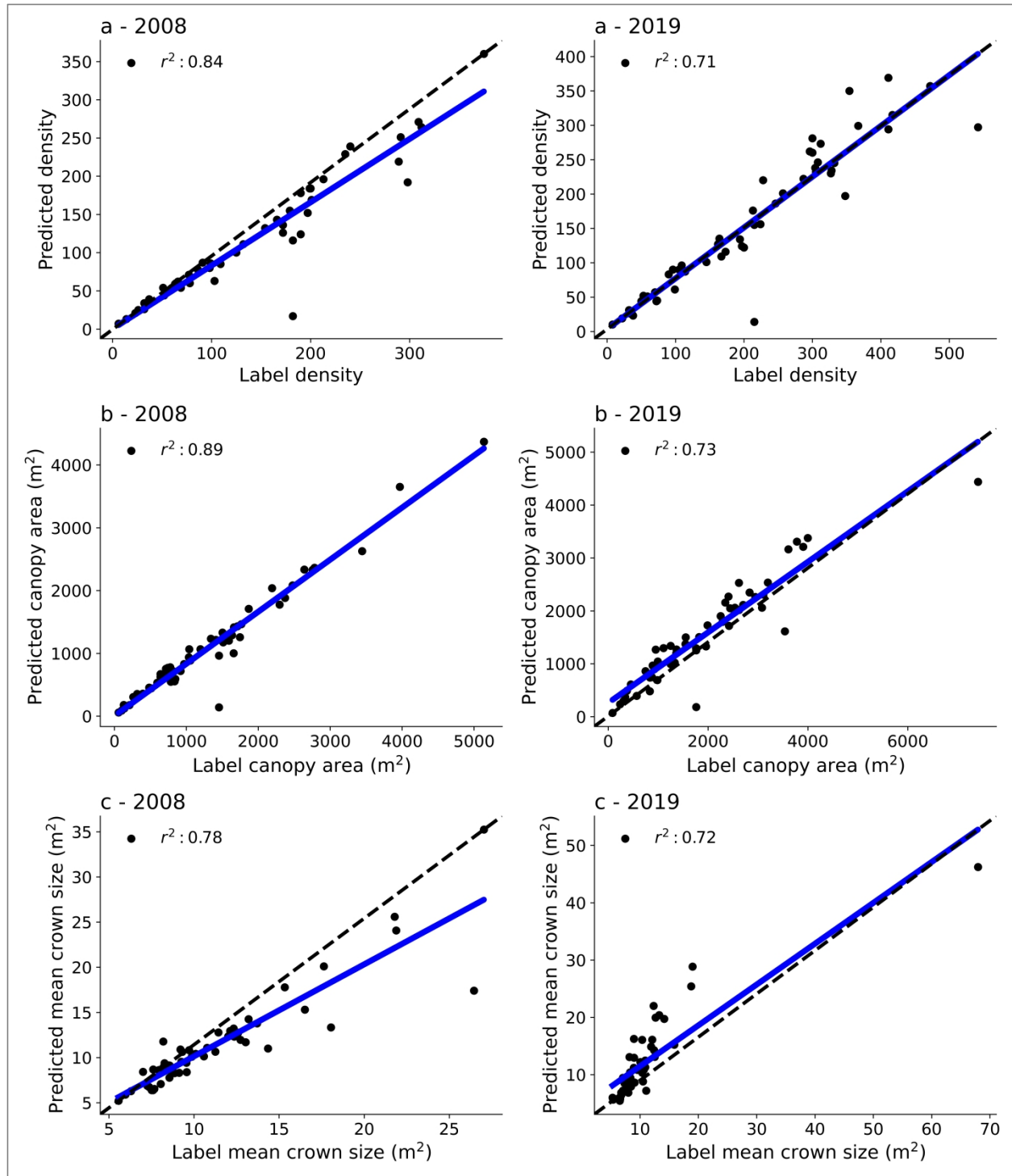
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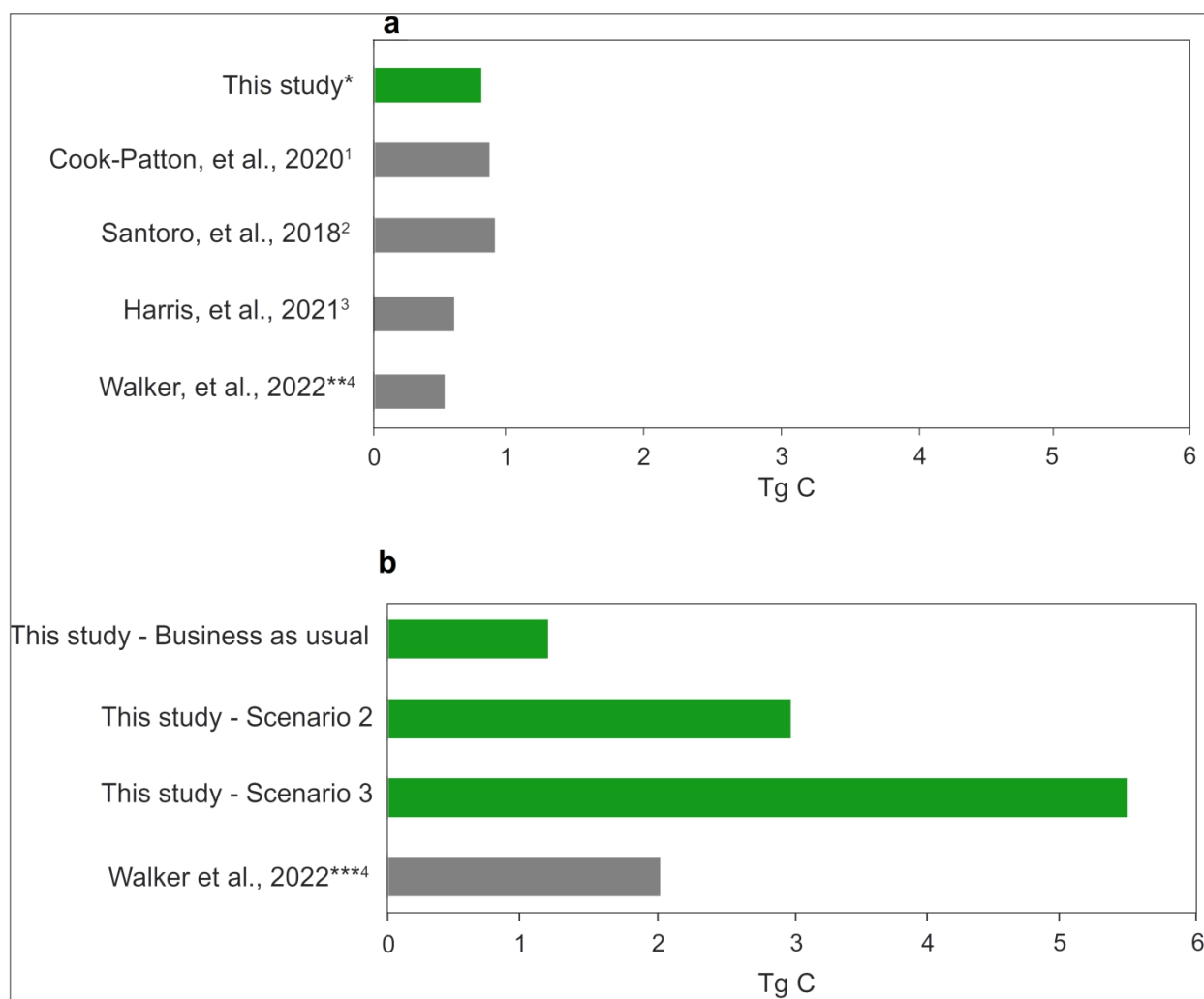
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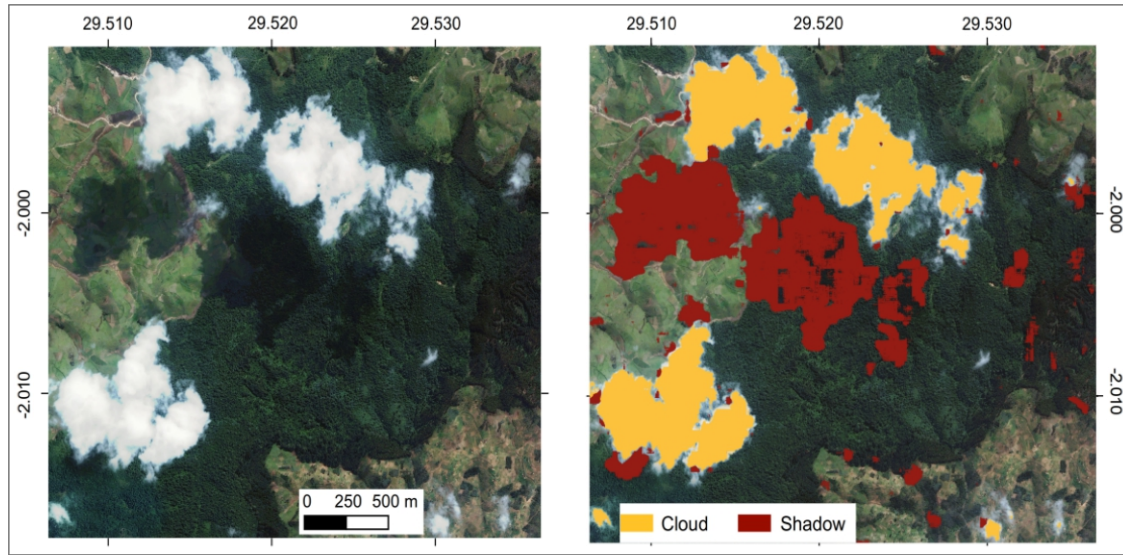
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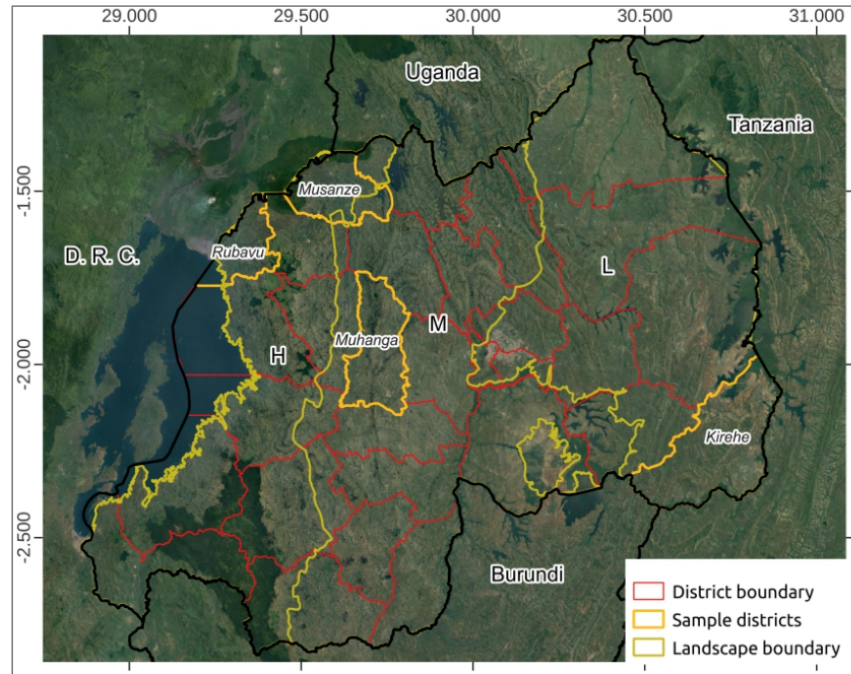
Supplementary Figure 1. Plot-level evaluation of tree crown segmentation model. We set aside 52 randomly selected patches containing 17,306 manual labels of individual trees (over 5% of the total manual labels) as an independent test set to select the best model. We compared the predictions and manual labels at each plot. **a**, Tree density for 2008 and 2019. **b**, canopy area for 2008 and 2019. **c**, mean crown size for 2008 and 2019. Each point represents one 100 x 100 m grid, $n = 52$.



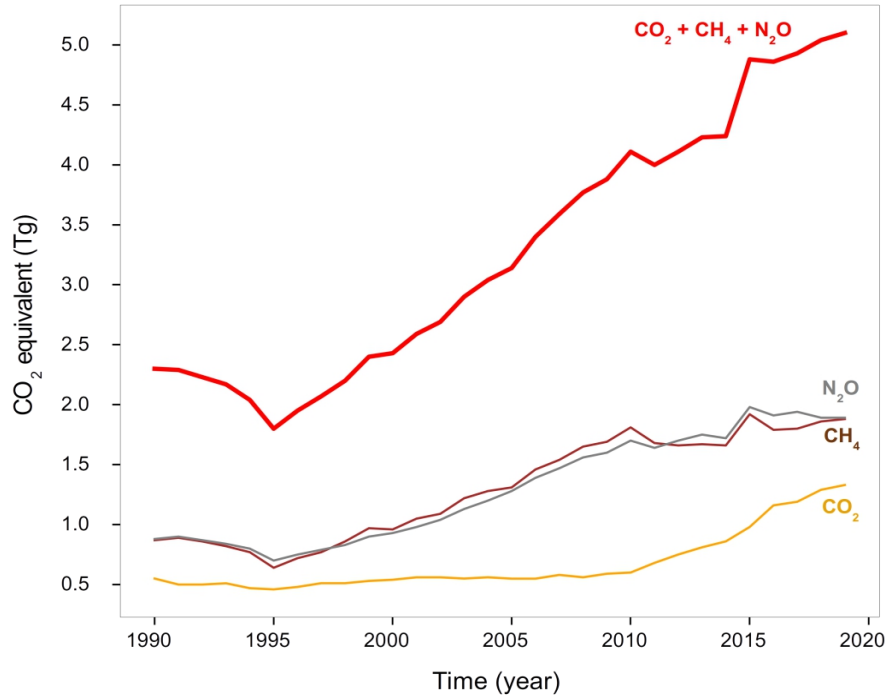
Supplementary Figure 2. Comparison of currently estimated (a) and future potential (b) C stock in degraded forests at country scale. a, Comparison of current estimates of total aboveground woody C stocks by this study and previous studies with global coverage^{71,72,73,74}. *We selected estimates for 2019. **We estimate C stock using the “Current (ca. 2016) aboveground biomass density (megagrams carbon per hectare) under baseline climate” from ref.⁴. **b,** Comparison of future potential aboveground C stock in degraded forests of Rwanda, taking the current estimates in (a) as a baseline. We present values for three scenarios presented in this study (see Fig. 4; Extended Data | Table 1; Extended Data | Table 2) and compare them with potential C stock estimated from ref.¹³. ***We estimate C stock using the “potential aboveground biomass density (Mg C ha⁻¹) under baseline climate” from ref.⁴.



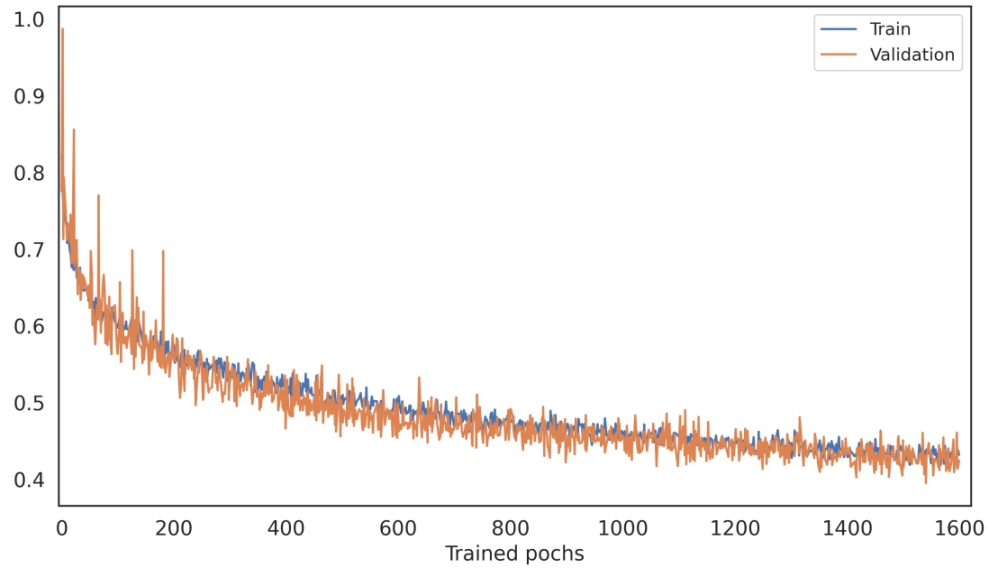
Supplementary Figure 3. Example of cloud and shadow detection and masking. A deep learning model was trained to detect areas covered by clouds and shadow in the 2019 satellite images. The detected cloudy and shadow pixels were then masked out in both the 2008 and 2019 images before further analyses, using spatial overlay analysis. Images are 0.5 m resolution from Worldview satellite by Maxar (<https://maxar.com/>), and were acquired from Rwanda Space Agency for this study as elaborated in the acknowledgments section.



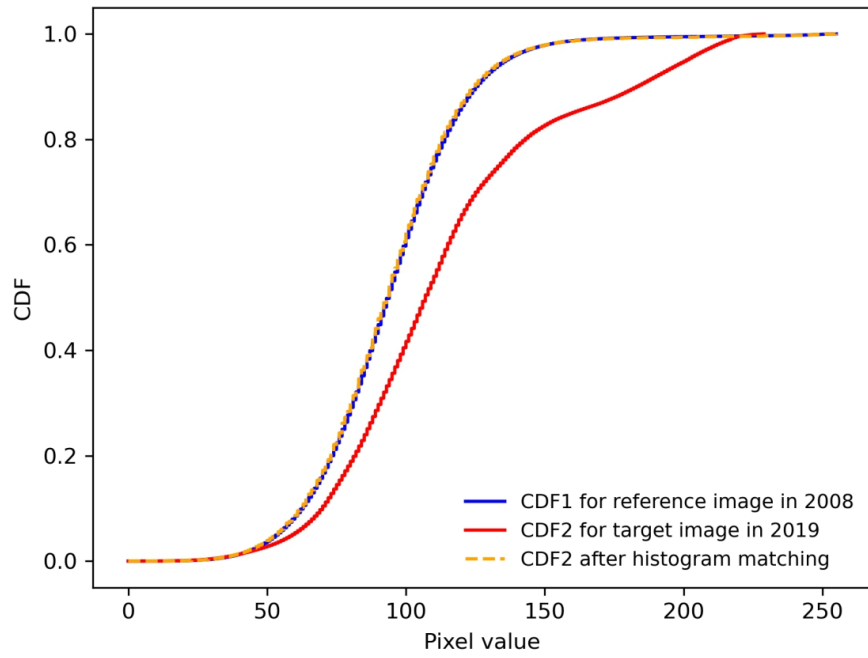
Supplementary Figure 4. Location of sample districts to analyse carbon gains in smallholder farms. We collected all (100%) plots in the districts ($n=2,468,648$) and selected only agricultural plots with at least one tree ($n=942,081$). The four sample districts are Rubavu in Western province of Rwanda, Musanze in Northern province, Muhanga in Southern province, and Kirehe in Eastern province. They represent the three major landscapes of the country, H: Highlands, M: Midlands, L: Lowlands. Background map: Google Earth satellite basemaps. Data on administrative boundaries were acquired from <https://gadm.org/> for international boundaries, and <https://geodata.rw/> for administrative boundaries.



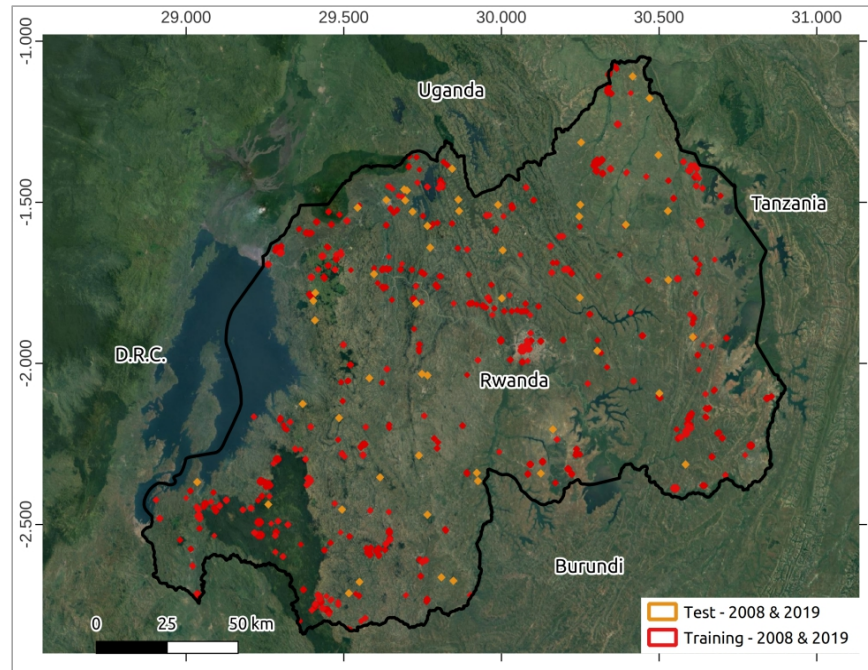
Supplementary Figure 5. Historical greenhouse gas emissions (CO₂ equivalent) of Rwanda since 1990. The data is from ref.⁵. CO₂ emissions are mainly from the burning of fossil fuels and the cement manufacturing. Methane (CH₄) emissions are from anthropocentric activities especially agriculture and industrial methane production (here presented in CO₂ equivalent units). Nitrous oxide (N₂O) emissions are mainly from the burning of agricultural biomass, industrial activities, and livestock management (here presented in CO₂ equivalent units).



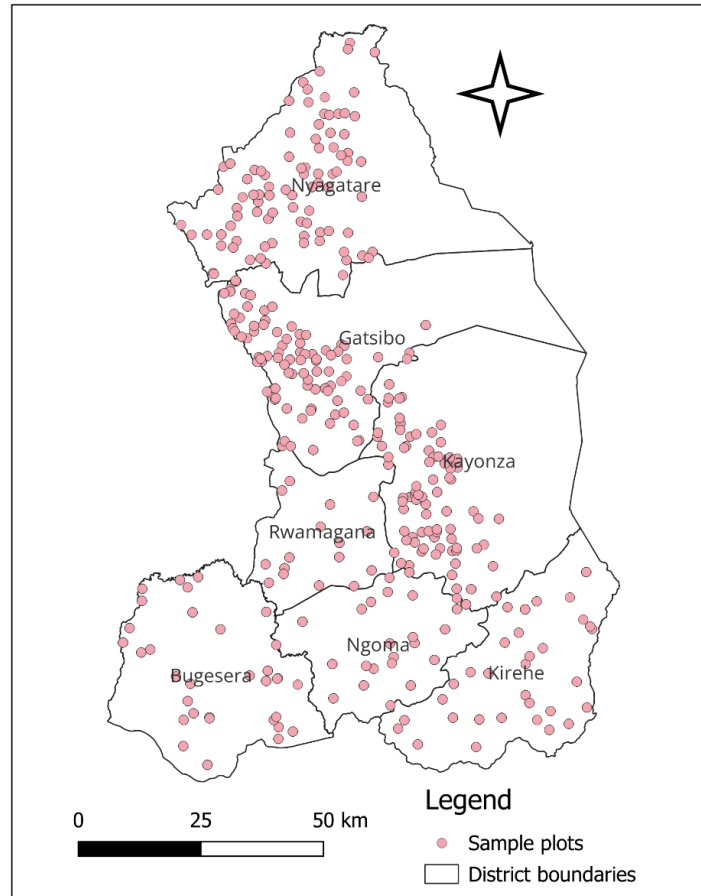
Supplementary Figure 6. The changes in loss values for both training and validation samples during training session for a cloud detection and segmentation deep learning model. The decrease in loss values indicates a lack of overfitting.



Supplementary Figure 7. An example of the Cumulative Distribution Function (CDF) of pixel values from an image composed of 202,514,256 pixels in 2008 (after adjusting to 0.5 m spatial resolution), and the CDF of the corresponding pixels of a target image in 2019 before and after histogram matching.



Supplementary Figure 8. Location of areas for manual training data labels for 2008 (n=207 areas covering about 1,698.8 ha, split into 4,039 patches with a size of 256 x 256 pixels, for 2008); and areas for manual data labels for 2019 (n=400 covering about 3,133.9 ha, split into 7,390 patches with a size of 256 x 256 for 2019). Independent test dataset for 2008 is composed of 52 areas of 1 ha containing a total of 6,639 manually delineated tree crowns; while the test set for 2019 is composed of the same 52 areas but with 10,667 manually delineated tree crowns. Background map: Google Earth satellite basemaps. Data for the administrative boundary were acquired from <https://gadm.org/> in shapefile format.



Supplementary Figure 9. Sample plot distribution in agroforestry landscapes and degraded forests of the Eastern province and peri-urban Kigali city in Rwanda. The number in the map indicates the number of sample plots (see Supplementary Notes).

Supplementary Table 1. Different sources of uncertainty and how they were evaluated and quantified⁶

Uncertainty source	Method	Evaluation	Forest	Non-Forest	Level
Tree count	Manual expert labels	Independent test data	error = 13%	error = 2.9%	Biome
Canopy area	Aggregate tree crowns	Independent test data	Crown area*0.27 to correct for gaps; bias = 13%	error = 14.9%	Biome
Crown diameter to DBH conversion	Allometry	4 equations each using 50% of the field data	error = 19%	error = 6%	Tree
Error propagation from allometry	Allometry	Prediction of each tree in Rwanda with 4 different equations	error = 2.3%	error = 3.9-6.2% (varies with land cover)	Biome
Wood density	Fixed at 0.54	ref 40, ref 64	error = 18.2%	error = 25% (n = 1985)	Tree
DBH to AGB	Allometry	ref 36; ref 37	error = 9.7%	error = 2.5%	Tree
AGB to AGC	Fixed factor of 0.47	ref 56	varies, highest error = 8.9%	-	Tree
Overall predicted crown area to AGB	See above	373 NFI permanent plots, 15 forest plots	error = 26%	error = 16%	Biome

Supplementary Table 2. Different scenarios for optimal contribution of agroforestry to the net zero emissions target in Rwanda

Ecosystem (area in ha; percentage of country land area coverage)	Potential restoration types to be applied	Main restoration targets in the next 20 years* ¹	Main restoration target(s) in the next 20 years	Estimated new investment cost (USD)* ⁵	Environmental benefits* ⁶	Estimated Year to reach net zero* ⁷	Direct economic benefits* ⁸
Agroforestry landscapes (1,316,389 ha; 61%)	Active restoration, i.e. agroforestry, creating woodlots	Business as usual; ensuring a net gain of 2 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level)	Tree density reaches 120 trees ha ⁻¹ * ² ; emissions remain at the same level as in 2019	208.5 million USD	- Net gain of 52.1 million new trees (or +49.3%); - Net gain of 3.11 Tg C; - Net gain of 2.36 Mg C ha ⁻¹ (or +0.12 Mg C ha ⁻¹ yr ⁻¹); - Offsetting 8.66 Mg CO ₂ ha ⁻¹ (or +0.43 Mg CO ₂ ha ⁻¹ yr ⁻¹); - Reducing additional 11.2% of national annual GHG emissions	2044	- Annual carbon credits worth between 5.7 and 57.0 million USD; - Return on investment (net gain) ranging between 25 and 79.2 million USD after 20 years - Annual carbon credits worth between 13 and 130 million USD;
		Planting 4.4 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level	Tree density reaches 168 trees ha ⁻¹ * ³ ; emissions remain at the same level as in 2019	461.3million USD	- Net gain of 115.3 million new trees (or +109%); - Net gain of 6.9 Tg C; - Net gain of 5.2 Mg C ha ⁻¹ (or +0.26 Mg C ha ⁻¹ yr-1); - Offsetting 19.1 Mg CO ₂ ha-1 (or +0.96Mg CO ₂ ha ⁻¹ yr ⁻¹) - Reducing additional 24.8% of national GHG emissions	2034	- Return on investment (net gain) ranging between 55.4 and 175.3 million USD after 20 years - Carbon credits worth between 29 and 289.6 million USD per year;
		Planting 11 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level	Tree density reaches 300 trees ha ⁻¹ * ⁴ ; emissions remain at the same level as in 2019	1.16 billion USD	- Net gain of 289 million new trees (or +273%); - Net gain of 17.2 Tg C; - Net gain of 13.1 Mg C ha-1 (or +0.7 Mg C ha-1 yr-1); - Offsetting 48 Mg CO ₂ ha-1 (or +2.4 Mg CO ₂ ha-1 yr ⁻¹); - Reducing additional 61.8% of national GHG emissions	2034	- Return on investment (net gain) ranging between 138.8 and 439.4 million USD after 20 years

*¹Restoration targets are based on ref.⁷, and ref.⁸. *²The target tree density is a density that could be attained in a 20-year period by keeping the same pace observed in this study. *³The target tree density is the maximum on-farm tree density observed in a survey from 457 farm plots surveyed in 2007 and 2008 across all the 3 major altitudinal gradients of Rwanda^{8,9}. *⁴The target tree density is the optimal on-farm tree density recommended by the Ministry of Environment of Rwanda to optimise both restoration and food security benefits from the country's agricultural plots¹⁰. *⁵We use the restoration cost ha⁻¹ estimated by the ministry of environment of Rwanda in 2014: about 1,200 USD required to restore 1 ha in farmlands to reach a density of 300 trees ha⁻¹ in a 20-year period, while leaving enough space for crops¹⁰. *⁶The environmental benefits are estimated by the approach from both this study and one adapted from ref.⁶. *⁷The year when tree cover could optimally contribute to country's net zero emissions target, with an assumption that the GHG emissions would be kept at the same levels as in 2019. Note that we assume no net gain until 10 years after plantation to ensure uncompromised carbon sink during the growth of trees¹¹. *⁸We estimate the value of carbon credits using the range of 10 to 100 USD per tonne of CO₂ according to ref.¹²; ref.¹³; and ref.¹⁴. The high cost range is due to the current high volatility and speculations in the carbon market¹⁵. Note that all of the scenarios presented here would have the same baseline. The baseline includes all actions and effort already carried out, which would lay a foundation for the start of the suggested scenarios. Examples include investment of about 530.7 million USD that the government of Rwanda has invested in 44 known restoration projects from 2011 up to 2018, which brought over 700 thousand hectares of land under restoration⁷; policies in place to support the restoration scenarios such as: the “Green Growth and Climate Resilience Strategy”, through which the country has committed to reduce 38% of the current emissions by 2030¹⁶; commitment to restore 2 million hectares by 2030 under RED+; among others.

Supplementary Table 3. Different scenarios for optimal contribution of degraded natural forests to the net zero emissions target in Rwanda

Ecosystem (area in ha; percentage of country land area coverage)	Potential restoration types to be applied	Main restoration targets in the next 20 years	Main restoration target(s) in the next 20 years	Estimated new investment cost (USD) ^{*5}	Environmental benefits	Estimated Year to reach net zero	Direct economic benefits
Degraded forests (10,932 ha; 0.5%)	Assisted natural restoration	Business as usual with dispersing indigenous tree seeds, removing exotic plants, protecting forests* ¹ and ensure annual gain of 5 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level	Tree density reaches 288.2 trees ha ⁻¹ * ² ; emissions remain at the same level as in 2019	0.6 million USD	- Net gain of 1.1 million new trees (or +53%); - Net gain of 0.4 Tg C; - Net gain of 38.7 Mg C ha ⁻¹ (or 1.9 Mg C ha ⁻¹ yr ⁻¹); - Offsetting 141.9 Mg CO ₂ ha ⁻¹ (or +7.1 Mg CO ₂ ha ⁻¹ yr ⁻¹); - Reducing additional 1.44% of national GHG emissions	2044	- Carbon credits worth between 0.8 and 7.76 million USD per year; - Net financial gain close to 0 USD, as carbon credits revenues would be almost equal to investment cost ³⁸
		Increased effort in dispersing indigenous tree seeds, removing exotic plants, protecting forests, and ensure annual gain of 25.6 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level	Tree density reaches 700 trees ha ⁻¹ * ³ ; emissions remain at the same level as in 2019	3 million USD	- Net gain of 5.6 million new trees (or +271.9%); - Net gain of 2.2 Tg C; - Net gain of 201.2 Mg C ha ⁻¹ (or + 10.1 Mg C ha ⁻¹ yr ⁻¹); - Offsetting 737.8 Mg CO ₂ ha ⁻¹ (or +36.9 Mg CO ₂ ha ⁻¹ yr ⁻¹); - Reducing additional 7.9% of national GHG emissions	2034	- Annual carbon credits worth between 4.0 and 40.3 million USD per year; - Net financial gain close to 0 USD, as carbon credits revenues would be almost equal to investment cost
		Increased effort in dispersing indigenous tree seeds, removing exotic plants, protecting forests, and ensure growth of 55.1 new trees ha ⁻¹ yr ⁻¹ ; and ensure that GHG emissions are kept at 2019 level	Tree density reaches 1,290 trees ha ⁻¹ * ⁴ ; emissions remain at the same level as in 2019	6.5 million USD	- Net gain of 12.0 million new trees (or +578.2%); - Net gain of 4.7 Tg C; - Net gain of 426.3 Mg C ha ⁻¹ (or +21.3 Mg C ha ⁻¹ yr ⁻¹); - Offsetting 1,563.2 Mg CO ₂ ha ⁻¹ (or +78.2 Mg CO ₂ ha ⁻¹ yr ⁻¹); - Reducing additional 16.9% of national GHG emissions	2034	- Annual carbon credits worth between 8.5 and 85.4 million USD per year; - Net financial gain close to 0 USD, as carbon credits revenues would be almost equal to investment cost

^{*1}Some of the restoration activities that have been implemented in the past in restoring degraded forests in Rwanda¹⁷. ^{*2}The target tree density is a density that could be attained in a 20-year period by continuing the assisted natural regeneration in degraded forests and ensure growth of at least 5 trees ha⁻¹ yr⁻¹ during the restoration period, as it has been observed during the period between 2008 and 2019 by this study. ^{*3}The target density is 70% (survival rate) of the recommended average number of trees to plant for an optimal forest restoration in the tropics¹⁸. ^{*4} The target density is 70% (survival rate) of the maximum number of trees with a diameter at breast height (DBH) smaller than 5 cm observed in 15 surveyed plots (plot size = 0.5 ha) in the African montane tropical rainforest in Rwanda¹⁹. ^{*5} We use the recommended cost of about 375 USD to restore 1 ha of natural forests via regeneration in a 20-year period in Rwanda¹⁰.

Supplementary Table 4. Accuracy assessment of the deep learning tree segmentation model.

a. Validating with independent test for 2008

	Tree detected	No tree detected
Tree label exists	TP = 0.74	FN = 0.26
No tree label	FP = 0.03	TN = 0.97

b. Validating with independent test for 2019

	Tree detected	No tree detected
Tree label exists	TP = 0.77	FN = 0.23
No tree label	FP = 0.05	TN = 0.95

Supplementary notes

Location and distribution of sample plots and sampling strategy: Fieldwork was conducted in 10 Districts of Eastern province and peri-urban of Kigali in different agroforestry systems. Overall, 296 field plots were randomly sampled across the area. The spatial distribution of the sample plots is illustrated in Supplementary Figure 9.

Sample plots demarcation and tree marking: The standard sample plots used are circular shaped with a radius of 40 m (equivalent to 0.5 ha). The location information of the plots was recorded via GPS-enabled tablets. The plot boundaries were marked by a red paint for identification, and any tree with a centre point at DBH level falling outside of the plot was excluded from measurements.

Data recording: The collected data were recorded using Open Data Kit (ODK) tool incorporated in the tablets for plot and tree characteristics, tree growth measurements with DBH ≥ 5 cm within sample plots. The data recorded were general description of the area included geographic coordinates and administrative locations (province, sector, cell, village), latitude, longitude, altitude; topographic information (slope in %), slope orientation, soil type, soil erosion, land ownership; tree age; tree canopy and density; vegetation cover; litter cover; human activities (fire evidence, grazing, wood harvesting). For tree growth measurements, the following data were collected: number of trees, species name, species code, tree origin, tree position, reference diameter (DBH) in cm and total height in m. The following section provides details on the main recorded measurements.

Diameter at Breast Height (DBH): Diameter at breast height above the bark (DBH), at 1.3 m above ground level, in centimeter approximation was measured for all sampled trees with a diameter tape (cm). A straight measuring stick of 1.3 m was utilized to assure homogeneity and accuracy of the point of measurement. Position for correct DBH measurement and particular situation were respected as: if tree forks immediately above breast height, the tree was counted as a single tree and DBH was measured just under any swelling that could inflate the DBH. In this case, coppice was considered in the same way as forked trees. Coppice shoots originating below 1.3 m were measured as a single tree; if a tree fork below breast height, the stems were considered as separate trees and recorded separately. If bulges, swellings, depressions, branches or other abnormalities occur at breast height, the DBH was measured just below or above the abnormality at a point where it ceases to affect normal stem form, and computed as the average of the two measurements.

Total height: Total height (H) in m was measured in full meters approximation for three trees within every sample plot. The closest trees to the plot center, the trees with the smallest, and with the largest DBH were measured. The total tree height was measured by using Silver and Haga clinometers.

Tree crown canopy measurement: The ellipse representing a tree crown canopy with long diameter (LD) and short diameter (SD) were measured. In the field, the measurement was measured using meter tape by standing at the edge of crown pulling measuring tape (or laying it on the ground to avoid that it bends), and record the distances (both SD and LD) in centimeters. More tree measurements recorded on the field include GPS location of a tree, and management techniques.

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