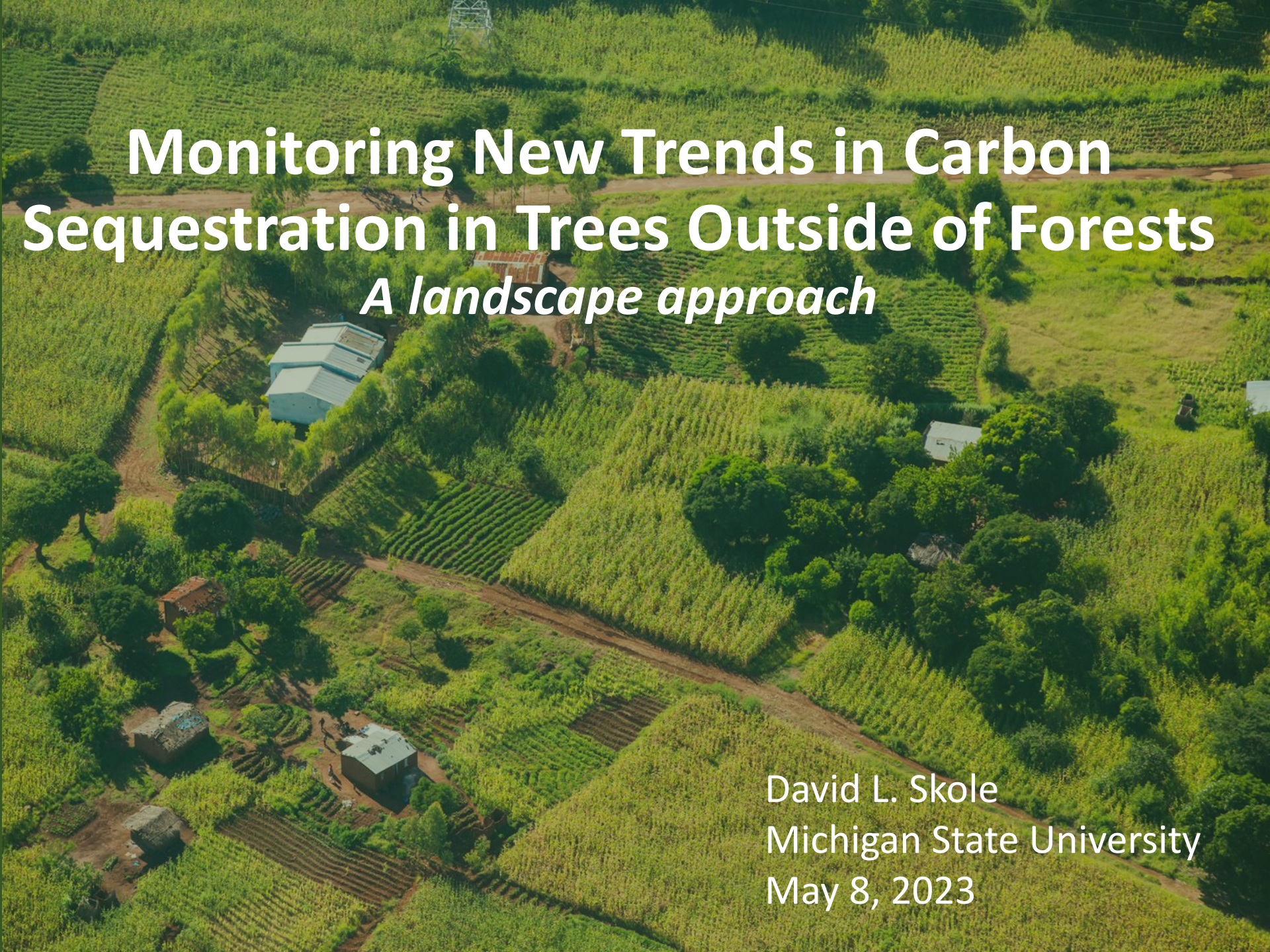


Monitoring New Trends in Carbon Sequestration in Trees Outside of Forests

A landscape approach

David L. Skole
Michigan State University
May 8, 2023

Initially: Forest Degradation and REDD

Science

Long-term forest degradation surpasses deforestation in the Brazilian Amazon

ERALDO APARECIDO TRONDOLI MATRICARDI, DAVID LEWIS SKOLE, OLÍVIA BUENO COSTA, MARCOS ANTONIO PEDLOWSKI, JAY HOWARD SAMEK, AND EDER PEREIRA MIGUEL Authors Info & Affiliations

SCIENCE • 11 Sep 2020 • Vol 369, Issue 6509 • pp. 1378-1382 • DOI: 10.1126/science.abb3021

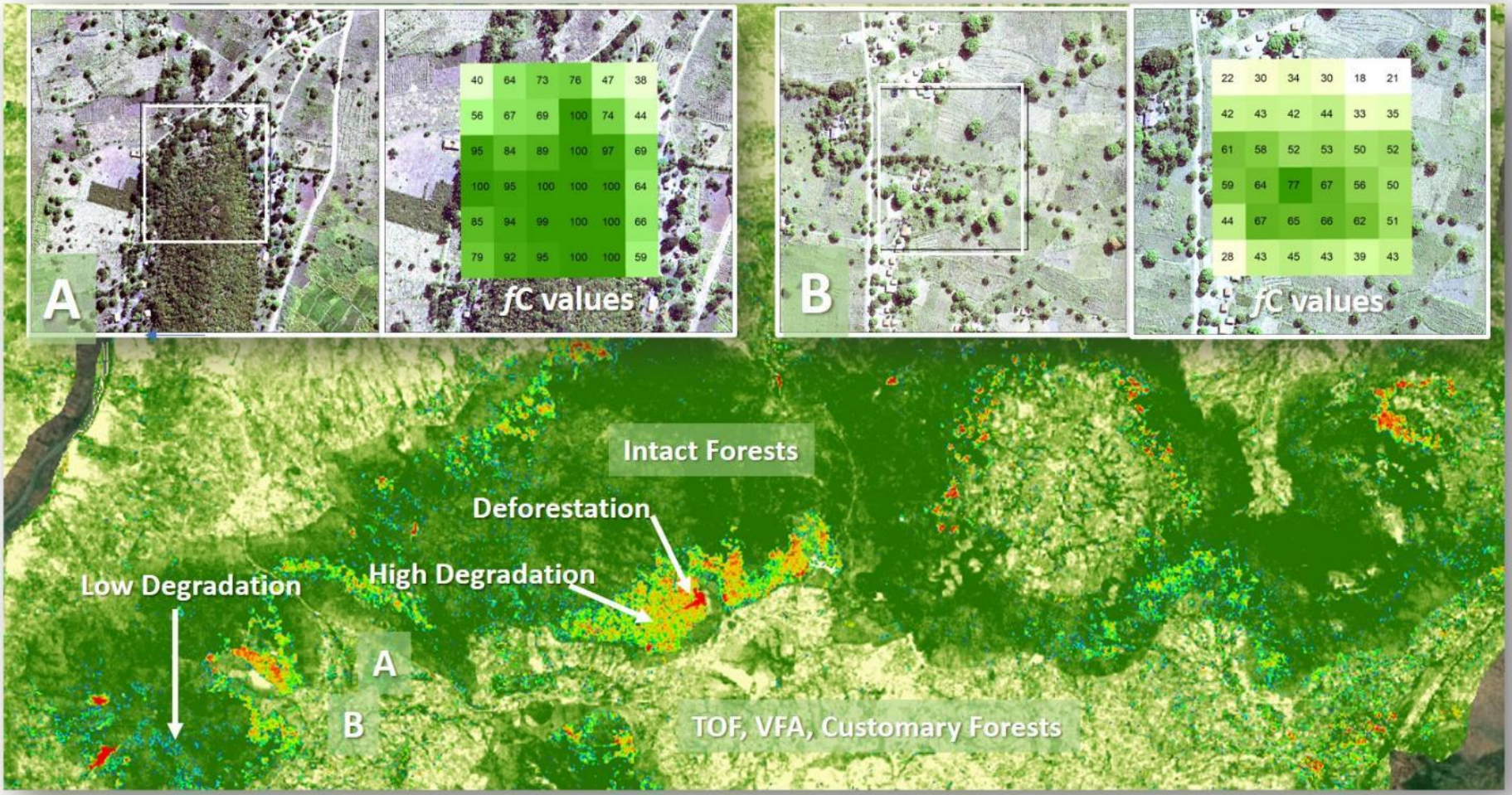
forests

Article

Direct Measurement of Forest Degradation Rates in Malawi: Toward a National Forest Monitoring System to Support REDD+

David L. Skole [1,*], Jay H. Samek [1], Cheikh Mbow [1,2], Michael Chirwa [1,3], Dan Ndalowa [1,4], Tangu Tumeo [5], Daud Kachamba [6], Judith Kamoto [6], Alfred Chioza [6] and Francis Kamangadazi [4]

Degraded Forest Landscapes



Significant degradation occurring outside of forest landscapes

But slowing considerably in recent years.

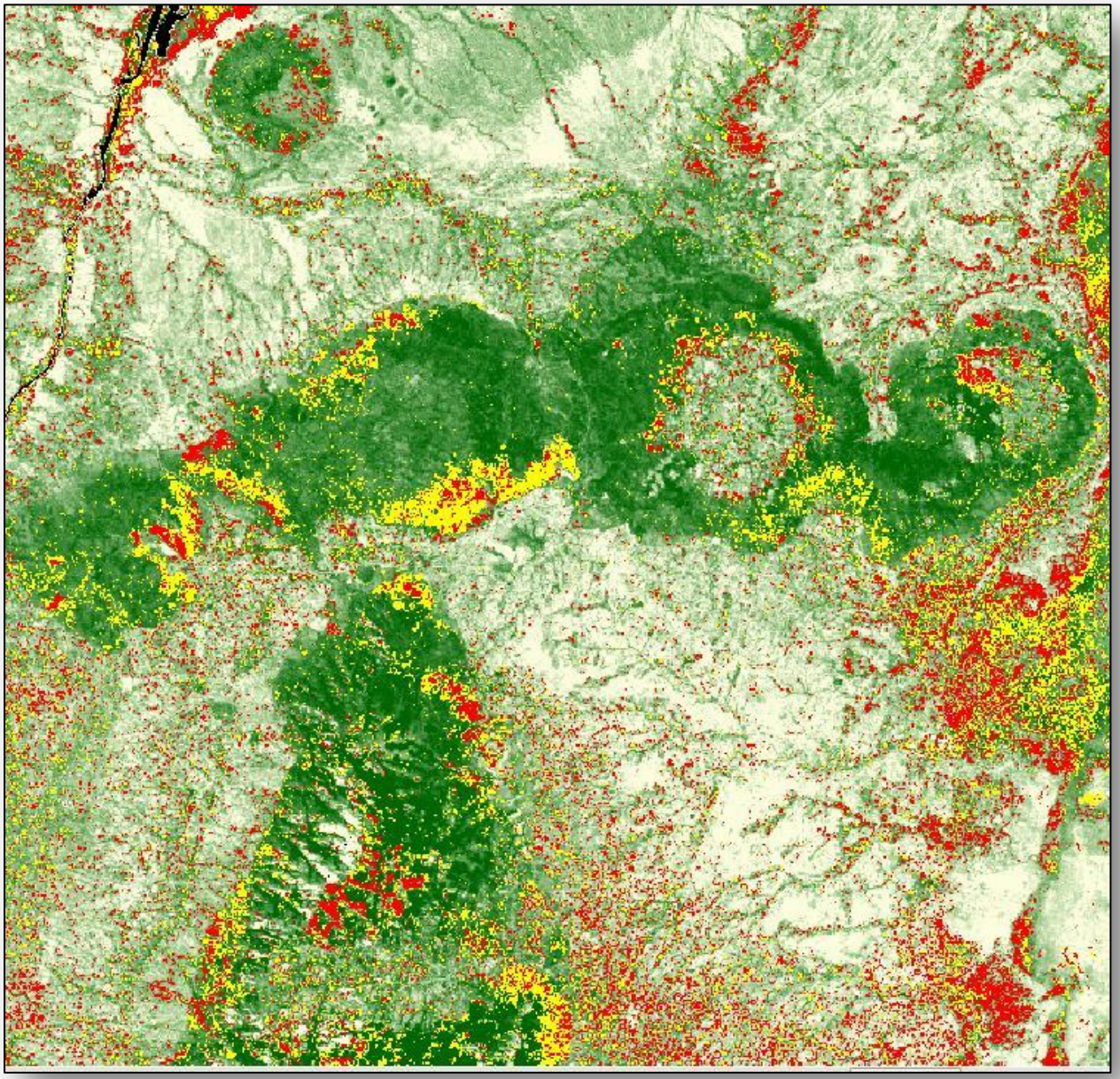
2000–2009:	Area (ha)		Rate (ha yr-1)	
	Deforested	**Degraded**	**Deforested**	**Degraded**
Intact forests, forest reserves and protected areas	39,661	248,576	4407	27,620
Customary forests + trees on agricultural land	162,028	138,072	18,003	15,341
TOTAL	**201,689**	**386,648**	**22,410**	**42,961**
2010–2015:				
	Deforested	**Degraded**	**Deforested**	**Degraded**
Intact forests, forest reserves and protected areas	136,040	309,694	22,673	5,161
Customary forests + trees on agricultural land	97,584	121,572	16,264	20,262
TOTAL	**233,624**	**431,266**	**38,937**	**25,423**
2016–2022:				
	Deforested	**Degraded**	**Deforested**	**Degraded**
Intact forests, forest reserves and protected areas	57,175	157,851	9,529	26,309
Customary forests + trees on agricultural land	78,662	102,874	13,110	17,146
TOTAL	**135,837**	**260,725**	**22,640**	**43,454**

How much *Forest* land available for restoration?

How much *non Forest* land available for tree restoration?

Skole, D.L., Samek, J.H., Mbow, C., Chirwa, M., Ndalowa, D., Tumeo, T., Kachamba, D., Kamoto, J., Chioza, A. and Kamangadazi, F., **2021**. Direct measurement of forest degradation rates in Malawi: toward a national forest monitoring system to support REDD+. *Forests*, 12(4), p.426.

2015-2022 LCLUC Change Deforestation (red) and Degradation (yellow)



NATURE CLIMATE CHANGE | VOL 11 | DECEMBER 2021 | 1006–1016 | www.nature.com/natureclimatechange

Trees outside of forests as natural climate solutions

Trees outside of forests are numerous and can be important carbon sinks, while also providing ecosystem services and benefits to livelihoods. New monitoring tools highlight the crucial contribution they can make to strategies for both mitigation and adaptation.

David L. Skole, Cheikh Mbow, Maurice Mugabowindekwe, Martin S. Brandt and Jay H. Samek

High-biomass natural forests are an important focal point for climate change mitigation action and thus are targets of large public and private investments, particularly in developing countries in the tropics. The most prominent international forest initiative for climate change mitigation is the framework for reducing emissions from deforestation and forest degradation in developing countries, or REDD+, which emphasizes closed canopy tropical forests. However, with emerging new capabilities for measuring and mapping trees outside forests (TOF), especially using new Earth-observation methods, there will be a missed opportunity if the mitigation dialogue does not include a range of non-forest tree-based systems, which could provide broad additional benefits, including landscape restoration, conservation of biodiversity and enhancing the livelihoods of more than a billion people, many of whom live in extreme poverty[1].

economic value as compared to annual crops (Fig. 1).

Worldwide, there are many non-forest landscapes with considerable tree cover and increasing biomass, which are important sinks for carbon[2,3]. An interesting recent analysis[4] mapped more than 1.8 billion isolated trees outside of forests across 1.3 million ha in West Africa, which is a relatively high and unexpected density of trees in areas previously thought to be desert or highly degraded savannah. These trees are both widely spaced natural trees and tree-based production systems actively managed by local farmers. We estimate that the carbon stocks here could be up to 22 MgC ha^{-1}, which is higher than what was estimated in global biomass mapping[5] and is thus essentially hidden from the international dialogue on natural climate solutions.

Some studies have suggested that extensive areas of TOF, and the trend that this area is increasing, are attributed to actions promoted and mediated by farmers as a deliberate way to capture market

Fig. 1 | Trees outside of forests in central Malawi. Naturally occurring trees and farmer-managed tree-based systems provide a range of ecosystem services and livelihood benefits, are often intentionally promoted across agricultural landscapes and provide opportunities for carbon sequestration. Credit: D. L. Skole.

from 1.8 Mg ha^{-1} yr^{-1} to 10 Mg ha^{-1} yr^{-1} as compared with 0.6 Mg ha^{-1} yr^{-1} for conservation agriculture[9]. Agroforestry is

nature climate change

Article

https://doi.org/10.1038/s41558-022-01544-w

Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda

Received: 8 April 2022

Accepted: 31 October 2022

Published online: 22 December 2022

Check for updates

Maurice Mugabowindekwe[1,2], Martin Brandt[1], Jérôme Chave[3], Florian Reiner[1], David L. Skole[4], Ankit Kariryaa[1,5], Christian Igel[5], Pierre Hiernaux[6], Philippe Ciais[7], Ole Mertz[1], Xiaoye Tong[1], Sizhuo Li[1,8], Gaspard Rwanyiziri[2,9], Thaulin Dushimiyimana[1], Alain Ndoli[10], Valens Uwizeyimana[11,12], Jens-Peter Ba... Fabian Gieseke[5,13], Compton J. Tucker[14], Sassan Saatchi[15] & R...

Trees sustain livelihoods and mitigate c... trees outside forests and limited resour... countries to conduct automated nation... an approach to map the carbon stock of... national scale of Rwanda using aerial im... We show that 72% of the mapped trees a... and 17% in plantations, accounting for 4... carbon stocks. Natural forests cover 11%... of the national carbon stocks, with an o...

nature communications

Article

https://doi.org/10.1038/s41467-023-37880-4

More than one quarter of Africa's tree cover is found outside areas previously classified as forest

Received: 6 September 2022

Accepted: 29 March 2023

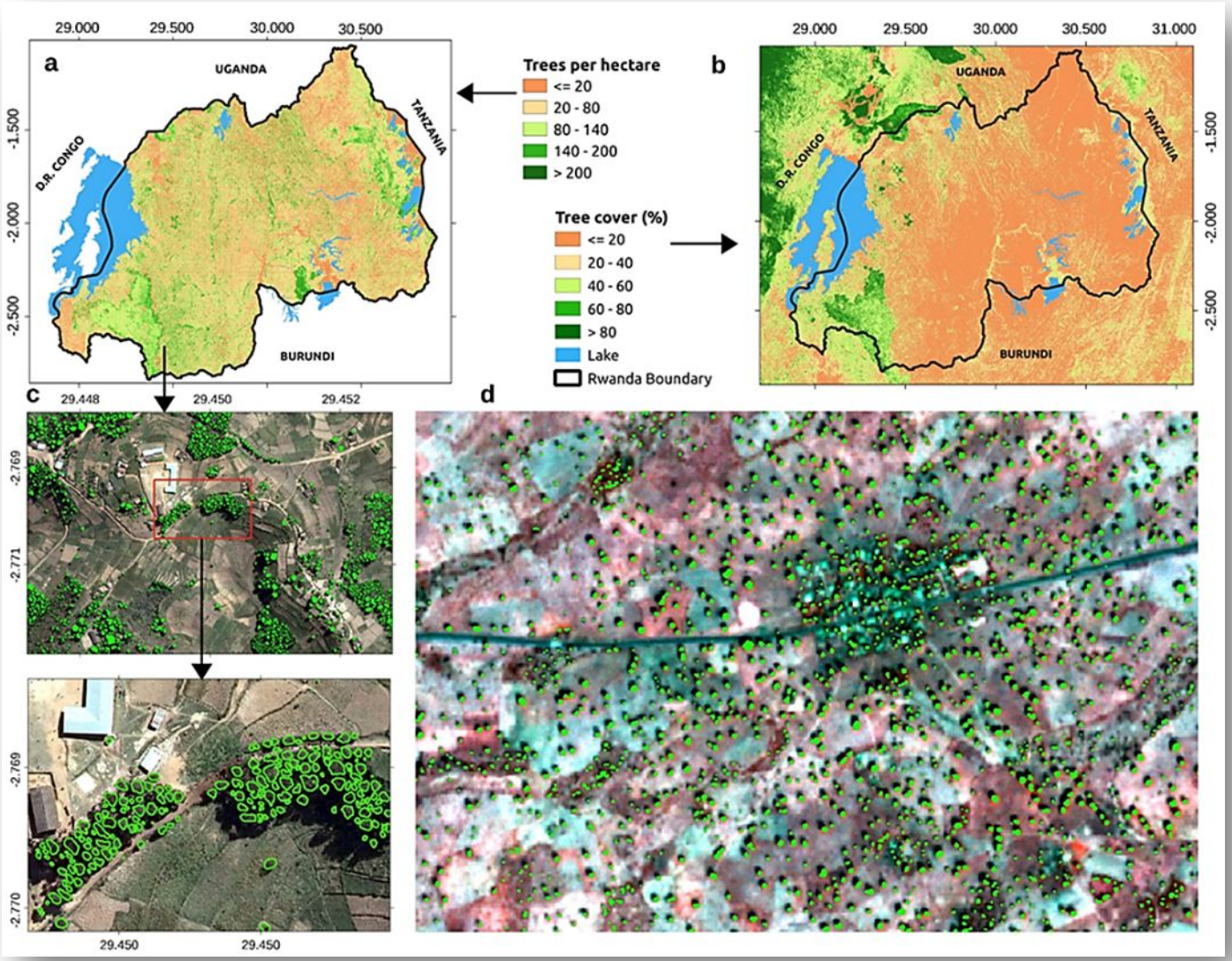
Published online: 02 May 2023

Check for updates

Florian Reiner[1], Martin Brandt[1], Xiaoye Tong[1], David Skole[2], Ankit Kariryaa[1,3], Philippe Ciais[4], Andrew Davies[5], Pierre Hiernaux[6], Jérôme Chave[7], Maurice Mugabowindekwe[1], Christian Igel[3], Stefan Oehmcke[1,3], Fabian Gieseke[3,8], Sizhuo Li[1,9], Siyu Liu[1], Sassan Saatchi[10], Peter Boucher[5], Jenia Singh[5], Simon Taugourdeau[11], Morgane Dendoncker[12], Xiao-Peng Song[13], Ole Mertz[1], Compton J. Tucker[14] & Rasmus Fensholt[1]

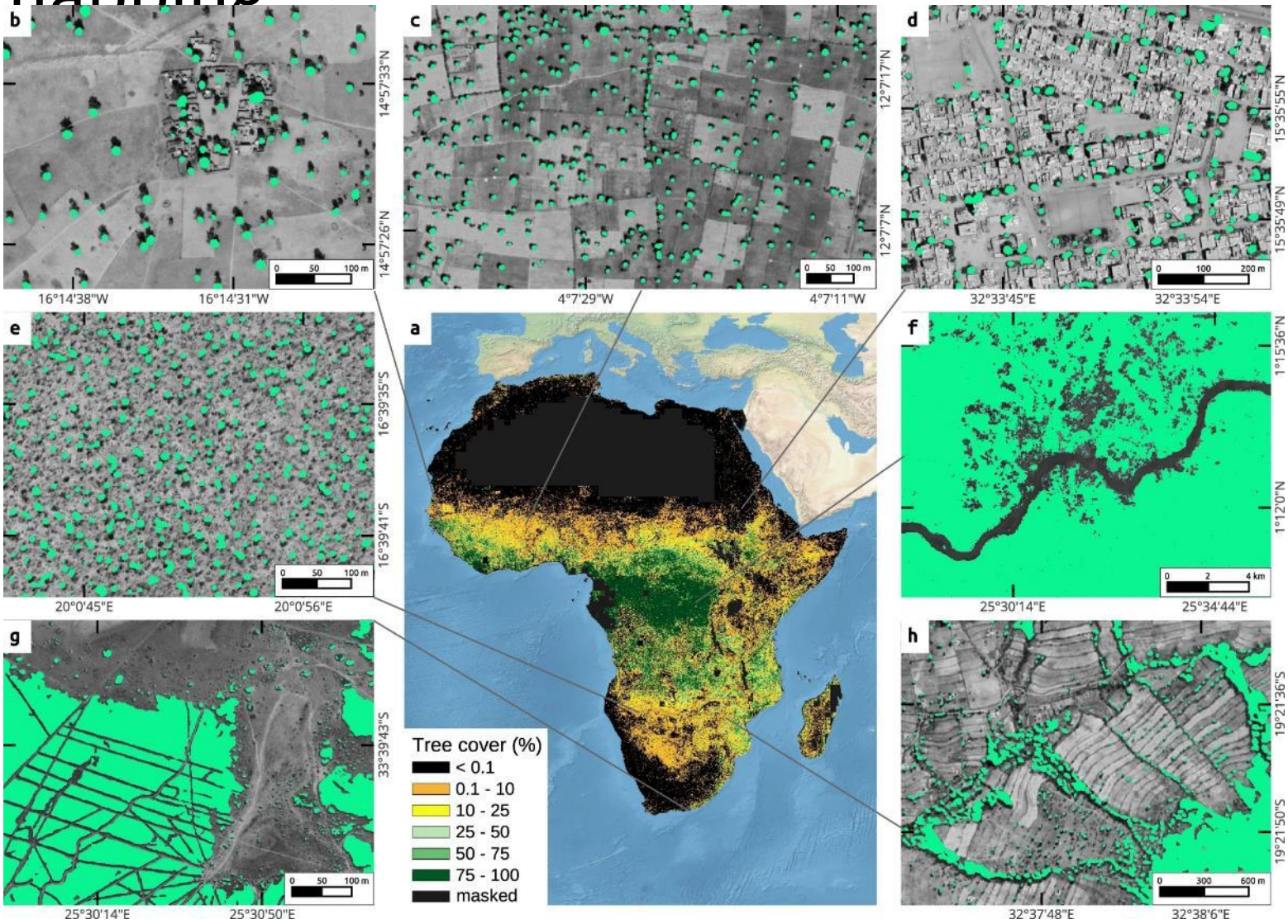
The consistent monitoring of trees both inside and outside of forests is key to sustainable land management. Current monitoring systems either ignore trees outside forests or are too expensive to be applied consistently across countries on a repeated basis. Here we use the PlanetScope nanosatellite constellation, which delivers global very high-resolution daily imagery, to map both forest and non-forest tree cover for continental Africa using images from a single year. Our prototype map of 2019 (RMSE = 9.57%, bias = −6.9%). demonstrates that a precise assessment of all tree-based ecosystems is possible at continental scale, and reveals that 29% of tree cover is found outside areas previously classified as tree cover in state-of-the-art maps, such as in croplands and grassland. Such accurate mapping of tree cover down to the

National-scale Individual Tree Carbon Mapping



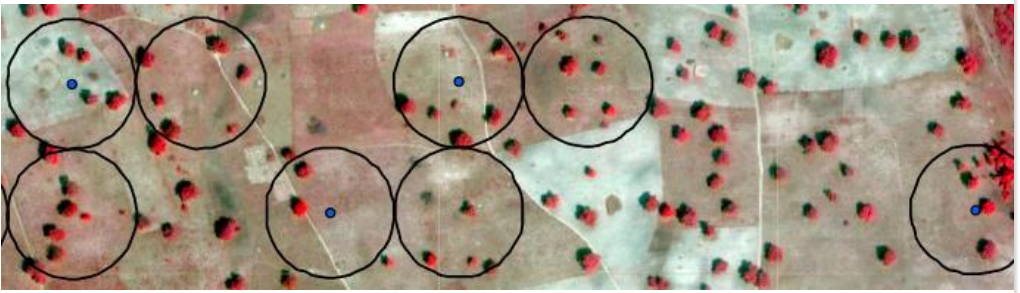
Source: Skole, D.L., Mbow, C., Mugabowindekwe, M., Brandt, M.S., Samek, J.H. **2021**.The importance of trees outside of forests as natural climate solutions. *Nature Climate Change*, 11(12): 1013–1016.

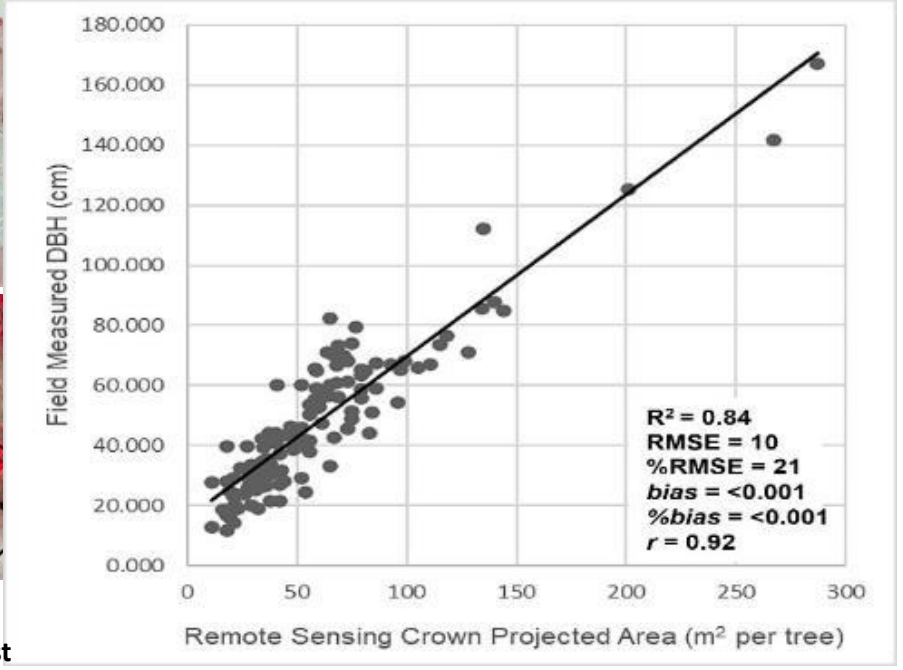
Continental-scale individual tree mapping



Reiner, F., Brandt, M., Tong, X., Skole, D., Kariryaa, A., Ciais, P., Davies, A., Hiernaux, P., Chave, J., Mugabowindekwe, M. and Igel, C., **2023**. More than one quarter of Africa's tree cover is found outside areas previously classified as forest. *Nature Communications*, 14(1), p.2258.

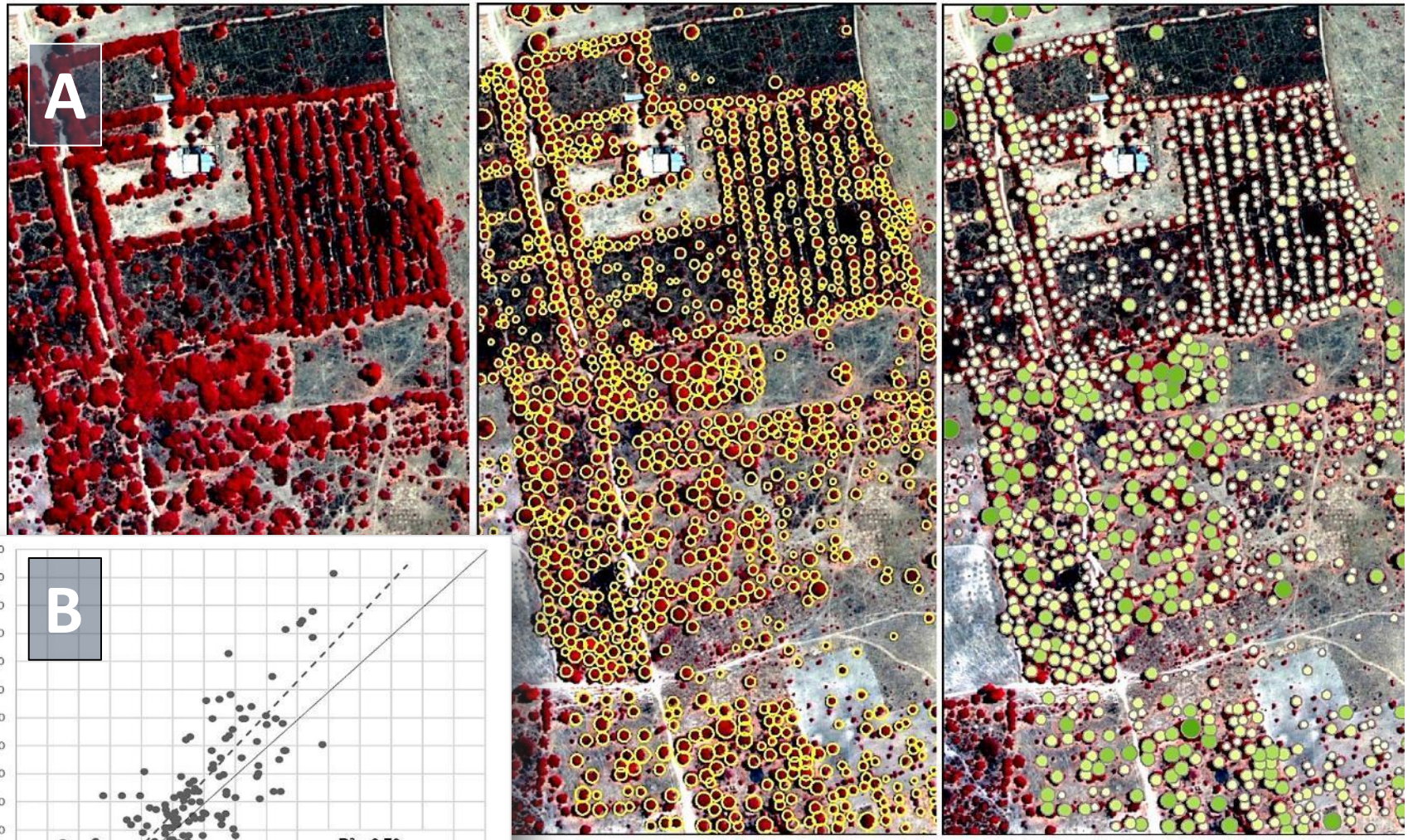
Proof of Concept in Senegalese Savannas





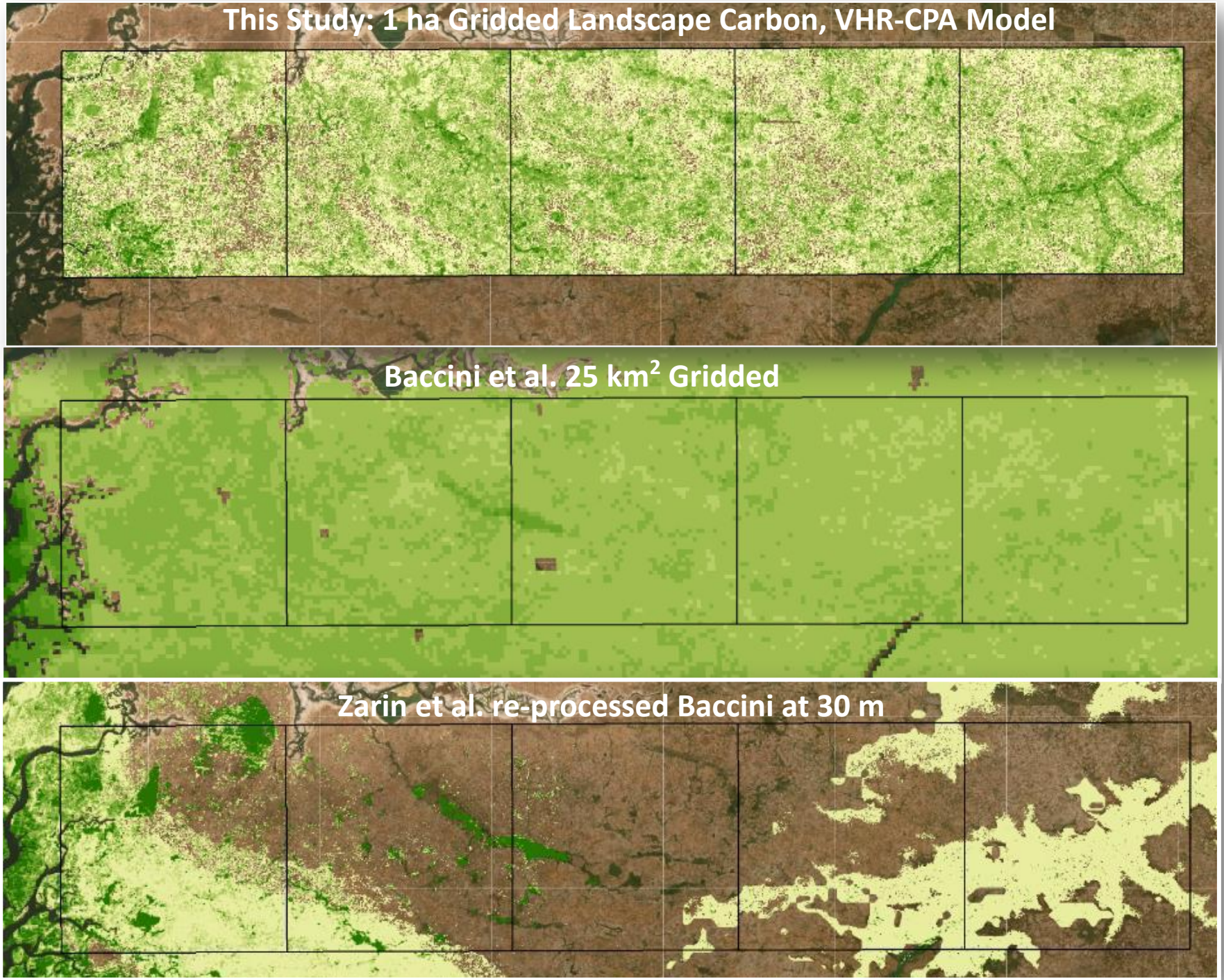
Source: Skole, D.L., Samek, J.H., Dieng, M., Mbow, C. 2021. The Contribution of trees outside of forests to landscape carbon and climate change mitigation in West Africa, *Forests*, *12*(12): 1652

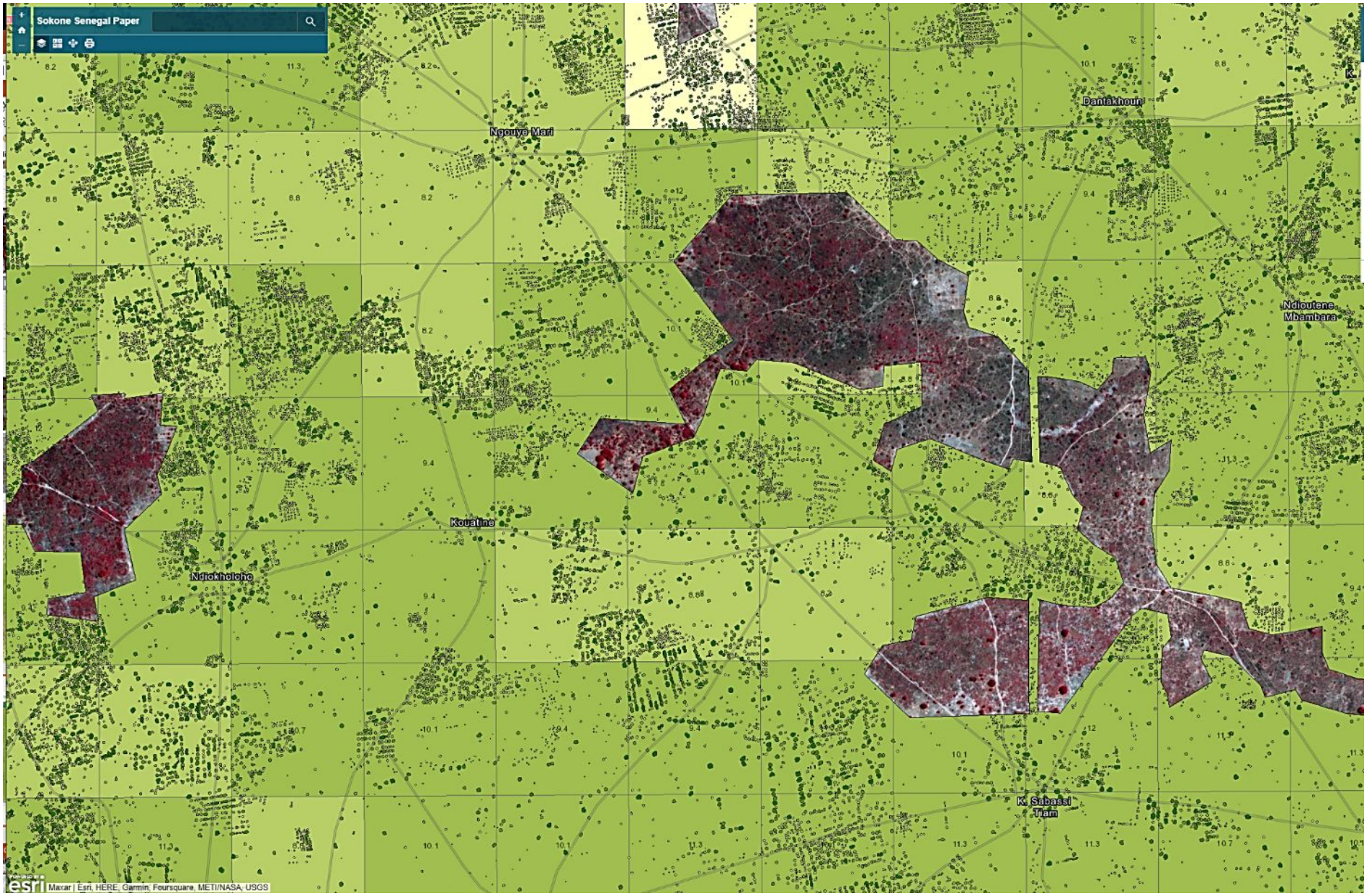
Allometric Scaling Model Training and Testing



A. Field analysis, B. model validation, estimated DBH from VHR-CPA

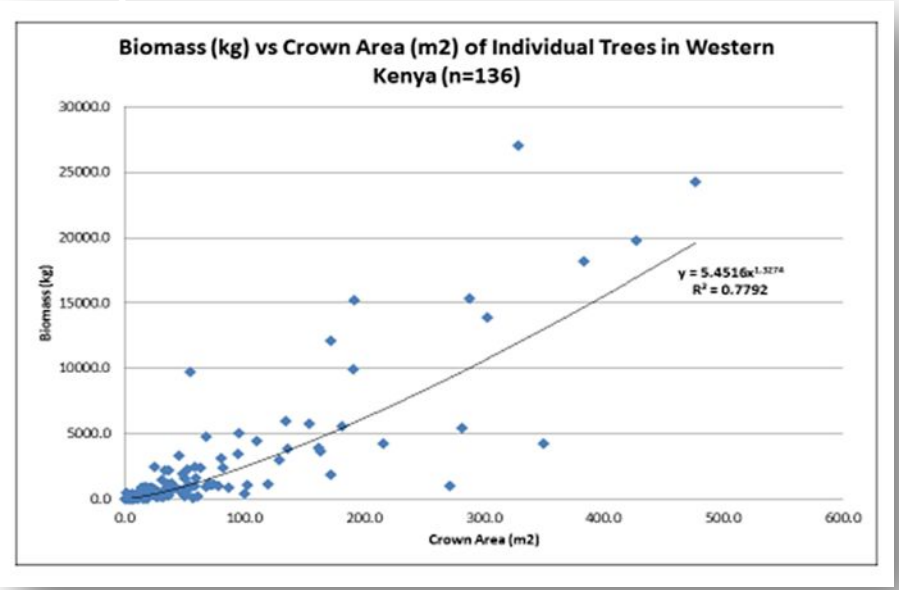
Source: Skole, D.L., Samek, J.H., Dieng, M., Mbow, C. 2021. The Contribution of trees outside of forests to landscape carbon and climate change mitigation in West Africa, *Forests*, *12*(12): 1652

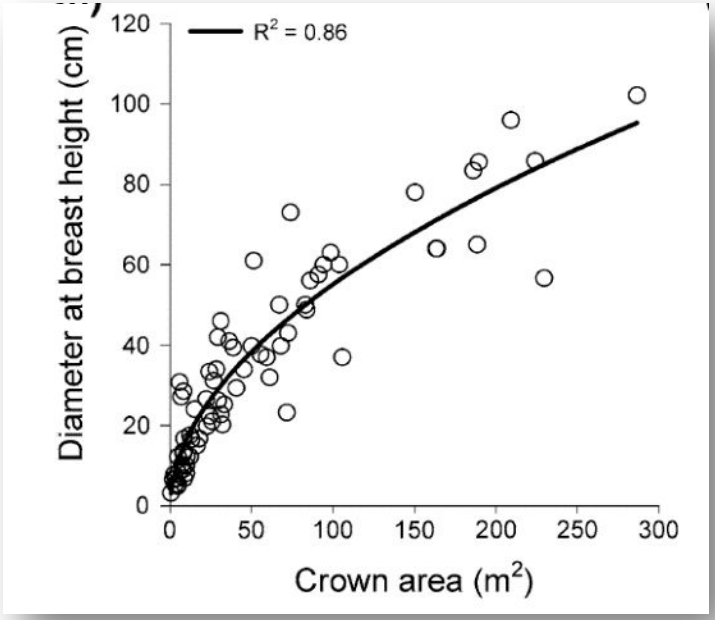

This Study: 1 ha Gridded Landscape Carbon, VHR-CPA Model
Baccini et al. 25 km^2 Gridded
Zarin et al. re-processed Baccini at 30 m


Sokone Senegal Paper
Ngouye Mari
Dantakhoun
Ndioutene Mbambara
Kouatine
Ndiokholoho
K. Sabassi Tram
Maxar | Esri, HERE, Garmin, Foursquare, METI/NASA, USGS

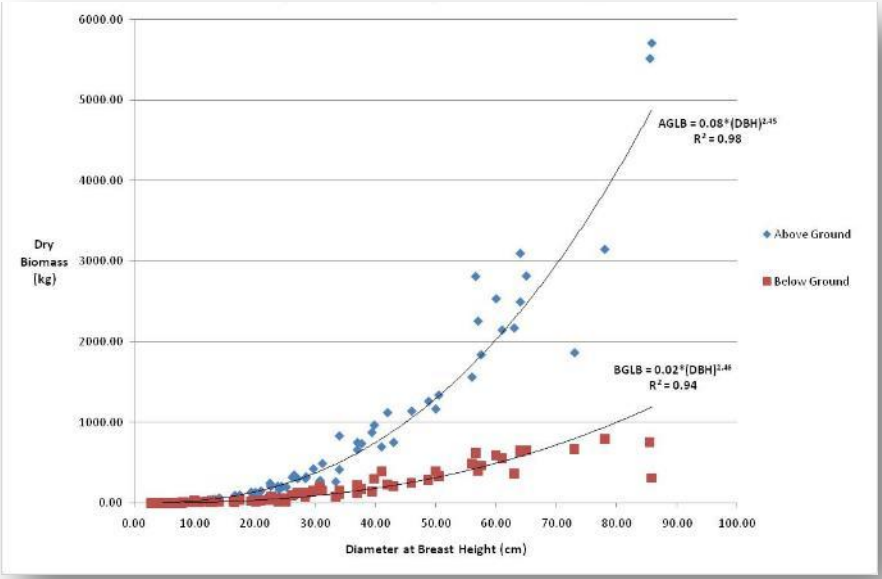
Two Options: Direct and Indirect estimators

Direct crown model

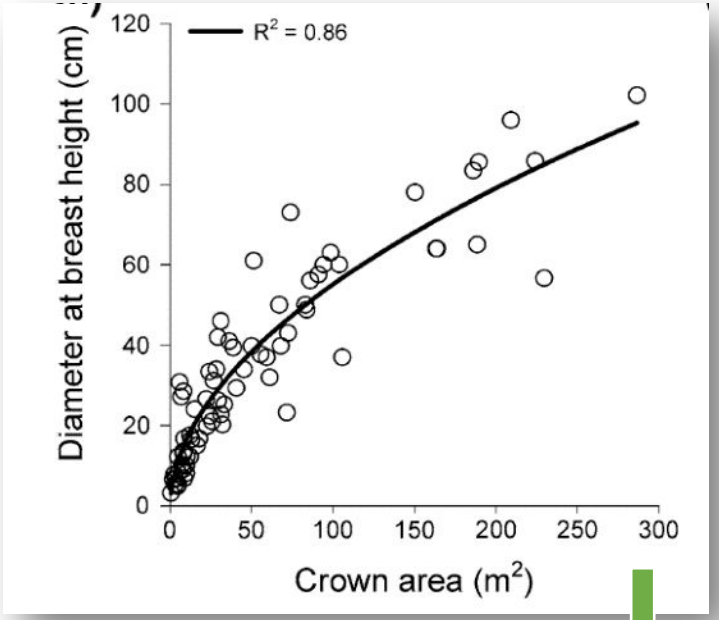




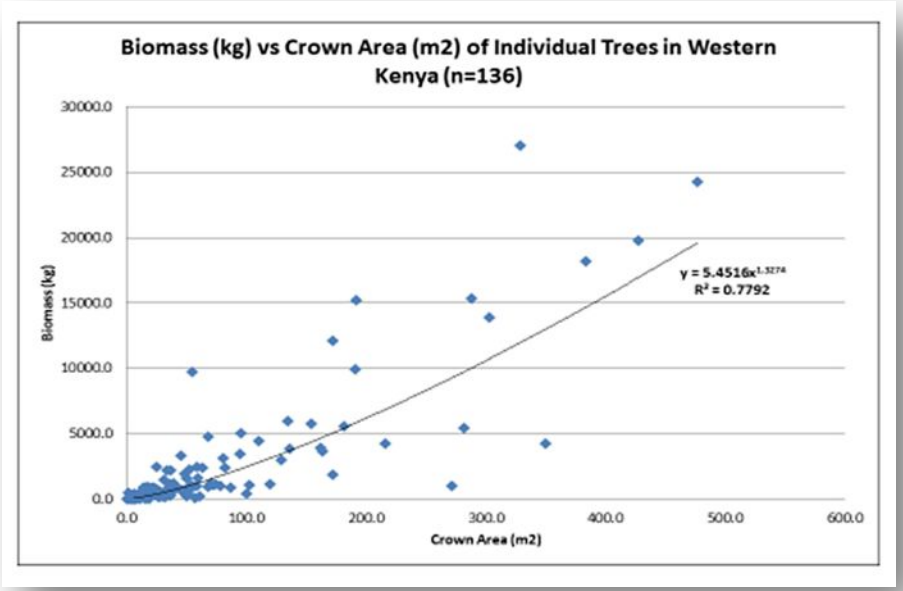
Biomass allometry

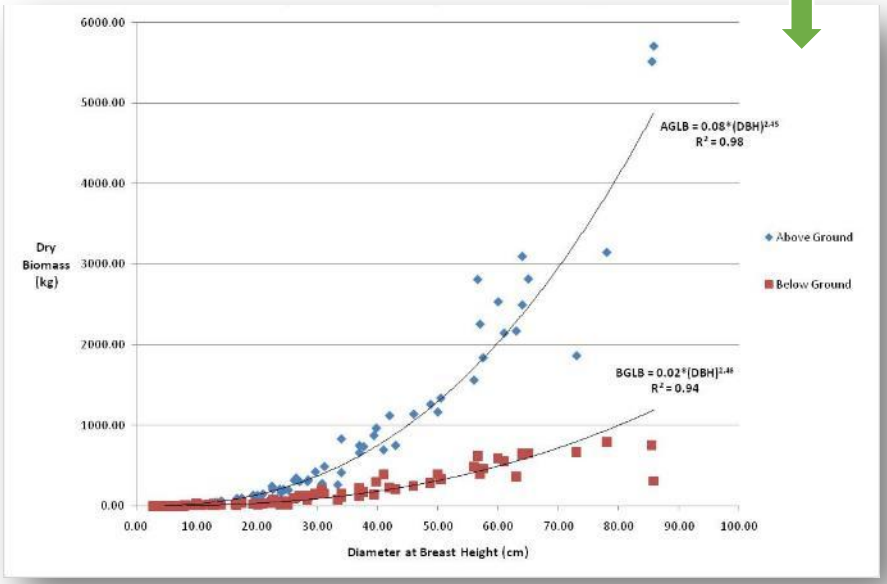


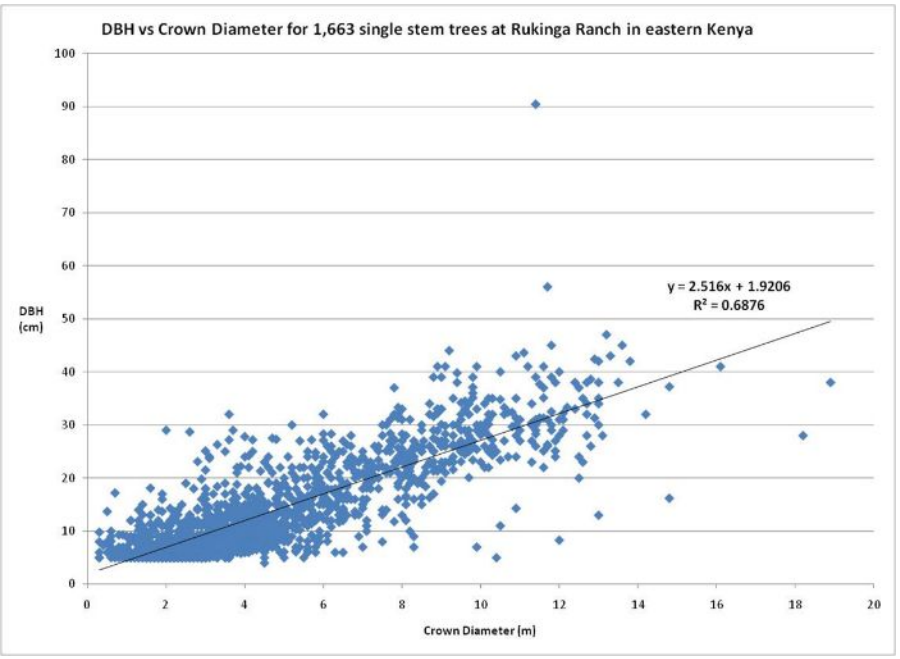
Indirect crown model, estimated DBH

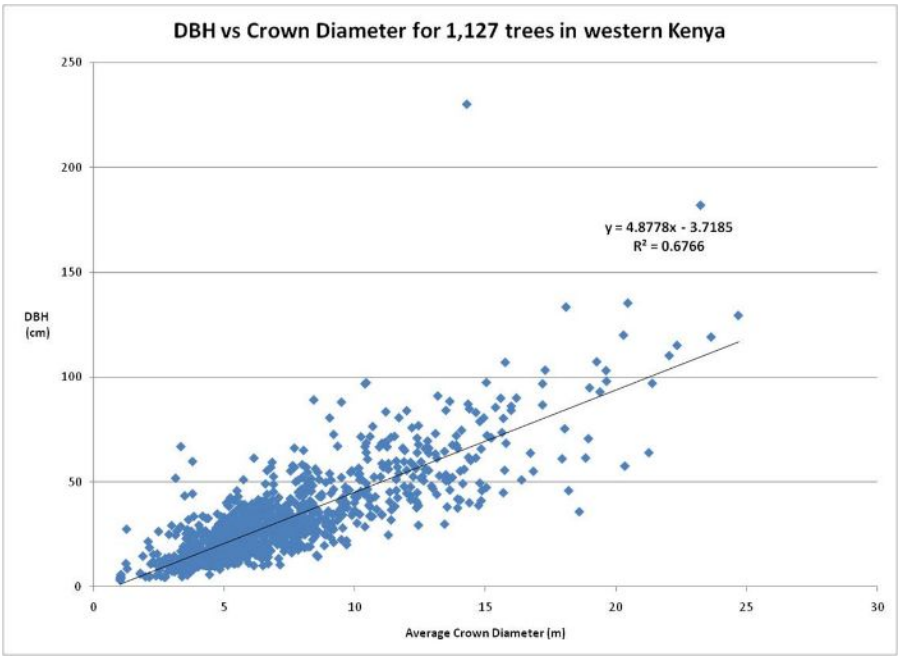


Biomass allometry

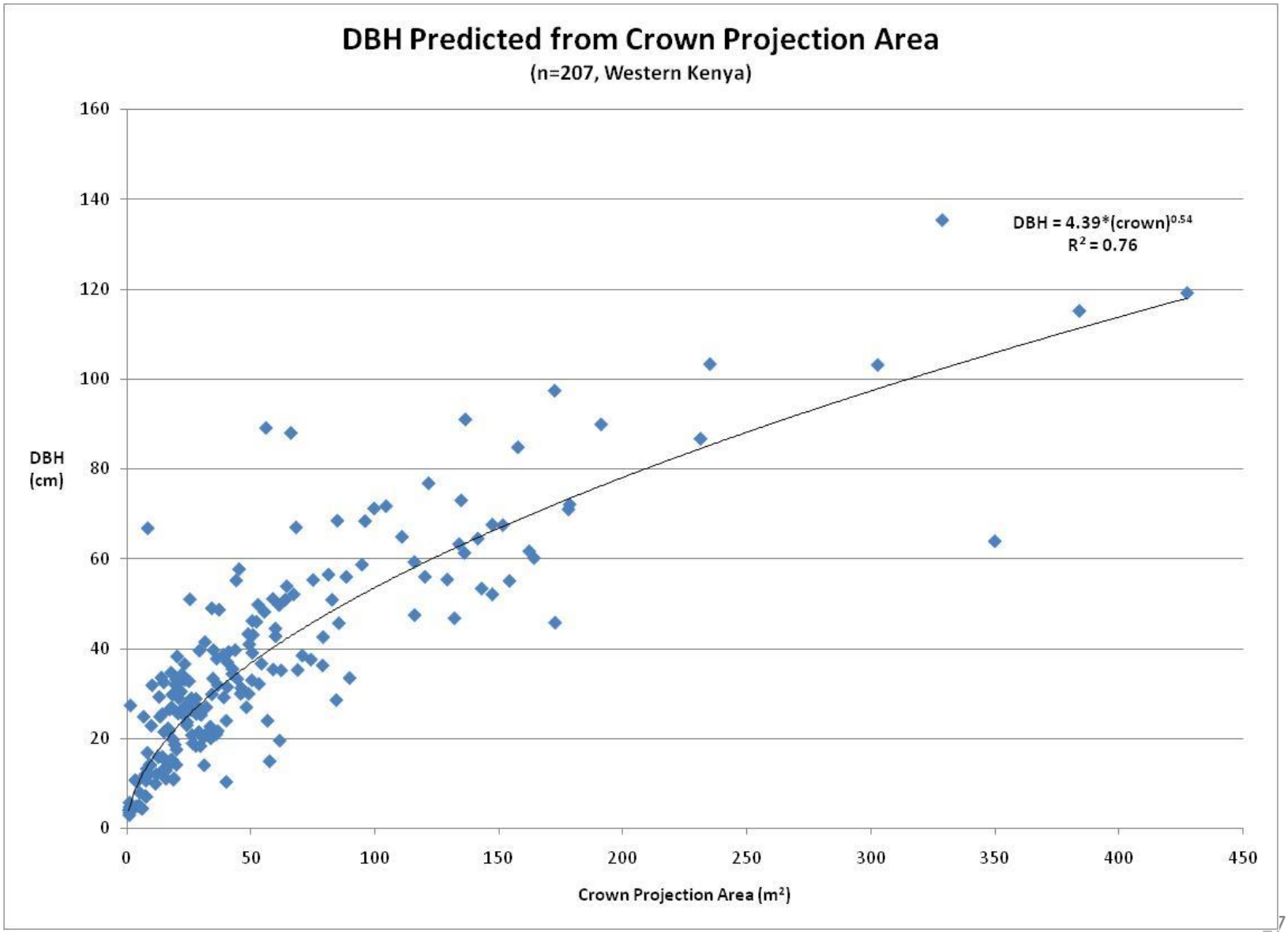




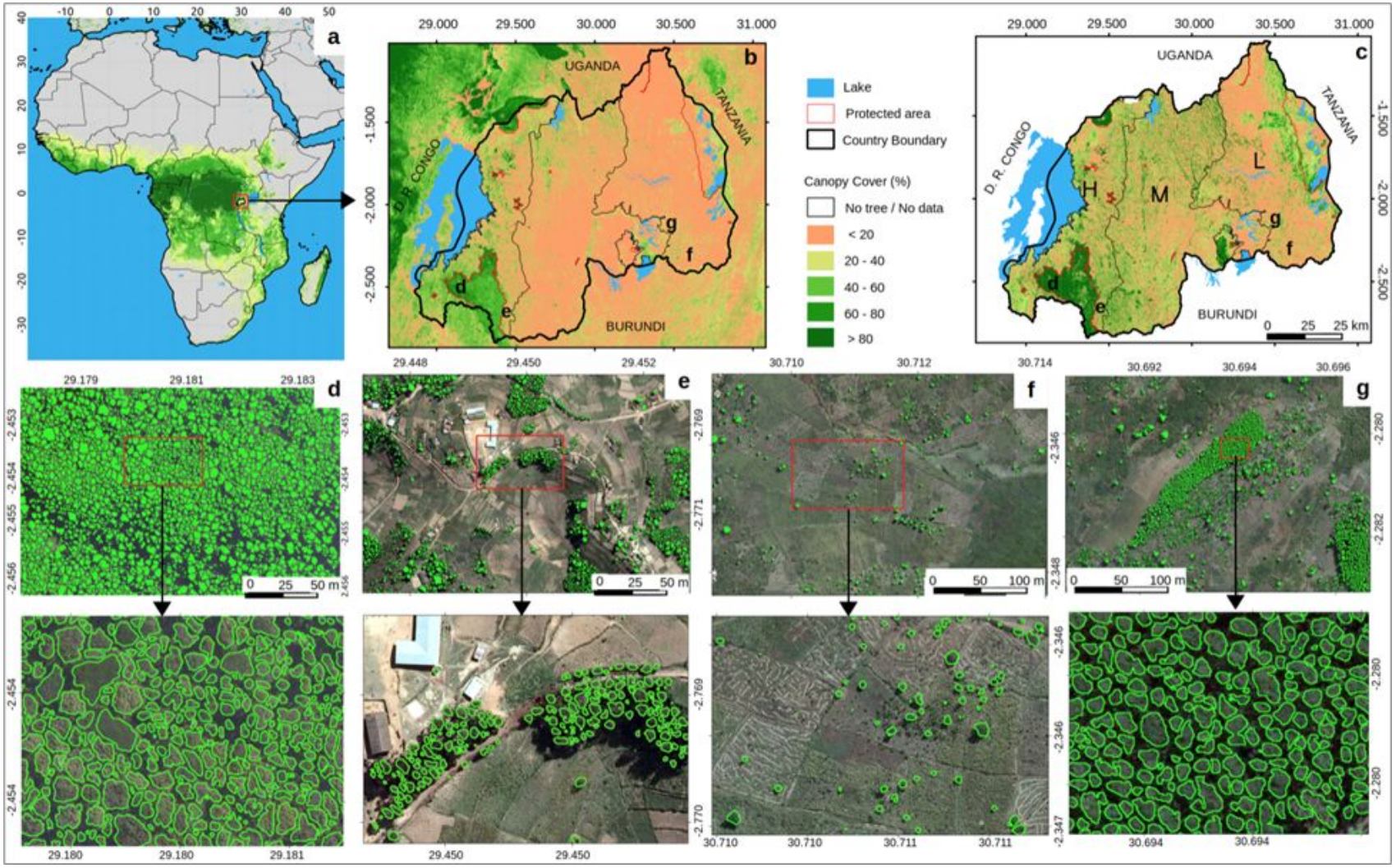

DBH vs Crown Diameter for 1,663 single stem trees at Rukinga Ranch in eastern Kenya
y = 2.516x + 1.9206
R² = 0.6876
DBH (cm)
Crown Diameter (m)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20


DBH vs Crown Diameter for 1,127 trees in western Kenya
y = 4.8778x - 3.7185
R² = 0.6766
DBH (cm)
Average Crown Diameter (m)
0
50
100
150
200
250
0
5
10
15
20
25
30

An example model from Kenya

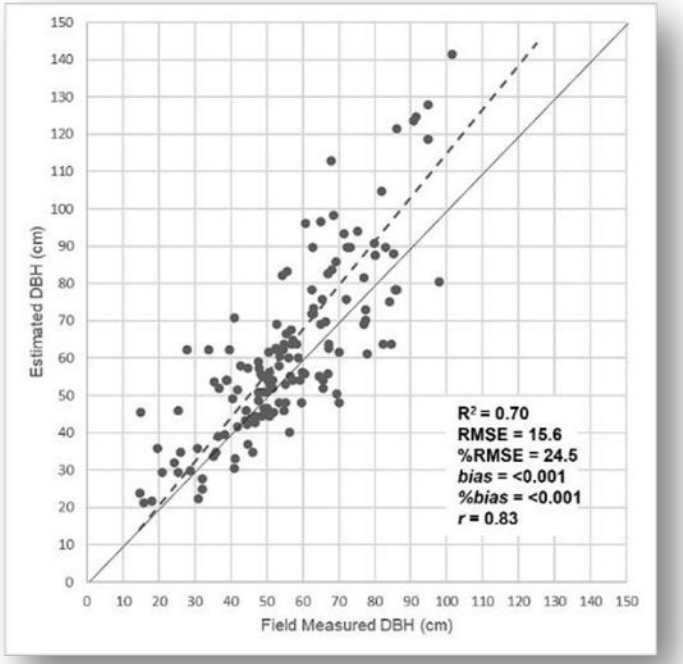


National Scale Application: Rwanda Carbon Stocks

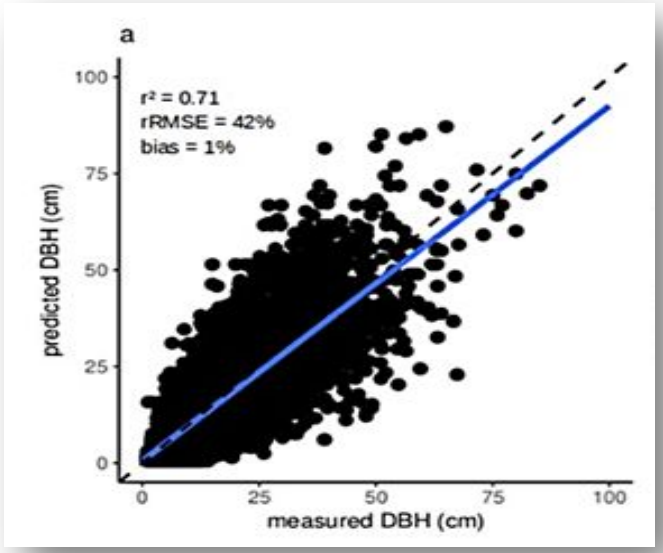


Mugabowindekwe, M., Brandt, M., Chave, J., Reiner, F., Skole, D.L., Kariryaa, A., Igel, C., Hiernaux, P., Ciais, P., Mertz, O. and Tong, X., 2023. Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda. *Nature Climate Change*, *13*(1), pp.91-97.

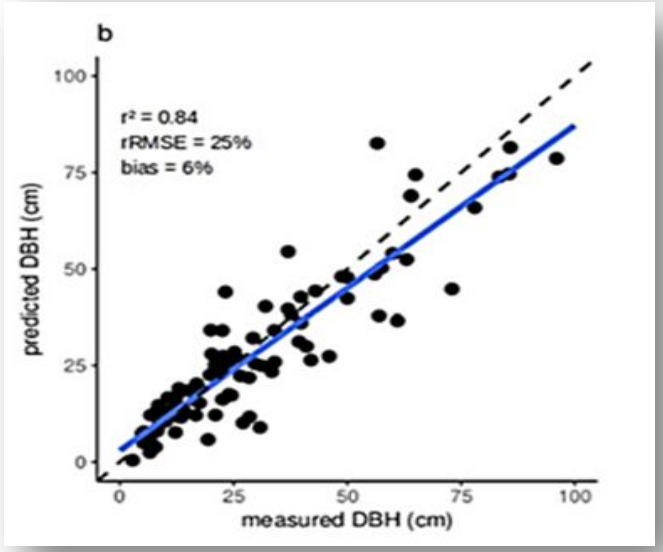
Rwanda Model Performance:
Estimated DBH from Remote Sensing CPA



West Africa

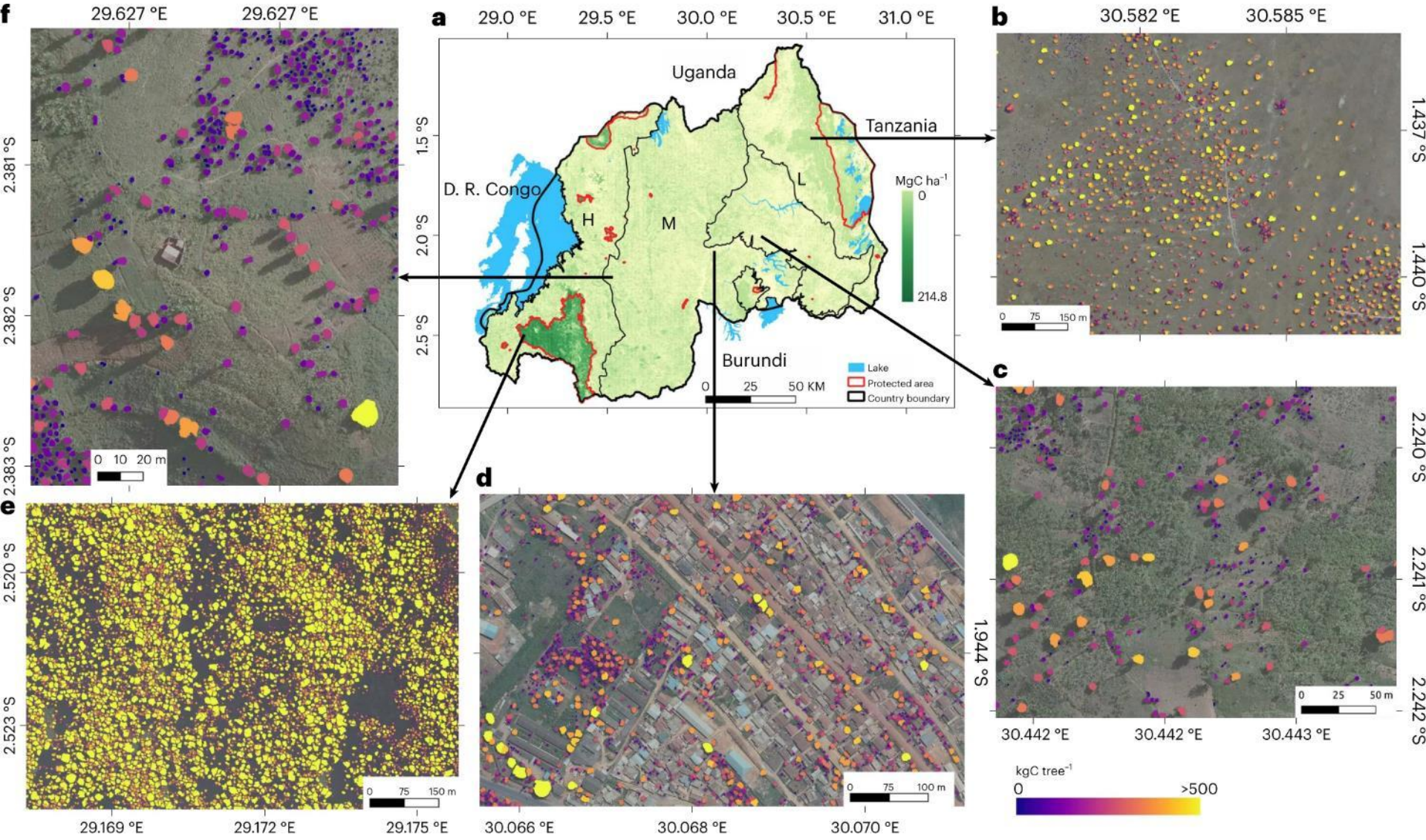


Global,
11,593 trees

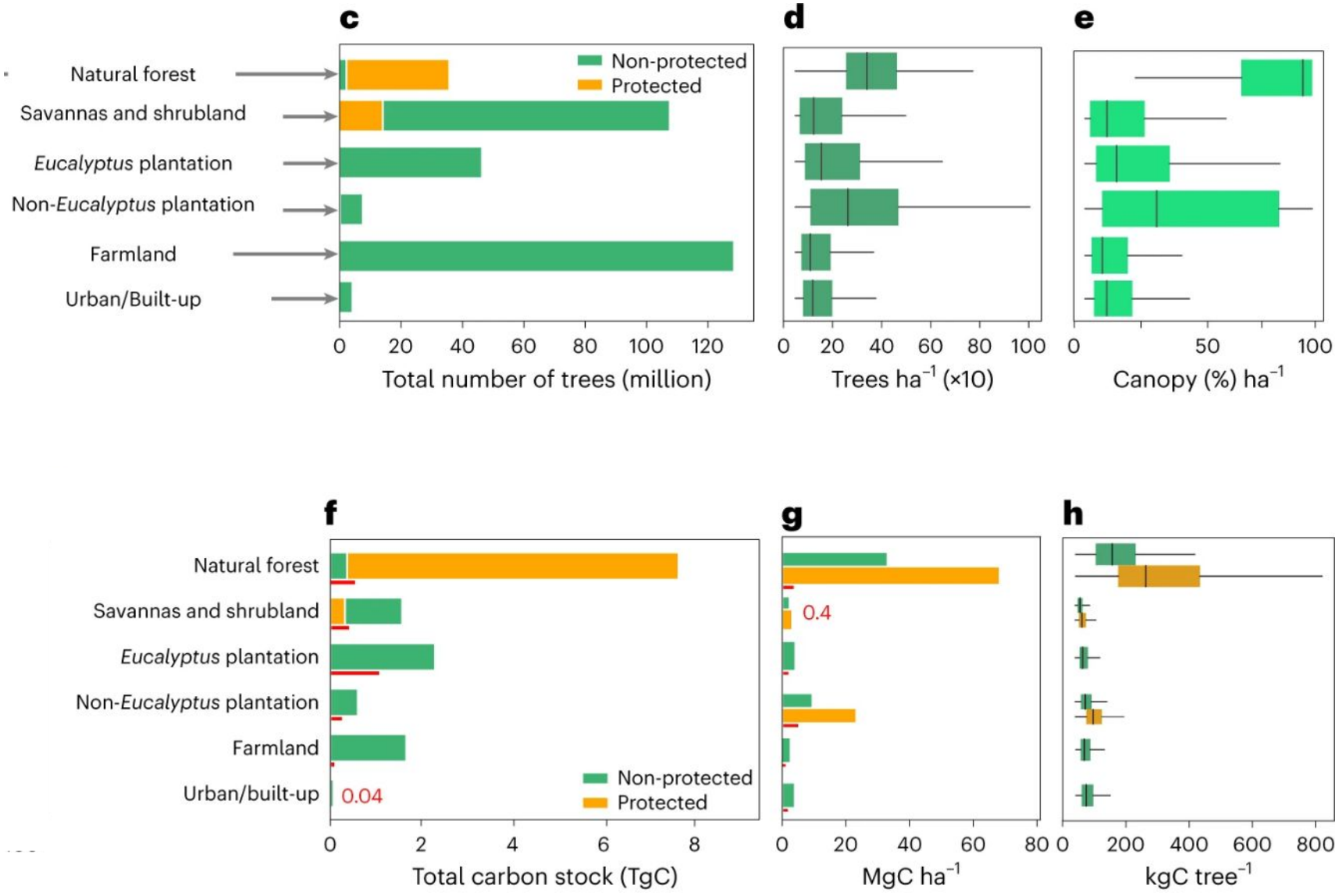


East Africa

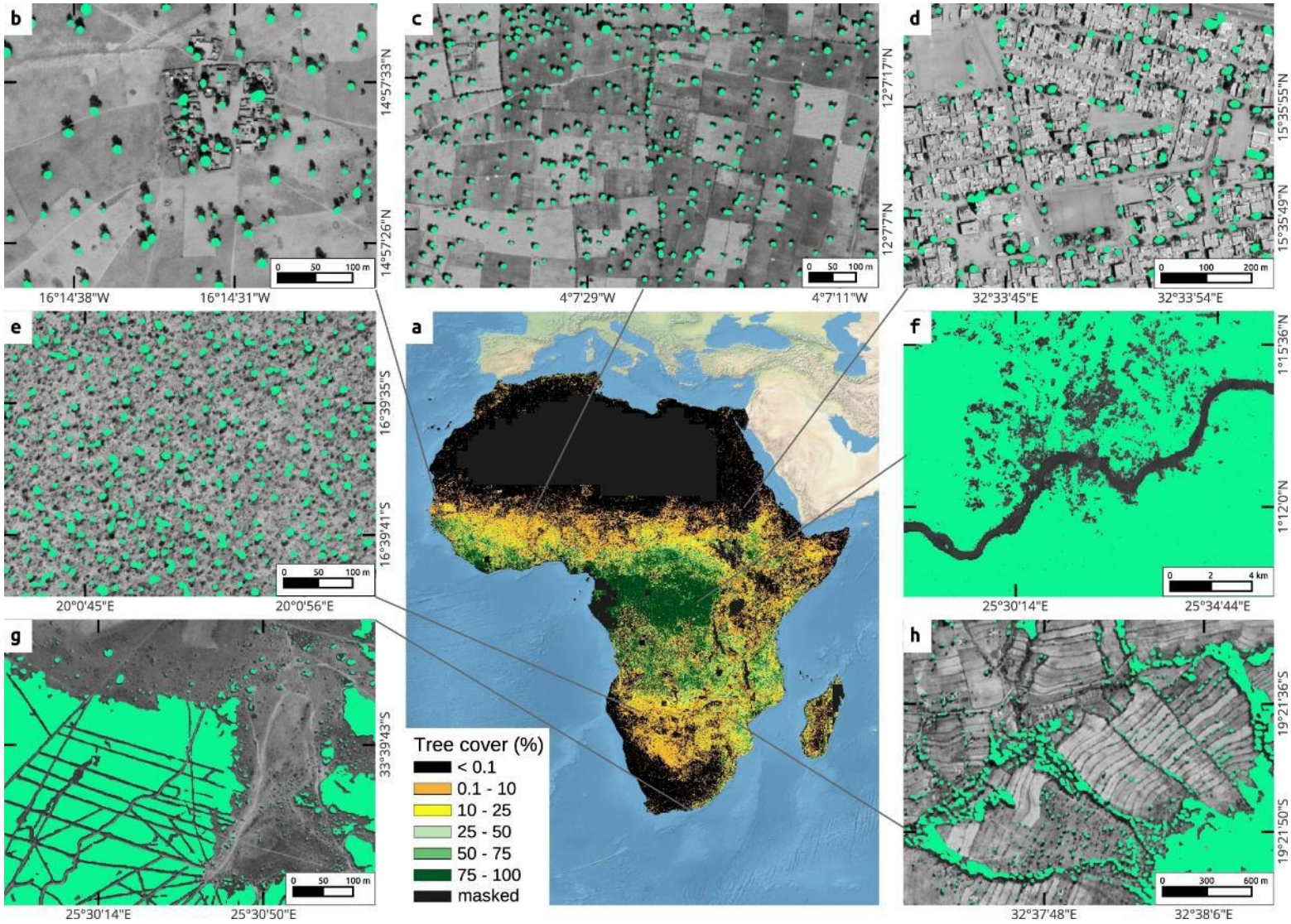
Individual Tree Carbon based on Allometry



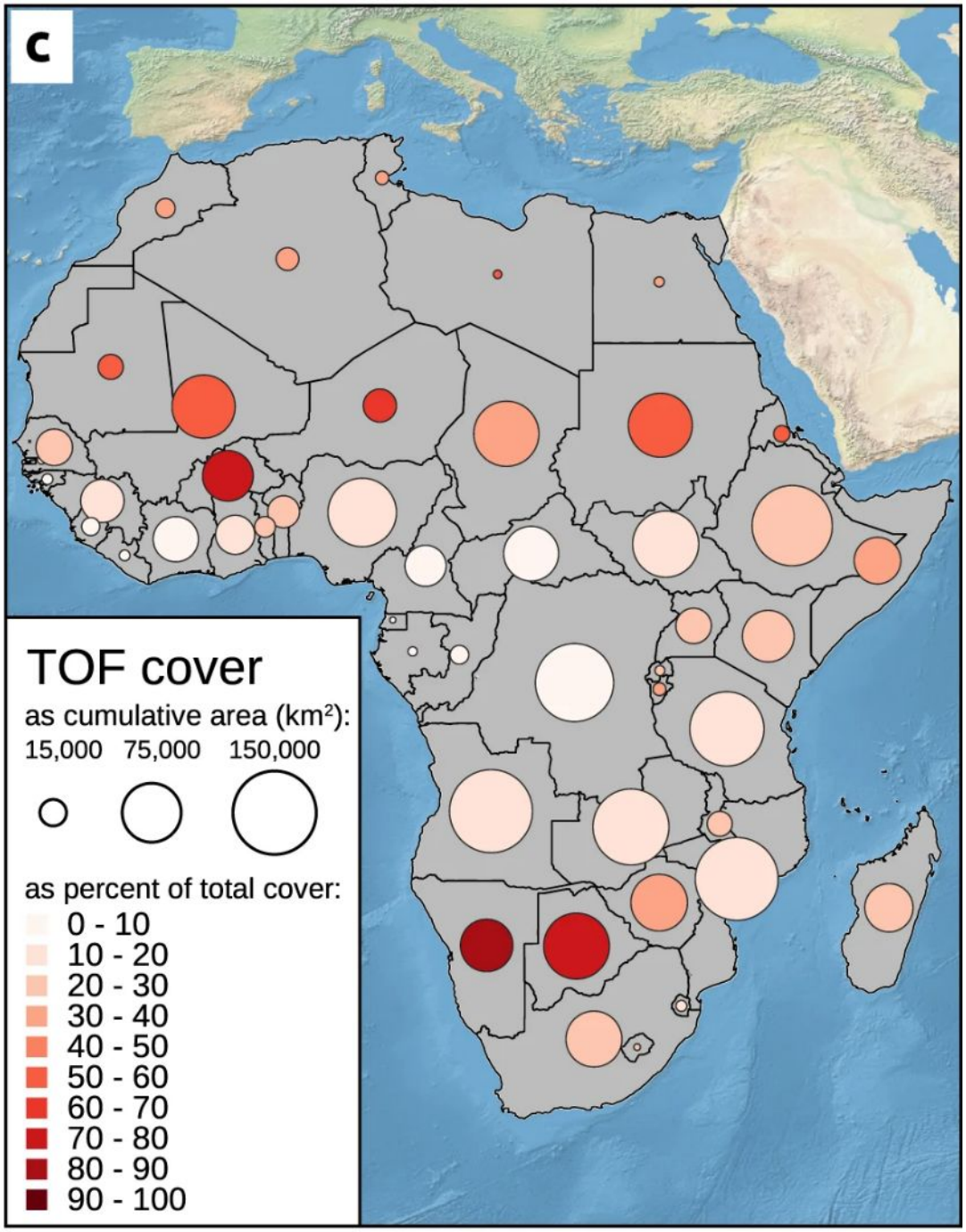
75% of trees and 49% of carbon in TOF



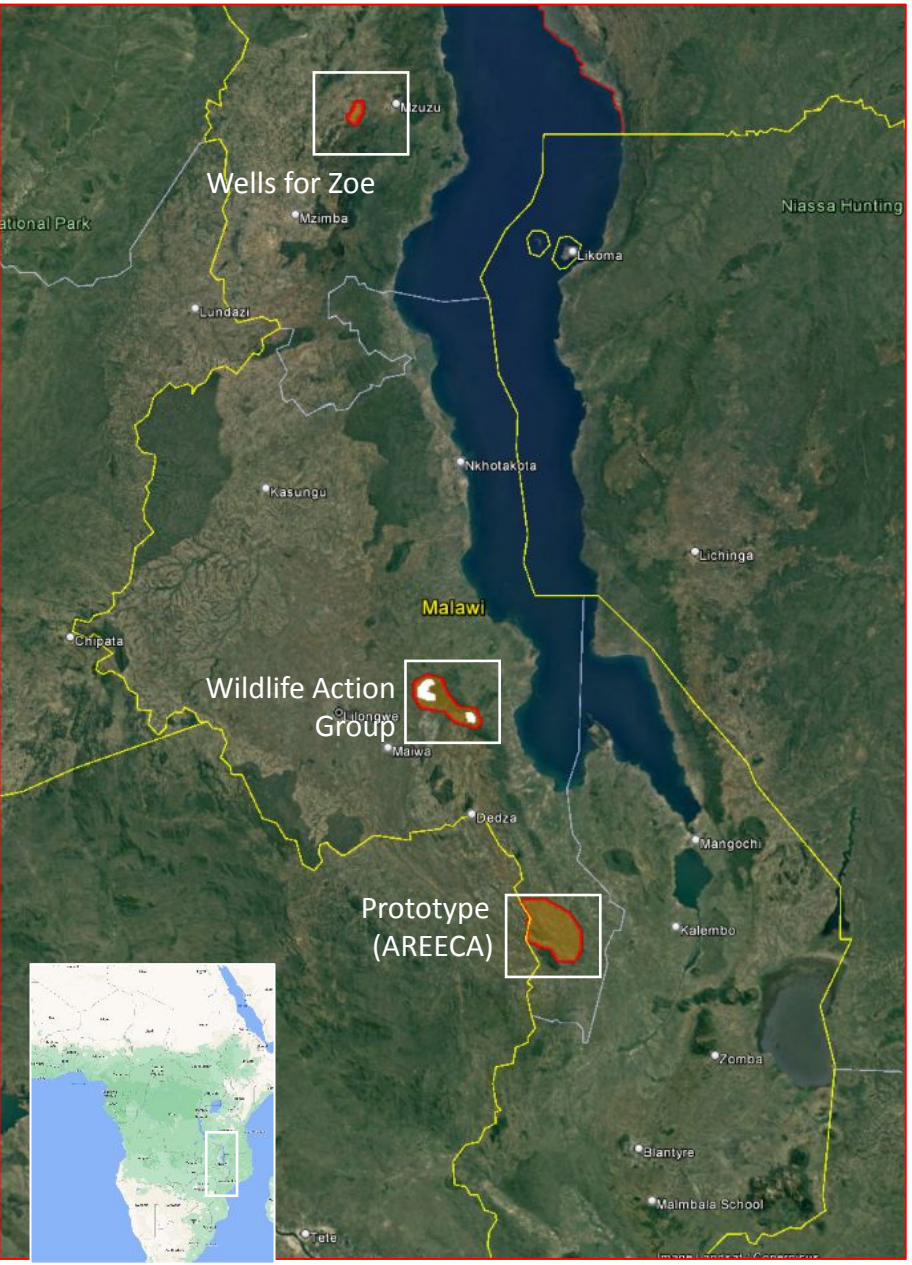
29% of tree cover is found outside areas previously classified as tree cover in state-of-the-art maps, such as in croplands and grassland.

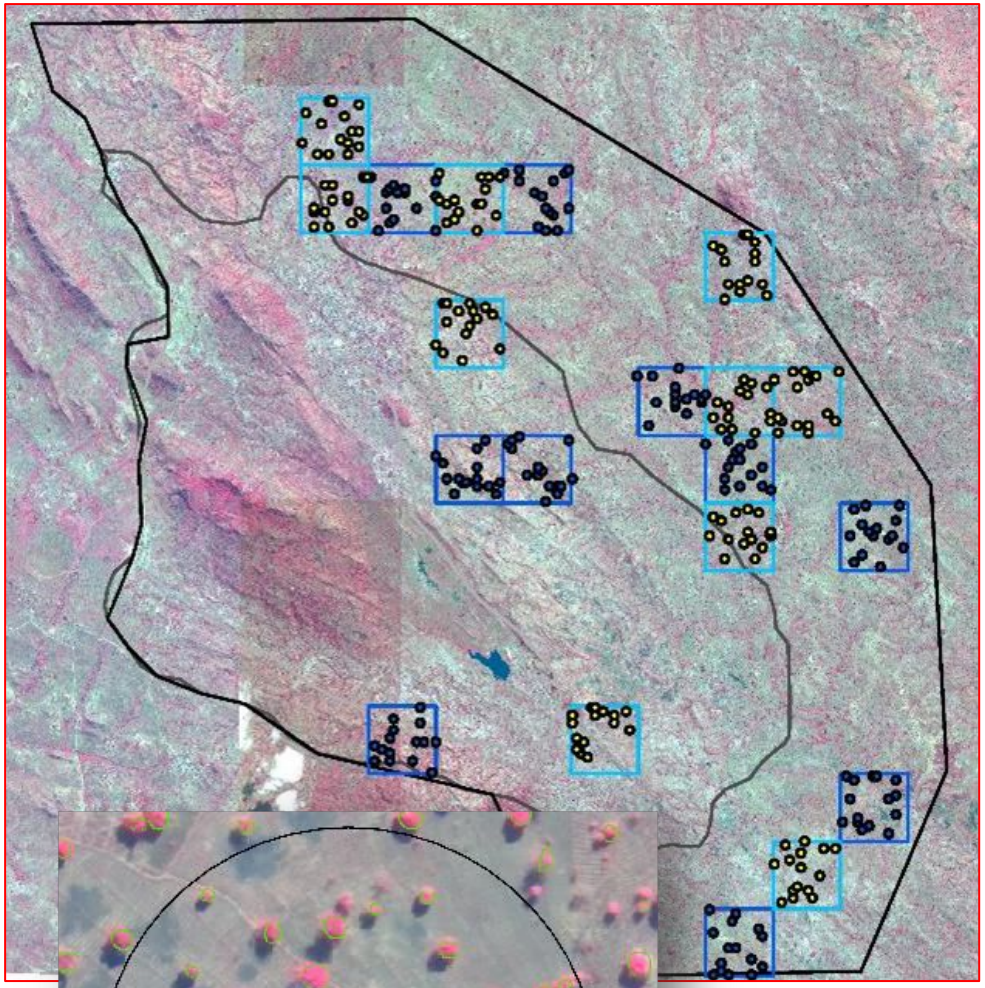


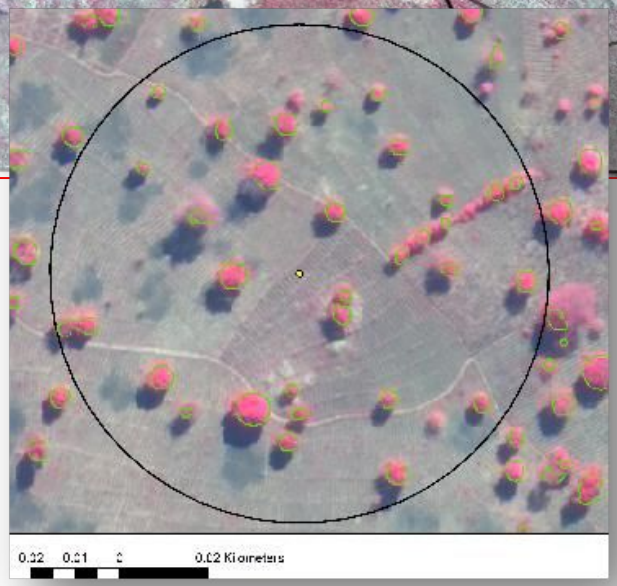
Reiner, F., Brandt, M., Tong, X., Skole, D., Kariryaa, A., Ciais, P., Davies, A., Hiernaux, P., Chave, J., Mugabowindekwe, M. and Igel, C., 2023. More than one quarter of Africa's tree cover is found outside areas previously classified as forest. *Nature Communications*, 14(1), p.2258.



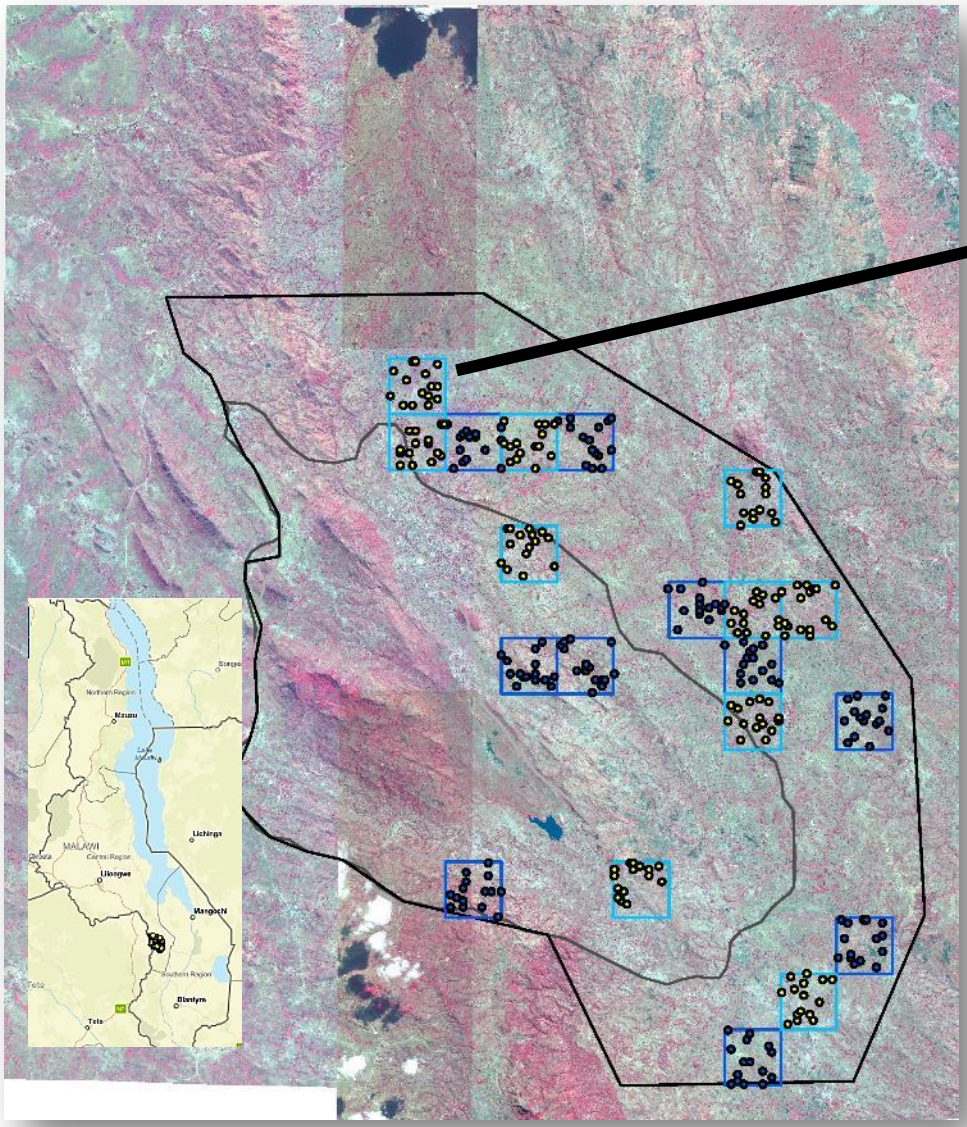
Some Countries have significant TOF contributions to total tree cover

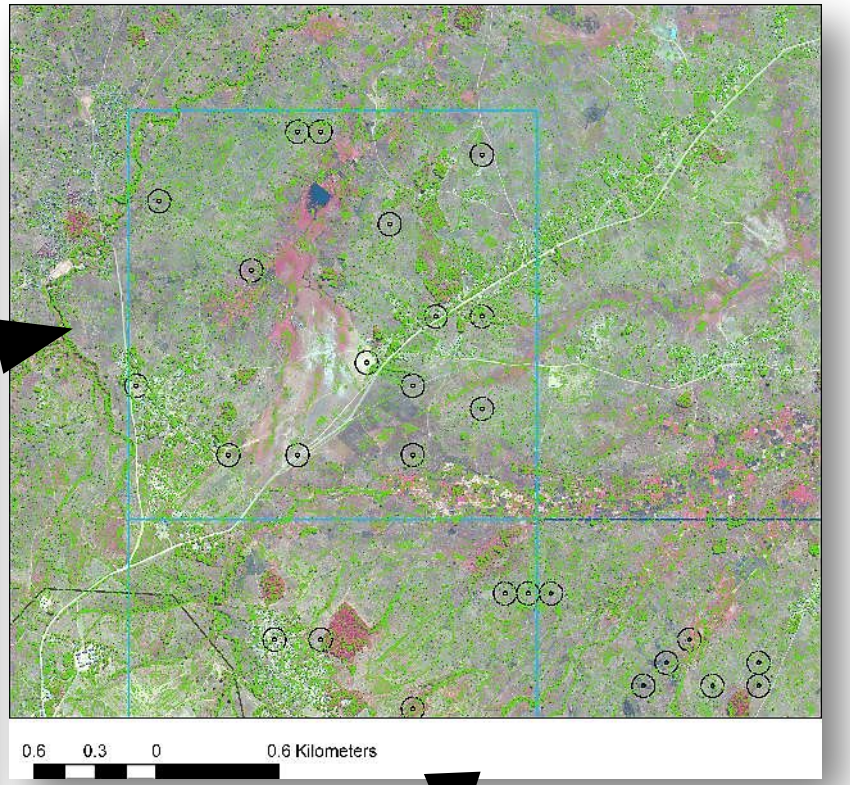

Wells for Zoe
Nzuzu
Mzimba
Niassa Hunting
Likoma
Lundazi
Nkhotakota
Kasungu
Lichinga
Malawi
Chipata
Wildlife Action Group
Mangochi
Prototype (AREECA)
Kalembo
Zomba
Blantyre
Malimbala School
Tete

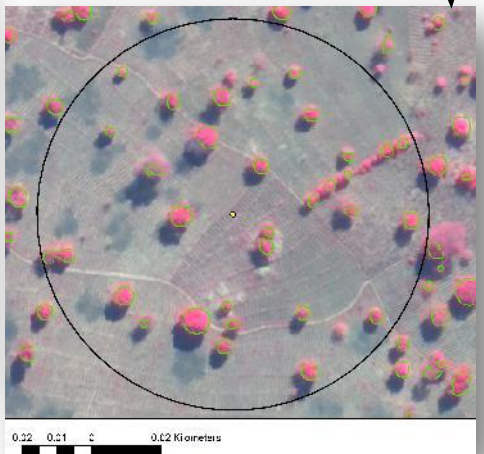



0.02 0.01 0 0.02 Kilometers

Sample Frame and Sample Allocation for Model Training and Testing in Malawi

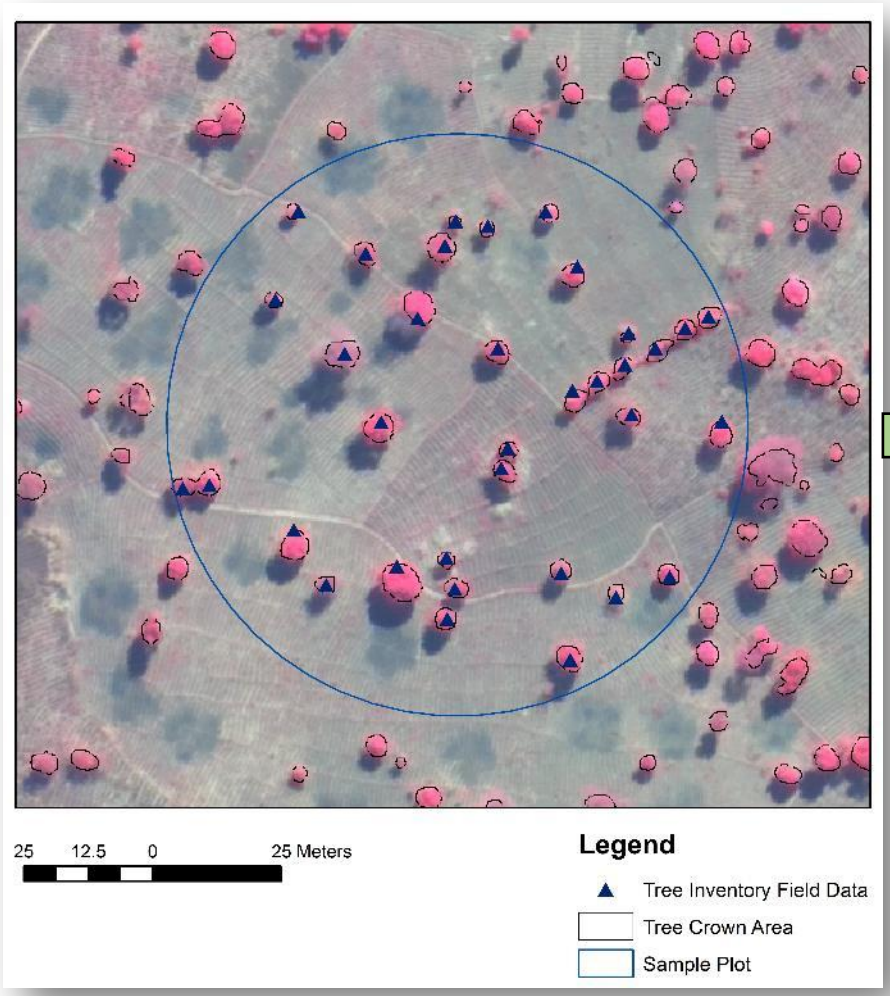




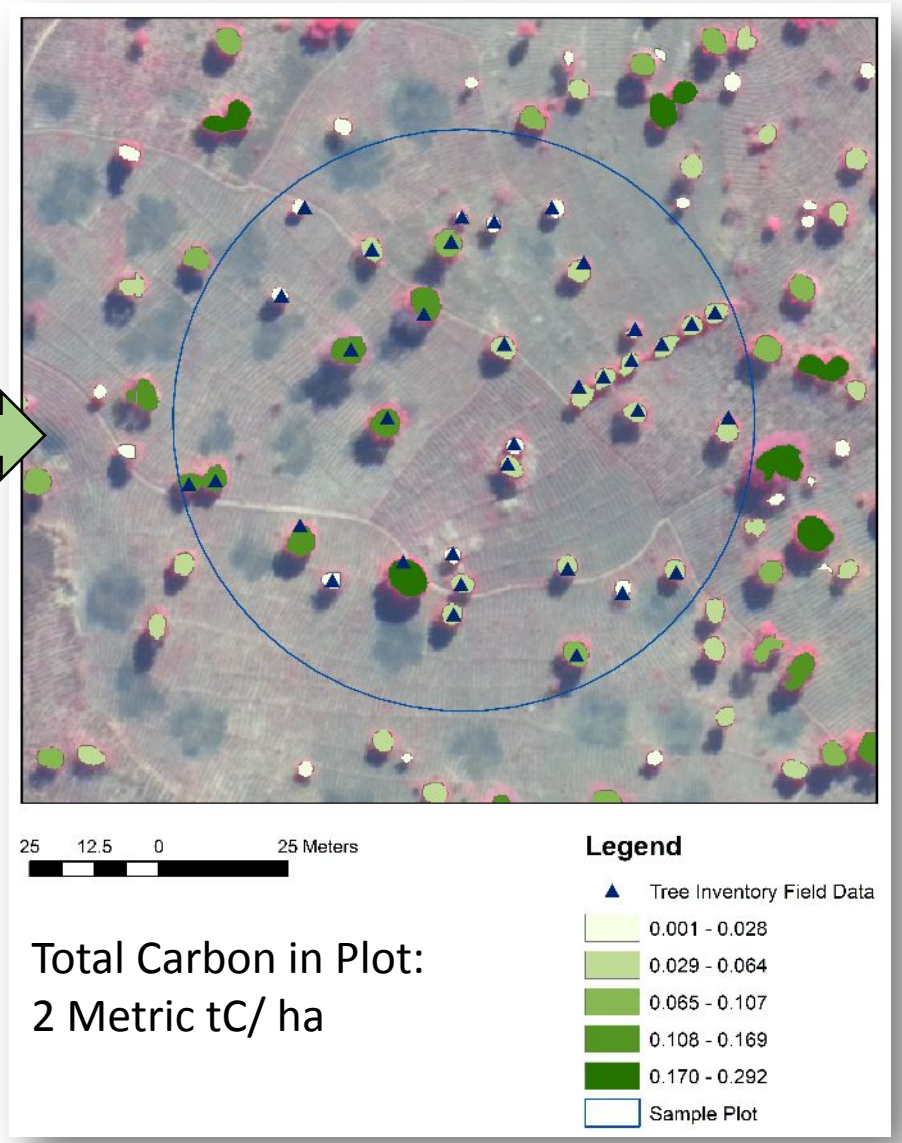


Malawi Prototype AFR100 Project Site: National Model Development

1 Ha. Sample Plot, Field Measured Trees, And Remote Sensing Model Tree Crowns

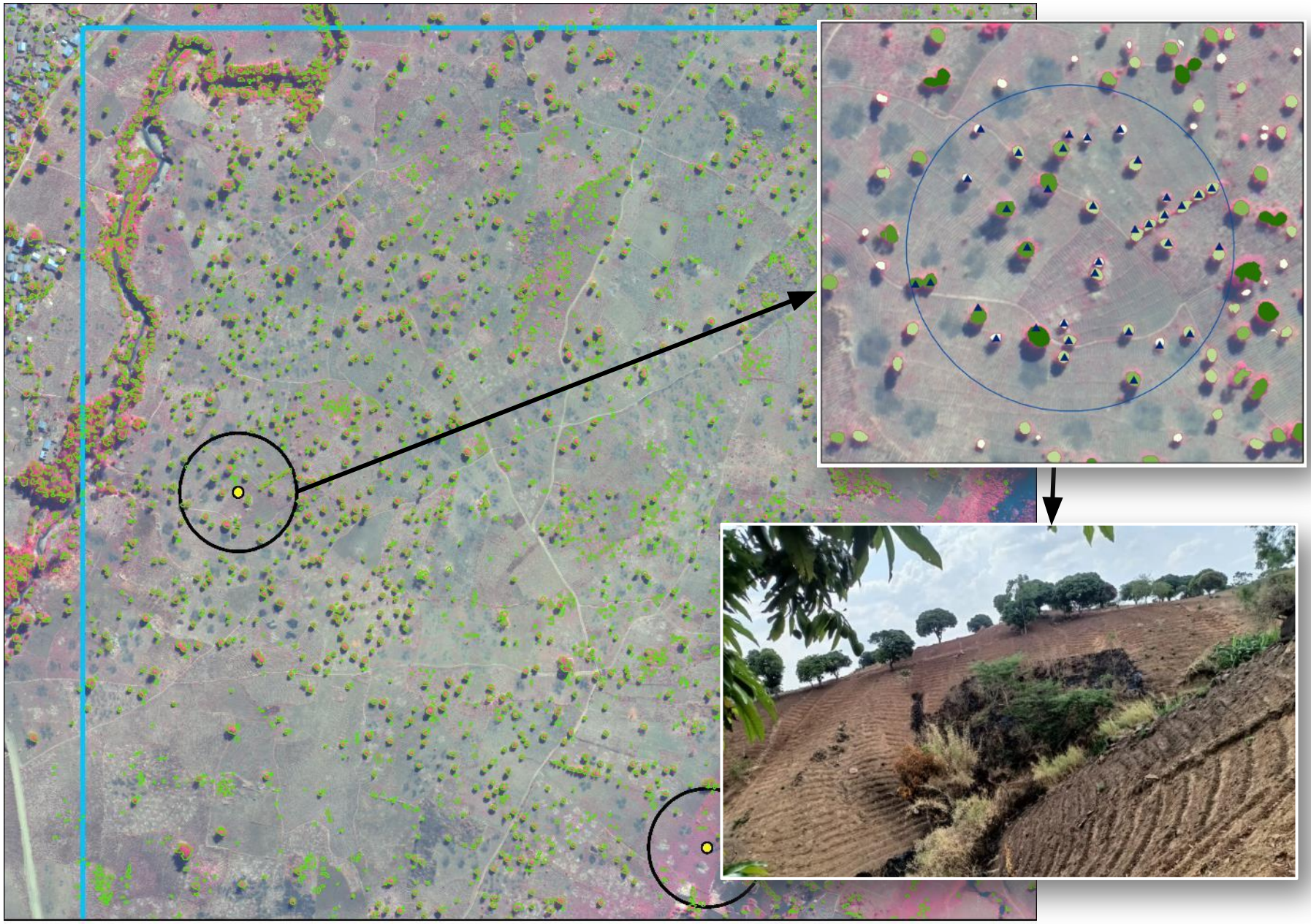


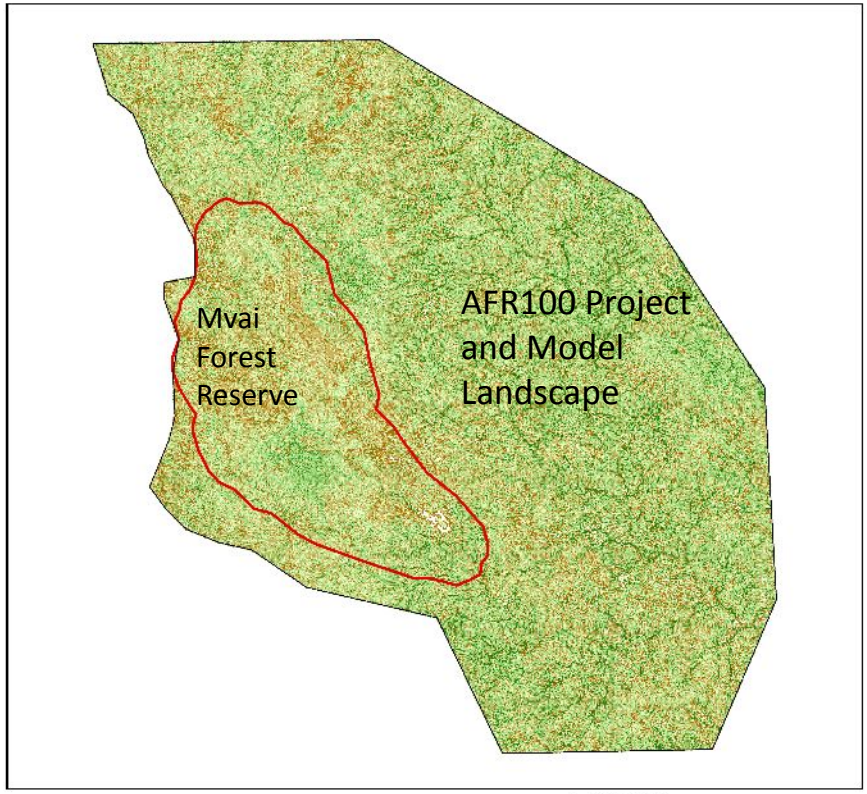
1 Ha Sample Plot, Field Measured Trees, Predicted Carbon Stock per Tree

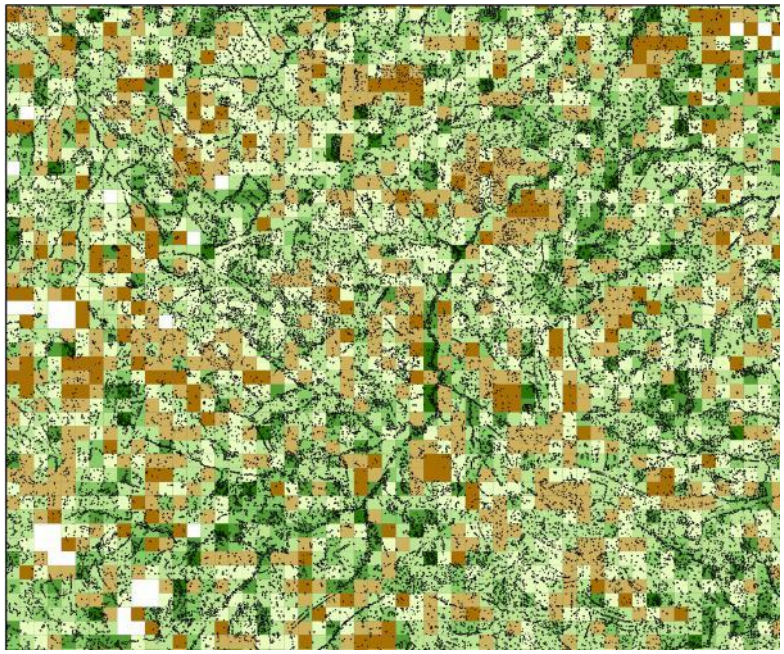


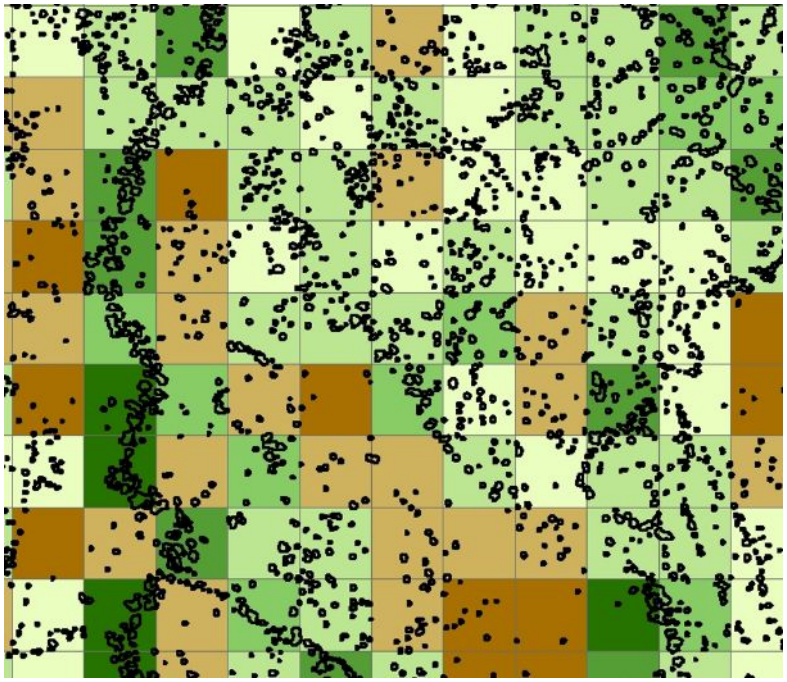
Total Carbon in Plot:
2 Metric tC/ ha

Landscape wide carbon estimate in TOF: A) Landscape crowns B) Plot scale showing estimated carbon, C) ground photo from plot (note terrace ridges in imagery)





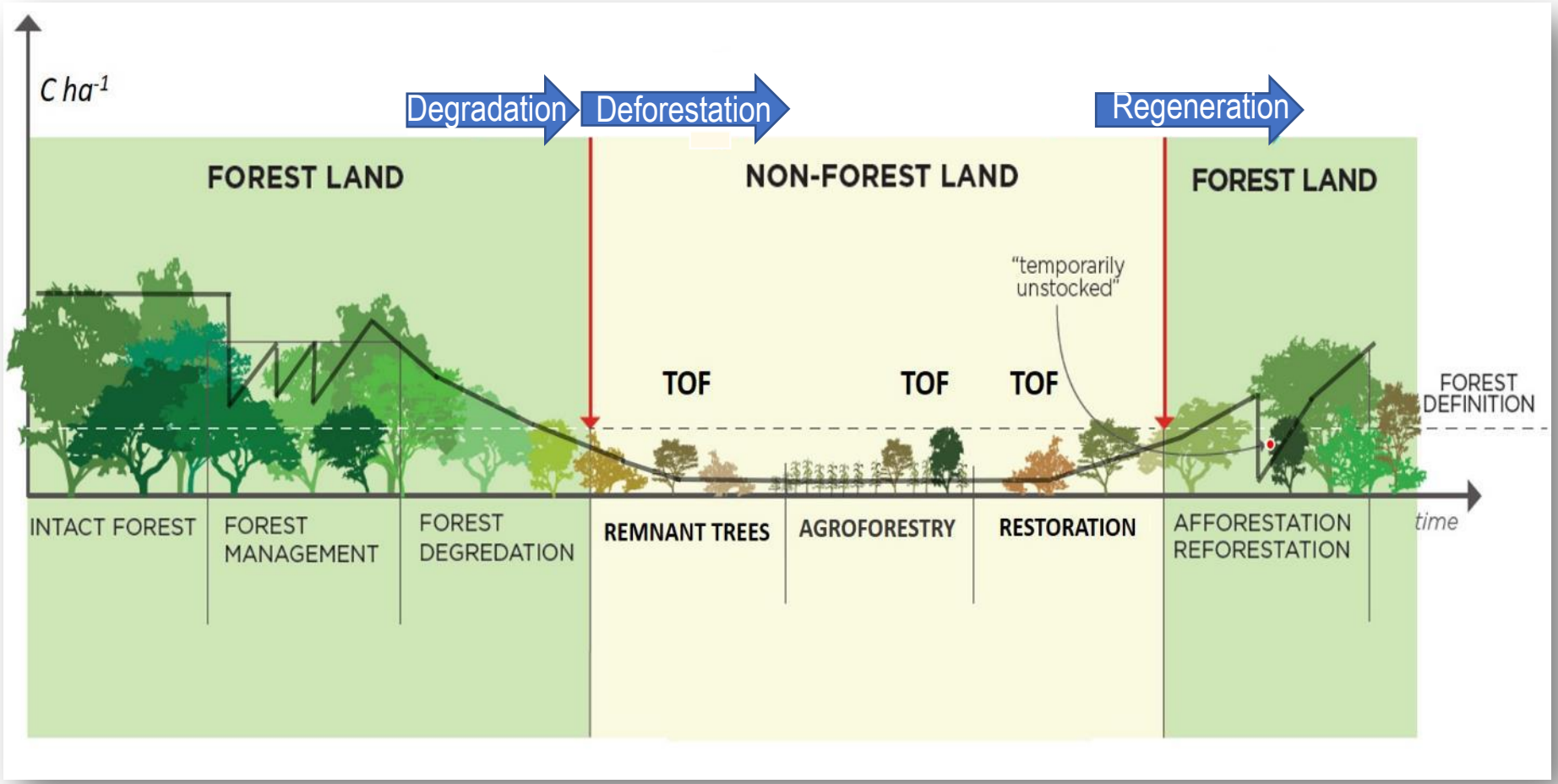




Carbon in Project

- 148,722 Metric tC
- 2.93 Metric tC per ha.
- Maximum is ~9 tC per ha.

Re-imagining REDD+ in a Landscape Perspective



Mbow, C., Smith, P., Skole, D.L., Duguma,L., Bustamante, B. 2014. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability* 6 (2014): 8-14.

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