Trees outside of forests as natural climate solutions

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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].

TOF systems are ubiquitous in the tropics and developing countries. They include both sparsely treed ecosystems and a variety of tree-based production systems, such as agroforestry, ally cropping small-holder plantations, energy farms, shelterbelts, village or community woodlots, scattered individual trees and other woody perennial establishments in predominantly smallholder agricultural landscapes. Tree-based systems provide important value chains for natural products and numerous indirect co-benefits for billions of people, including water retention, increased site fertility and productivity, food security, livestock fodder, energy from fuelwood and charcoal, direct incomes, conservation of biodiversity and provision of timber and non-timber products. TOF systems enable smallholders to create a diversified portfolio of products other than annual crops alone, often with significantly higher

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.

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 and non-market benefits from ecosystem services, including those that provide enhanced adaptation to climate change impacts[6,7]. For instance, African agricultural landscapes are known for using traditional tree systems to capture a range of ecosystem functions and as a source of food, fibre and energy. Many of the farming practices in Africa are tree-based systems that combine trees with land management practices for food and animal production. In West Africa, elevated tree biomass was observed around village areas as compared to stocks in natural savannahs[8]. If TOF cover is widespread and increasing carbon sequestration and farmers are intentionally promoting these tree-based systems, this represents an existing lever for rapidly scaling up carbon sequestration interventions because these systems would already be linked to traditional knowledge and practices.

Sequestration rates in native African tree-based production systems range 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 the second-best land-based climate change mitigation option after natural-forest restoration; it is seven times more effective than timber tree plantations[10], and it facilitates attainment of sustainable development goals, conservation of biodiversity and combatting desertification and land degradation.

Notwithstanding a few notable studies[2], the global extent of TOF in the tropics and its influence on the global carbon budget remain uncertain, but there are some important indications from country studies. For instance, in a study of six countries, Schnell et al.[3] showed that a significant amount of carbon is stored in TOF; indeed, in Bangladesh, TOF biomass was more than twice the total national forest biomass. The latest *State of Forest Report* for India by the Forest Survey of India suggests that, nationally, tree cover is improving outside the official recorded forest areas, mostly on individual smallholder's agricultural land. Across Africa, a carbon sink in the Sahel has become strongly positive since 1981 (ref. [11]) due to woody cover growth outside dense forests.

With the availability of new measurement and monitoring tools using high-resolution Earth-observation satellite data, it is now possible to obtain very good estimates of TOF area and biomass change at continental scales, which will significantly reduce this uncertainty.

New methods for monitoring

For TOF-focused climate and carbon policies to be actionable, as in the context of REDD+, TOF cover and carbon must be readily measured, reported and verified. The good news is that measurement capabilities are emerging across a wide spectrum of remote-sensing platforms, from medium (10–30 m) to high (~3 m) and very-high-resolution (<1 m) products[4,12]. Recently, deep learning, which has emerged as a disruptive technology in different fields of object detection, is increasingly used with satellite imagery. Deep learning uses manual training to teach artificial intelligence models tree features, such as shapes, shadow length and orientation, as well as other physical attributes, which allows the computer to map more trees over a desired spatial extent, which could be up to millions of square kilometres. Brandt et al.[4] have demonstrated this by mapping the crown sizes of 1.8 billion isolated trees across a 1.3×10^6 km^2 area of the West African Sahara and Sahel. This study reported an unexpectedly high density of non-forest trees (13.4 trees per ha) in landscapes that had been considered pure desert or severely degraded.

Although some applied satellite images at sub-metre resolution are relatively expensive, new micro-satellite constellations (for example, from Planet Labs) provide cost-efficient alternatives for mapping trees outside forests at unprecedented accuracy. Figure 2 illustrates a deep learning–based country-scale assessment of individual trees (using publicly available aerial photos) in Rwanda (Fig. 2a,c). While the tree density is relatively high over the entire country (Fig. 2a), tree cover derived from a global map (Fig. 2b)[13] has high values only in protected forests, demonstrating that traditional fractional cover maps miss the quantitatively important woody resources in each country.

Multi-temporal application of the methods provides estimates of cover and density change. However, a method for estimating carbon, such as allometric scaling, is required. Precise remote sensing–based mapping of the tree crowns of individual trees can be used in allometric scaling models to estimate biomass. Recent studies are demonstrating successful methods that substitute ground-based allometric parameters with remotely sensed crown area[14]. These tie into existing allometric scaling models using parameters from high resolution, large-area remote-sensing observations.

Rethinking natural climate solutions

There is an urgent need for climate change actions to be applied across a range of landscapes, including those other than high-carbon-density forests. One reason for including TOF in the overall portfolio of climate actions is that it strengthens policies and measures for both future emissions reductions and current removals. A stronger focus on TOF would facilitate meeting net-zero goals by adding landscapes that cover extensive areas in Africa, Asia and Latin America. These landscapes have the potential for important atmospheric-carbon removal while directly contributing to enhancing adaptation and livelihoods and more stable income generation under climate-stress

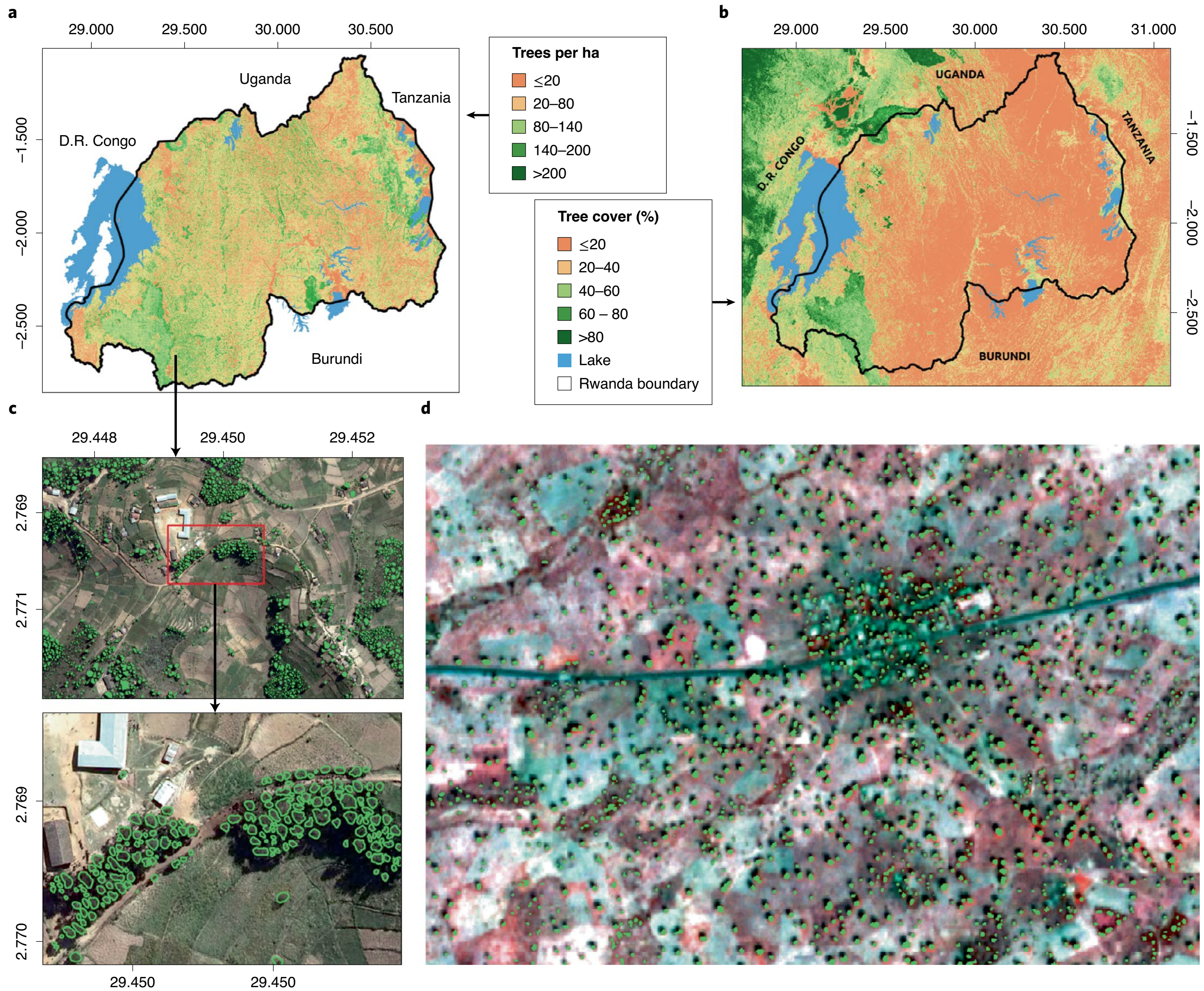

Fig. 2 | Country-scale assessment of trees in Rwanda using digital aerial photos and an example of digital satellite-derived data coverage of savannah ecosystems in Senegal. a, Deep-learning-derived national tree density. **b**, The existing (2010) global tree cover map from Hansen et al.[13]. **c**, Examples of individual tree crown detection using deep learning and 25-cm aerial photos. **d**, As in **c** but using PlanetScope images at 3 m resolution from Senegal. The image in **b** is adapted with permission from ref. [13], AAAS. The image in **d** is adapted from Planet Labs.

conditions. A TOF strategy would ensure participation is not restricted to the countries with high-carbon forests. Many countries already include actions involving TOF removals in their reporting on Nationally Determined Contributions (NDC). Mitigation targets for land use, forestry and agriculture are included in 73% of all NDCs submitted so far[15], which surpasses all other priority areas, including those in the energy sector. Agroforestry is specifically identified in more than 50% of all domestic NDC mitigation activities. The current REDD+ and other mitigation frameworks will need to expand to embrace agriculture and the AFoLU framework, for example by making measurement, reporting and verification less forest-centred.

There are many field-tested operational frameworks available to support the practical implementation of TOF-based natural climate solutions. These include farmer-managed natural regeneration practices, land degradation neutrality models, multifunctional agriculture, multiple agroforestry systems and other options[10,16–18]. In addition to providing carbon value chains, these tree-based models inherently include livelihood strategies and other environmental co-benefits from TOFs. Thus, there are important environmental, socio-economic and practical reasons to expand the climate dialogue to include meeting sustainable development goals through tree-based production systems in working landscapes such as tropical agroforestry. Capital investments, even those including multi-lateral development financing, should be leveraged for TOF-related climate activities.

The TOF framework supports many important international programs at the same time. There are 14 UN Sustainable

Development Goals that relate to TOF. A closer link between the aims of the UN Framework Convention on Climate Change and the Sustainable Development Goals would embrace the sustainable development aims of the Paris Agreement. National actions to implement components of the UN Convention on Biodiversity are enhanced by close links to national climate change mitigation actions, such as promoting tree-based systems and conserving fragile semi-arid sparsely treed ecosystems. Creating a cross-convention initiative using TOF as the centrepiece would strengthen both climate and biodiversity goals.

The Bonn Challenge recognizes the value of forest landscape restoration in climate change mitigation and adaptation. It recognizes that a forest-only approach will miss opportunities for climate-smart land-based mitigation options in non-forest landscapes, where tree-based systems can increase carbon removals while supporting nature-based adaptation and development. Most of the national commitments in the Bonn Challenge and its African contributions from the AFR100 program, along with other new initiatives in Africa, including the African Resilient Landscapes Initiative, focus on tree-based activities outside of forests and thus should be prioritized for financing. To achieve this, these activities should drive an overt effort to ensure that TOF is explicitly counted, inventoried and measured in climate change programs.

While new public–private partnerships are raising large capital investments for high-biomass forests, including the Green Gigaton Challenge, the Lowering Emissions by Accelerating Forest finance Coalition (LEAF) and the new Architecture for REDD+ Transactions (ART), a greater inclusion of TOF would increase the relevancy and effectiveness of these investments because they create incentives for tree-based carbon removals in places and ways that matter to people and livelihoods and would thus secure permanence and scale from these investments more effectively.

New measurements using Earth observations are quickly being deployed, and we now have the the ability to measure at the scale of individual trees across expansive areas. These measurement and monitoring tools have opened a window of opportunity to expand the existing dialogue on forests to include TOF and, in turn, to create an improved and more inclusive environment enabling large-scale investment in natural climate solutions. ❐

David L. Skole[1✉], Cheikh Mbow[2], Maurice Mugabowindekwe[3,4], Martin S. Brandt[3] and Jay H. Samek[1]
[1]*Global Observatory for Ecosystem Services, Department of Forestry, Michigan State University, East Lansing, MI, USA.* [2]*Future Africa Institute, University of Pretoria, Pretoria, South Africa.* [3]*Department of Geosciences and Natural Resources Management, University of Copenhagen, Copenhagen, Denmark.* [4]*Centre for Geographic Information Systems and Remote Sensing, College of Science and Technology, University of Rwanda, Kigali, Rwanda.*
✉*e-mail: skole@msu.edu*

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Author contributions

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Competing interests

The authors declare no competing interests.