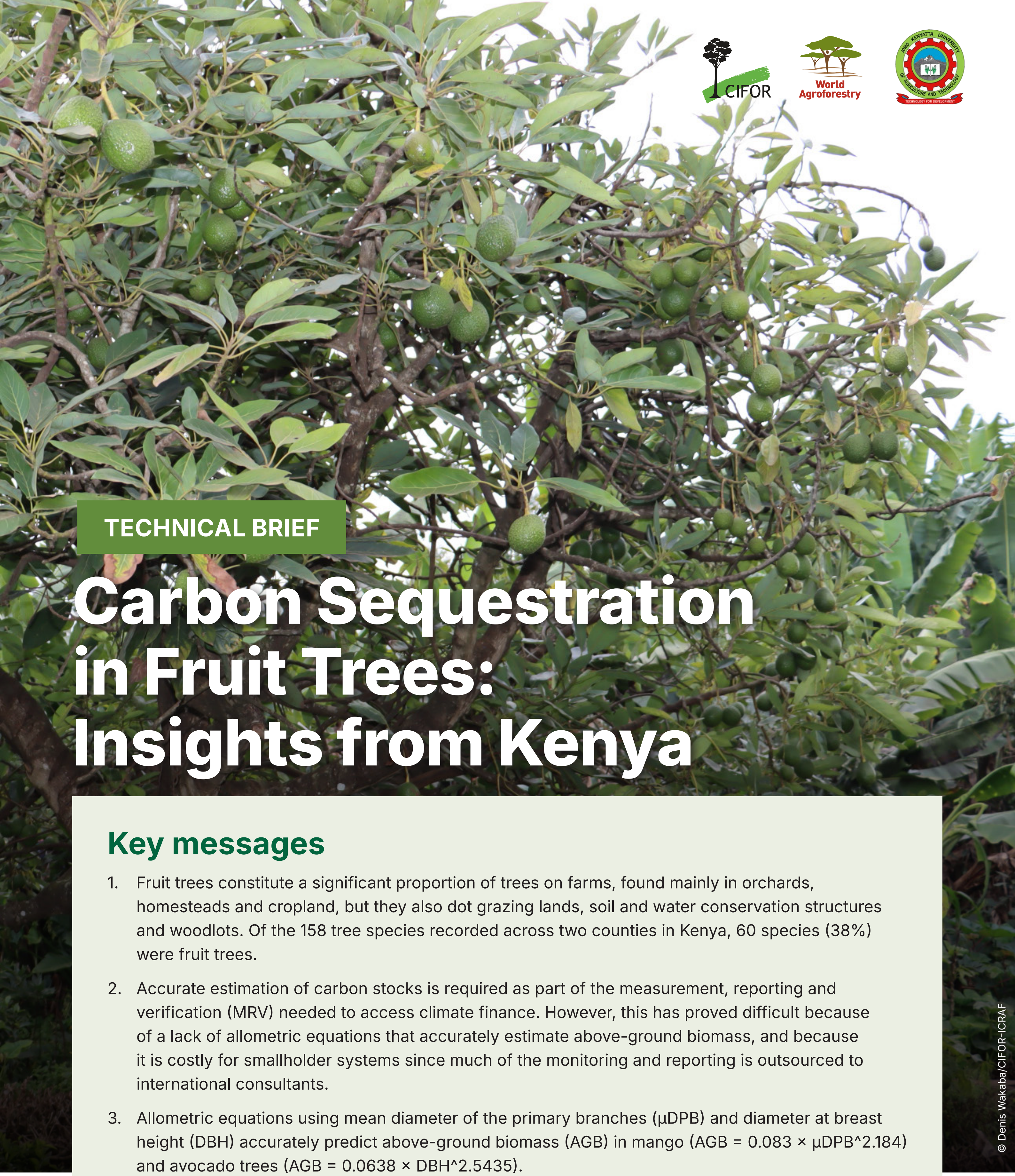

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TECHNICAL BRIEF

Carbon Sequestration in Fruit Trees: Insights from Kenya

Key messages

1. Fruit trees constitute a significant proportion of trees on farms, found mainly in orchards, homesteads and cropland, but they also dot grazing lands, soil and water conservation structures and woodlots. Of the 158 tree species recorded across two counties in Kenya, 60 species (38%) were fruit trees.
2. Accurate estimation of carbon stocks is required as part of the measurement, reporting and verification (MRV) needed to access climate finance. However, this has proved difficult because of a lack of allometric equations that accurately estimate above-ground biomass, and because it is costly for smallholder systems since much of the monitoring and reporting is outsourced to international consultants.
3. Allometric equations using mean diameter of the primary branches (µDPB) and diameter at breast height (DBH) accurately predict above-ground biomass (AGB) in mango ($AGB = 0.083 \times \mu DPB^{2.184}$) and avocado trees ($AGB = 0.0638 \times DBH^{2.5435}$).
4. Fruit trees store significant amounts of carbon in above-ground biomass; on average, 10.5±2.9 Mg C ha^{-1} and 9.7±2.5 Mg C ha^{-1} in mango and avocado, respectively. Much of this biomass is found in farm orchards where a great number of fruit trees exist, and in homegardens where large-size trees are common.
5. The regeneration of fruit tree species was good to fair in Kiambu, but poor and limited to five exotic species in Makueni.

Summary

This technical brief summarizes the main findings of a study to better understand the contribution of fruit trees to climate change mitigation. The objective of the study was to develop allometric equations and estimate carbon storage in fruit trees as a first step to determining the potential for access to international climate finance. Simple, easy-to-use allometric equations are provided to help farmers estimate the amount of carbon present in their trees. This will empower the farmers to negotiate better results-based payments and hopefully evade exploitation by carbon marketing schemes. Using fruit trees in carbon projects can help prevent unintended loss of livelihoods and food security as a result of sequestration efforts and accelerate scaling up of agroforestry.

Background

Agroforestry can support Kenya's ambition to reduce greenhouse gas (GHG) emissions by 32% by abating 4.1 MtCO_2e by 2030. It is also expected to contribute to the national target of growing 15 billion trees, restoring 10.6 million hectares of degraded lands where agroforestry is allocated 3 million hectares of that, and increasing tree cover to 30% by 2032 (Government of Kenya, 2023). Large-scale implementation of agroforestry can increase soil fertility and crop yields enhance the water cycle including providing a variety of products and thus improve farmers livelihoods and food and nutritional security, and contribute to climate resilience. A major challenge regarding these ambitions is monitoring and reporting the potential of agroforestry. Agroforestry systems are complex because of the variety of trees and the land use within which the trees are located and associated management practices. This complexity limits inclusion of agroforestry in the national GHG inventories of many countries by affecting two fundamental aspects of accounting for GHG emissions. First, is the challenge on how to integrate the contribution of agroforestry to the existing agriculture, forestry and other land use sectors since agroforestry is not included under the IPCC classification of land use types (Cardinael et al. 2020). Second, is the lack of data on carbon stocks and stock changes under different agroforestry systems, which limits access to financial and technical support required to scale up agroforestry (Rosenstock et al. 2019). The dearth in data has been attributed to a lack of robust methods on quantification of carbon stocks, including in fruit trees.

Lack of allometric equations applicable to trees in Africa has remained a major constraint to estimation of carbon stocks across all land use types. This forces researchers to select general purpose equations from a large collection of models in the literature. Generalized equations do not give accurate biomass estimates since they are not developed from a sample representative of the inventory. In fact, the most widely used generalized equations are developed using data from outside Africa, which excludes local species, growth forms and environmental conditions of interest. Besides, there is a general lack of suitable allometric equations for estimating above-ground biomass in fruit trees in literature.

Figure 1. Fruit trees are a major component of agricultural landscapes and grafted ones tend to have multiple branches

Fruit trees are widespread in smallholder farming systems (and are retained for many years due to their multiple benefits), where they occur in orchards, homesteads, cropland, perennial-tree crop systems, grazing land, woodlots, farm boundary and soil conservation structures. These locations are not typical of the forest environment where data used to develop the majority of allometric equations were obtained. Allometric equations for regular trees are based on the measurement of diameter at breast height (DBH) found in literature, and where applicable, height and/or crown area. Fruit trees are largely grafted, and therefore tend to have multiple branches (Figure 1). This phenomenon is beneficial as it increases canopy size and fruit production, but complicates biomass estimation in that it leads to underestimation of tree sizes when averaging the stems to obtain a common diameter, or overestimates carbon stocks when each of the stems above breast height is considered an independent tree. Pruning is another common management practice in fruit trees that change the geometry of trees, making the use of conventional allometric equations unsuitable for fruit trees

Methodological approach

An inventory involving total enumeration of trees on cultivated land was conducted on 36 and 26 farms in Kiambu and Makueni counties respectively. Cultivated land is the area used for growing crops recurrently or permanently, including land that was (at the time of survey) fallowed but would be used for cultivation in the following season or year.

A multistage sampling procedure with simple random selection was used to select households from six wards in two sub-counties in Kiambu and four wards in two sub-counties in Makueni (Table 1). Farm surveys identified eight land use types where trees on farms are located / incorporated in: homestead, cropland, orchard, perennial tree-crop systems, woodlots, grazing land, boundary and soil conservation structures. All trees in each land use type were identified and recorded. The DBH (measured at 1.3 m above the ground), collar diameter (CD, measured at 30 cm above the ground), diameter below the graft union (DBGU), and diameter of the primary branches (DPB) were measured on trees with DBH 2.5 cm or height ≥2 m using a diameter tape. Standard procedures for measuring trees with anomalies were applied on leaning trees, trees on slope, trees with swellings around breast height, forked trees and multi-stemmed trees. The area of the land use category where the trees were measured was determined by walking around it with a GPS device.

Allometric equations were developed using “a leave-one-out cross-validation” method, where the data were split into a training set used to build the equations and a test set (validation data) used to assess the quality of the predictions. Allometric coefficients were estimated using the power law function with DBH, CD, DBGU and DPB as the primary predictors, and height, age and/or crown area as secondary predictor variables.

Table 1. **Locations and the agroecological conditions of the study sites where the inventory and biomass sampling were conducted**

County/Attribute	Makueni	Kiambu
Location	1°35′S–3°00′S; 37°10′E–38°30′E	00°25′S–10°20′S; 36°31′E–37°15′E
Sub-counties	Makueni, Kaiti	Githunguri, Gatundu South
Wards	Makueni, Wote, Ukia, Mukuyuni	Kiambu, Komothai, Githunguri, Kiganjo, Ndarugu, Ng’enda, Ngewa
Agroecological zone	Semi-arid	Sub-humid
Rainfall (mm year^{-1})	250–400	600–2,000
Elevation (m)	600–1,900	1,200–2,550
Mean annual temperature (°C)	24.19	20.82
Soil fertility	Very low soil organic carbon (SOC) (0.43–1.87%)	Moderate to adequate SOC (1.46–3.26%)

Main findings

Proportion and location of fruit trees cultivated on farms

Fruit trees constitute more than one-third (38%) of the tree species documented across two counties (n=158), and 38% of all individual trees recorded across the two counties (n=4,386). This includes 41 species with 811 individuals in Makueni and 31 species with 846 individuals in Kiambu. Of these, 13 fruit tree species were common across the two counties. Exotic fruit tree species in Kiambu totalled 17 (58%) but accounted for most (95%) of the individuals measured in the county. The 14 species native to Africa were only represented by 5% of the individuals recorded. In Makueni, more species (61%) are native, but are represented by very few individuals (12%); a few (39%) exotic species dominate (88%) the landscape. Mango and avocado are the two main fruits widely cultivated in Kenya, representing 23% and 48% of all the fruit trees recorded in Makueni and Kiambu, respectively. Mango and citrus (*Citrus sinensis, C. aurantium, C. reticulata*) account for 71% of all the individual fruit trees documented in Makueni.

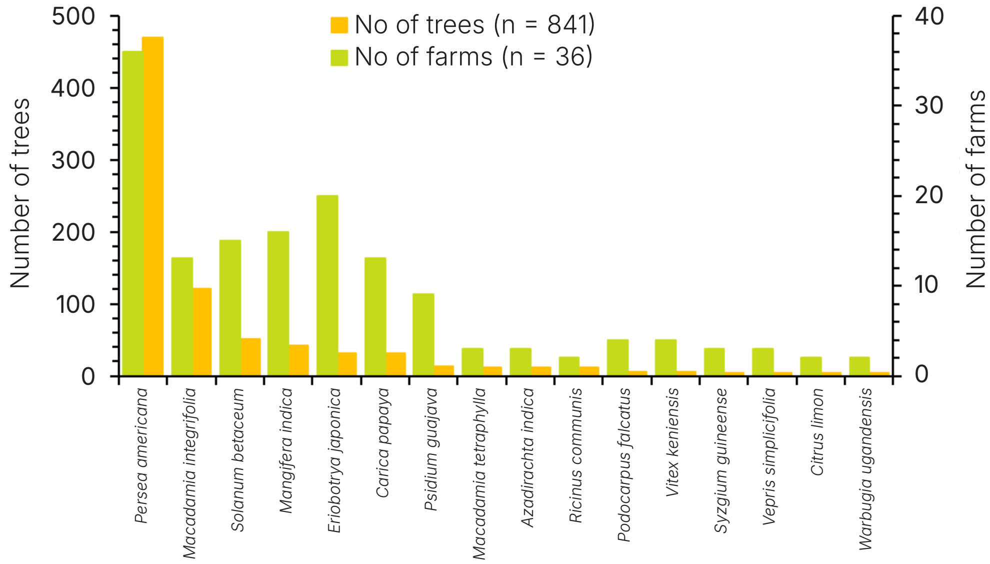

Figure 2. The distribution of fruit tree species and the corresponding number of individual stems per species recorded on farms in Kiambu County. The graph represents those species that were found on two or more farms and had a minimum of four individuals across the county

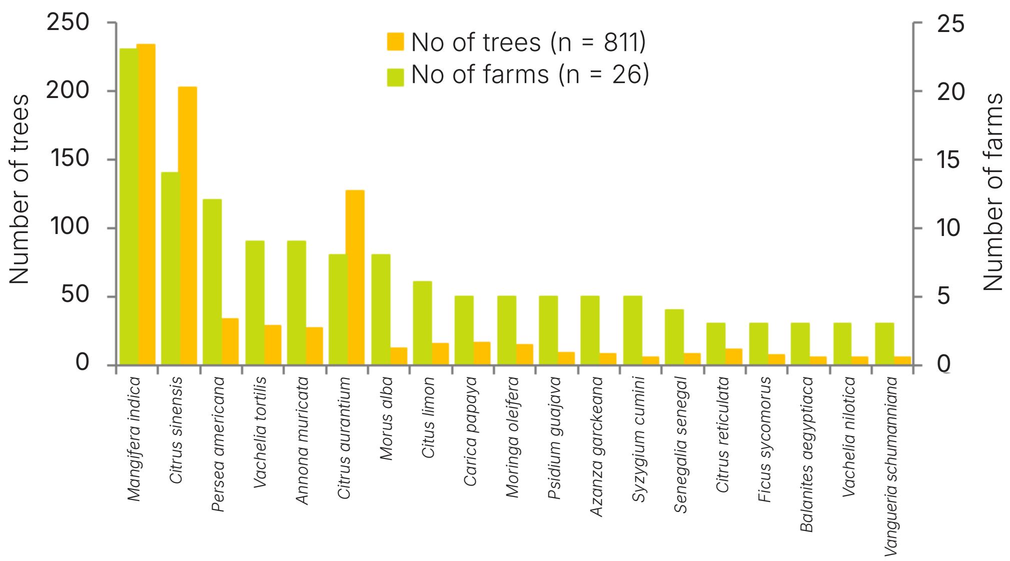

Figure 3. The distribution of fruit tree species and the corresponding number of individual stems per species recorded on farms in Makueni County. The graph represents those species that were found on three or more farms and had a minimum of five individuals across the farms

Allometric equations for estimating above-ground biomass in fruit trees

This study developed allometric equations for priority fruit trees to address the drawbacks of existing equations and increasing interest in the contribution of fruit trees to climate change mitigation. Allometric equations were developed from data collected on 51 mango trees and 40 avocado trees harvested in Makueni and Kiambu counties in Kenya (Table 2).

Allometric equations are mathematical relationships that relate biomass of the tree with measurable parameters such as diameter of the stem. There are very few allometric equations in the literature for tropical fruit tree species, most of which are either developed from a small sample size, have a narrow range of the predictor variable or lack information on the scope of applicability.

Table 2. Allometric equations for estimating above-ground biomass in mango (Eq. 1) and avocado (Eq. 2) using diameter at breast height (DBH) and the mean diameter of the primary branch (µDPB). R^2 = coefficient of determination, MAPE (%) = mean absolute percentage error

Eq. No.	Allometric equation	DBH range	Age	R^2	MAPE
Eq. 1	AGB = 0.083 × µDPB^2.184	4.5–33.2	3–24	0.93	28.8
Eq. 2	AGB = 0.0638 × µDBH^2.5435	5.3–96.2	2–52	0.86	18.4

The µDPB was the best predictor of above-ground biomass in mango trees while DBH was a better predictor for above-ground biomass in avocado trees (Table 2). Inclusion of height, age and crown area as supporting predictor variables provided a mix of marginal improvement and negative effects on the accuracy of diameter-only equations. Including these parameters as supporting predictor variables is therefore not considered necessary since the additional resources needed to obtain accurate data for these inputs will deliver only a small (at best) reduction in prediction error.

Allometric equations developed in this study require only one predictor variable (DPB or DBH) which is easier to measure with relatively high accuracy and the variables have low prediction error (Table 2). A scatter of the actual and predicted biomass showed agreement between the estimate and the measured biomass (Figure 4). Allometric equations developed in this study will support rapid estimation of carbon stocks in projects aimed at reducing atmospheric CO_2 by managing fruit trees in the study area or areas with similar conditions.

Carbon storage in fruit trees

Fruit trees stored significant amounts of carbon on smallholder farms, on average 10.5±2.9 Mg C ha^{-1} in mango and 9.7±2.5 Mg C ha^{-1} in avocado. Much of the carbon in above-ground biomass was found in homegardens and orchards (Table 2). This concurs with the observations from the systematic review by Muthuri et al. 2023, where homegardens were reported to be the most multifunctional agroforestry practice with the largest amount of carbon stocks in aboveground biomass. The differences in above-ground carbon stocks among the land use categories reflect existing trends in the management of trees in smallholder systems and the implication in terms of loss or gain of carbon. Also, majority of the avocado trees sampled being young (7-10 years) in Kiambu which have replaced many of the coffee bushes due to growing demand for the fruit. The values of carbon estimates for both mango (10.5 Mg C ha^{-1}) and avocado (9.7 Mg C ha^{-1}) are within the range of agroforestry systems in semi-arid (9 Mg C ha^{-1}) and sub-humid (21 Mg C ha^{-1}) tropics in Africa (Montagnini and Nair, 2004) but lower than estimates for tropical forest ecosystems. Also, majority of the avocado trees sampled being young (7-10 years) in the area which have replaced many of the coffee bushes due to growing demand of the fruit. Above-ground biomass depends on several factors, for example, tree species, climate conditions, tree age, tree density and management of the trees in the landscape. The need for species-specific allometric equations is underscored by the huge variations in biomass estimates for mangoes in the literature, for example, as low as 3.0 Mg ha^{-1} in a 10-year old

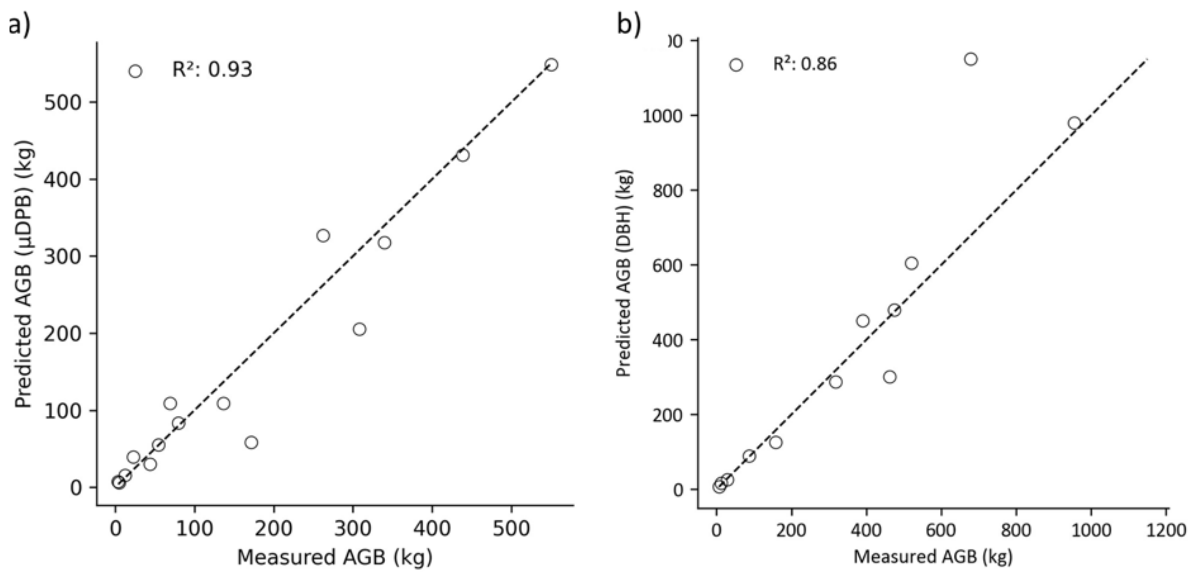

Figure 4. Scatter plots of actual (measured) above-ground biomass (AGB) and AGB predicted using allometric equations developed in this study for mango trees (a) and avocado trees (b)

orchard in a sub-humid climate in eastern India (Naik et al. 2019) to 55.4 Mg ha^{-1} for mangoes grown on degraded lands in the Indian Sub-Himalayas (Rathore et al. 2021), and 62.7 Mg ha^{-1} for mango parklands in Burkina Faso (Dao et al. 2021).

Table 3. Above-ground biomass (AGB, Mg ha^{-1}) and carbon stocks (AGB-C, Mg C ha^{-1}) in avocado trees in Kiambu, and mango trees in Makueni

Kiambu						
Land use type	**Area (ha)**	**No. of farms**	**No. of trees**	**Tree density**	**AGB, mean±SE**	**AGB-C, mean±SE**
Cropland	8.98	25	243	27	16.88±4.15	7.93±1.95
Homestead	3.33	27	95	29	25.57±10.39	12.02±4.89
Orchard	0.37	5	73	198	71.21±29.01	33.47±13.63
Perennial tree crop system	1.46	8	50	34	5.64±2.88	2.65±1.35
Woodlot	0.28	4	5	18	3.22±1.05	1.51±0.49
All land use	14.42	36	466	32	20.55±5.35	9.66±2.51
Makueni						
Cropland	3.01	9	56	19	14.70±10.77	6.91±5.06
Grazing land	0.03	2	3	86	6.83±1.91	3.21±0.90
Homestead	0.19	9	28	150	53.28±18.16	25.04±8.53
Orchard	1.14	13	143	125	21.67±5.80	10.18±2.72
All land use	4.37	23	230	53	22.28±6.26	10.47±2.94

Above-ground biomass data provided in this study fill a critical gap in the literature, where estimates of agroforestry in general or on specific agroforestry practices are considered broad and limited in application (Nair and Nair 2014). This underscores the high potential for mitigation of climate change if fruit trees are scaled up to increase carbon sequestration, as farmers are likely to protect and maintain fruit trees on farms.

Regeneration status of fruit trees

The proportion of seedlings relative to the total population of fruit trees was highest followed by trees and saplings (Figure 5). A similar trend was observed in Kiambu, where the regeneration of dominant fruit tree species and other fruit trees adapted to sub-humid and dryland ecosystems was good to fair. The proportion of trees, saplings and seedlings in Kiambu was 43%, 26% and 31%, respectively (n=1,969). The regeneration of fruit trees in Makueni was poor and limited to five exotic species: *P. americana, C. limon, C. sinensis, C. aurantium* and *P. guajava.* The proportion of trees, saplings and seedlings here was 83%, 5% and 12%, respectively (n=983). Absence of seedlings of some species could be attributed to their characteristic poor seed germination and establishment, especially in dryland ecosystems. The presence of saplings of the major exotic fruit tree species is attributed to planting initiatives involving nursery-raised trees.

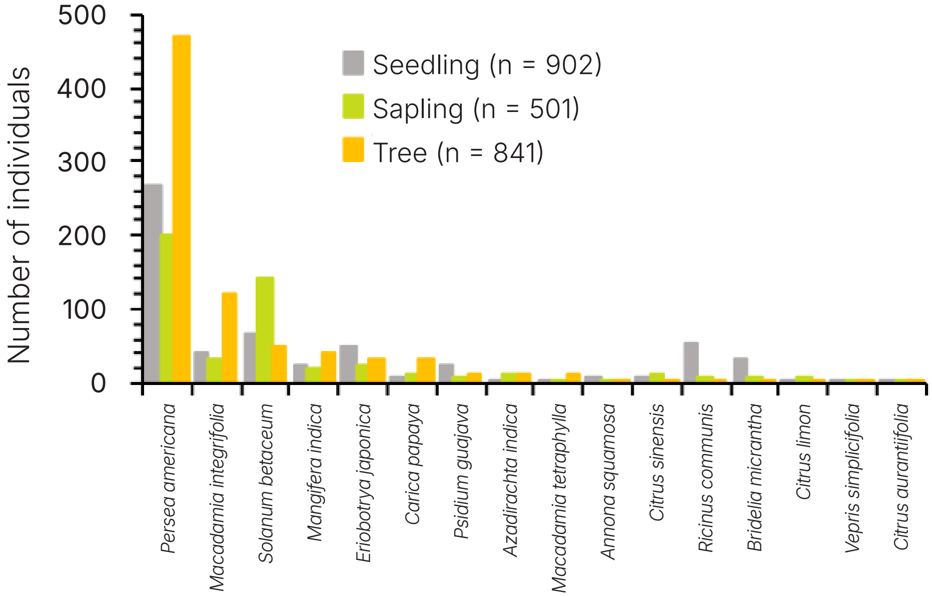

Figure 5. Regeneration patterns of fruit tree species in Kiambu and Makueni, Kenya

Recommendations and next steps

Planting and growing fruit trees presents many opportunities to improve farmers' livelihoods while contributing to climate change mitigation (Muthuri et al. 2023). Financial incentives and governance infrastructure associated with climate change mitigation initiatives can catalyse the scaling up of agroforestry. However, the use of fruit trees for carbon finance is still tricky because of the need to standardize methods of measuring, monitoring, reporting and verifying the amount of carbon sequestered by the trees, unclear risks, and the unrealistic expectations about benefits of carbon schemes to communities. The following are recommendations from this study:

- Include agroforestry in the national forest inventory database. Currently, the design of Kenya's national forest inventory does not cover agroforestry landscapes. Experience from this study can be used to develop standard operating procedures for assessments in agroforestry in Kenya to be integrated into the National Forest Monitoring System.
- Train communities to be able to measure carbon on their farms. There are worries that farmers who do not have capacity to measure and monitor carbon on their farms may not be able to bargain for better results-based payments and could be exploited by carbon marketing schemes. Improving the capacity of communities to support MRV of carbon sequestration (e.g., through community monitoring of carbon) in fruit trees can reduce dependence on consultants and therefore lower the transaction costs, which are high for smallholder farmers.

- Establish the conservation status of species with no regeneration, as these can be exterminated if they are susceptible to climate change. The low populations of native species in both counties coupled with poor representation of seedlings and saplings point to a compositional shift that has favoured exotic species.
- Clarify carbon and non-carbon benefits of fruit trees in incentive systems. Carbon finance can incentivize wide-scale adoption of agroforestry by providing additional income, however small it may be. However, it is important to clarify and prioritize non-carbon benefits of fruit trees in order to account for all the benefits arising from carbon projects. Non-carbon benefits of fruit trees have greater value than their carbon counterparts, given the current value of carbon prices and the high administrative costs, and continue to provide benefit to farmers in the absence of carbon payments.
- Measure and monitor carbon sequestration in agroforestry at scale. This requires a combination of allometric equations and remote sensing tools. A series of images taken at different times are needed to determine changes in carbon stocks in different agroforestry systems. Increased funding or improved access to high-resolution satellite imagery can improve the ability to clearly identify fruit trees in orchards or in other land use types.

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