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RESEARCH ARTICLE

Carbon Sequestration of Fruit Trees under Contrasting Management Regimes

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Abstract. This study aimed at establishing the potential of fruit trees in carbon sequestration. The specific objectives were to establish the carbon stocks in fruit trees, compare the potential of carbon stocks in Citrus and mango trees and examine the relationship between the management practices and carbon stocks in fruit trees. At the farm level, plots were identified, transects established, and individual fruit trees were selected along the transect across the fruit-chosen farms. At the tree level, measurements of tree height and diameter at breast height were made. They were converted to biomass using allometric equations. Analysis of Variance was used to compare the differences of carbon stocks between the fruit trees and also between the different management practices. Findings revealed higher biomass and carbon stocks in mango trees as compared to citrus (74.57 ± 14.95 and 13.52 ± 1.25 t/ha, respectively). Significant differences are also reported in carbon stocks in the different management practices ($p < 0.05$). Irrespective to the species type, above-ground carbon under different management practices followed the order (from highest to lowest): Inorganic fertilizer < Intercrop < Monocrop < organic fertilizer and irrigation < Intercrop and inorganic fertilizer. The results also point out that mango fruits have a high potential to sequestrate carbon emissions hence mitigating to global warming.

1. Introduction

Climate change has recently become more real and evident as several communities are falling victim to its negative impacts. This is manifested in extreme climatic conditions and associated crop diseases, which have all negatively impacted on crop yields (Kumar et al., 2018). The concentration of carbon, a dominant greenhouse gas, rose from approximately 277 parts per million (ppm) in 1750 to 405.0 ± 0.1 ppm in 2017 (Le Quéré et al., 2018) and current projections indicate increasing concentration to as much as 500 ppm by 2025. This build-up is driving the development and adoption of interventions to not only cope with the changes but also design new models that are responsive to the community's changing needs (Thornton et al., 2018). Such interventions have promoted the conservation and restoration of forests after recognizing their potential as carbon sinks. Trees (fruit trees) play a significant part in the lessening of atmospheric carbon dioxide by carbon sequestration (Patil & Kumar, 2017). Active absorption of CO2 from the atmosphere through the process of photosynthesis and its subsequent storage in different plant parts in the form of biomass in the tree trunks, foliage, branches, roots, and soil.

The global forest resources assessment reported an annual rate of forest loss in Africa, at 3.9 million ha, between 2010-2020, arguably due to increased population pressure, fire, and over-dependency on biomass (FAO, 2020). In Uganda, the National State of the Environment Report 2016/17 indicated a general decline in natural forest cover but an increase in the area of underplanted trees outside the forest line. This can be attributed to various tree-planting programs which have been promoted in the country (Benin et al., 2007). However, these efforts to plant more trees conflict with the need to expand agricultural land to meet the food requirements of an ever-increasing population, which explains the reduction in global forest cover (Curtis et al., 2018).

With forest areas continuing to shrink and the subsequent increase in agricultural land, fruit tree growing is popularised as a viable option for food security and climate change mitigation. But overall, there is uncertainty on the sequestration potential of many fruit trees (Gauthier, 2013; Nair, 2014), despite their common presence on farmlands, around homes, and more recently, on large farms (Dijkxhoorn, et al., 2019).

As such, options necessary for managing the carbon cycle need to be widened to include non-conventional means that were hitherto not given much attention. One such option is positioning fruit trees in sequestration and ascertaining their potential. The fruit trees provide an alternative to sequestration by forests in addition to meeting the food requirements of communities (McPherson & Sundquist, 2013), and therefore, assessment of the potential of fruit trees under different management options is necessary to allow comparison with stocks of the traditional trees as a starting point for dialogue on their inclusion in carbon trading. In Ngora District, fruit growing has been promoted to ensure food security and combat climate change. The adoption of fruit growing varies across the district depending individual needs of the farmers and land availability. As such, the farm sizes vary, ranging from small holdings comprising a few fruit trees surrounding the homestead to large farms spanning tens of acres of land (Miller et al., 2020; Okullo et al., 2014). The production Department distributed 500,000 orange and mango seedlings in 1919. In the two parishes of Kees and Kumel 204 households had more than 50 citrus trees on their farms (Ngora local government report, 2020, Achuu et al., 2022). This study was hence designed to a) estimate available carbon stocks in the selected fruit trees and b) relate different management practices with carbon stocks of the selected fruit trees in Ngora district, eastern Uganda. This area was purposively selected because it is an exemplar of fruit growing in the country (UBOS, 2015).

2. Methods

Description of the study area

The study was conducted in Ngora district, Eastern Uganda ($1^{o}10'$ to 0^{o} 35′ N and $33^{0}30'$ to 34^{0} 20′E), with a total land area of about 715.9 sq. km (Figure 1). The area's geological formations include rocks formed in the pre-Cambrian era, characterized by undifferentiated gneissic complex formation of the basement system (Uganda Government, 1967). The area is largely underlain by older, wholly granitic, or medium to high-grade metamorphic formations. The major soil units in the area include the Serere and Amuria catena, Meta complex and the Usuk series. These soils are basically ferralitic, with sandy sediments west of the district, and sandy loams in parts of Ngora (Uganda Government, 1967). Specifically, much of the district is covered by petric plinthosols, while vertisols are found northeast of the district, and gleysols are in the west at the border with Soroti. The climate of Ngora is modified equatorial type with rainfall ranging between 800 -1000 mm and a mean annual temperature of up to $24^{0}C$ (NEMA, 2012). Land use/cover types in the area are broadly classified into open water, built-up areas, wetlands, plantations, and tree cover (Akello et al., 2016).

Field data

In January 2020, field data was collected and used to determine available carbon stocks in selected fruit trees. The study area was stratified by plantation type and age. Knowledge of the variation of species, as captured in the district agronomical dataset, was sought to guide the estimation of the number of plots required for the study. Recent records in the district show the total number of citrus and mango farms to be 1309, with differences based on management practices and location. Sampling was done in all the five sub-counties of the district (721.4 km^2)but with different sampling intensities based on the distribution of farms, minimum farm size, species, and accessibility. This area is a tropical grassland dominated by grass with scattered wood trees. The scope of this study was limited to fruit trees (mangoes and Citrus) because it is a government intervention aimed at mitigating climate change at the same time, improving on community welfare. The fruit trees have been integrated and adopted in the agroecosystem. Also, Biomass equations are available only for some dominant commercial tree species (Patil & Kumar, 2017). Previous research has focused on naturally occurring vegetation and agroforestry systems (Montagnini & Nair, 2004). As such, the sequestration potential of other vegetation is known but not for fruit trees (Tobias, 2011).

Samples were selected proportionately using; $n_i = \frac{N_i}{N} * n$ (1)

Where n_i- is the sample to be used; N_i- the population size of each stratum; N - the total population size; and n - the sample size.

Using the above formula, a total of 20 farms (6 mangoes and 14 citruses) were selected, and the number was found to be within the acceptable ranges (Chave et al., 2005; Brown et al., 2007; Sileshi, 2014). Single plots were used in each of the selected farms, owing to the homogenous nature of the plantations.

Biophysical measurements

The 20 farms were identified and on each, transects were set following two diagonal lines on the farm. Circular plots of radius 20m were constructed with the center at the intersection of the transect lines (center of the farm). All trees (study species) falling in the plot and having DBH greater than 5cm were considered for measurement. We focussed on the above-

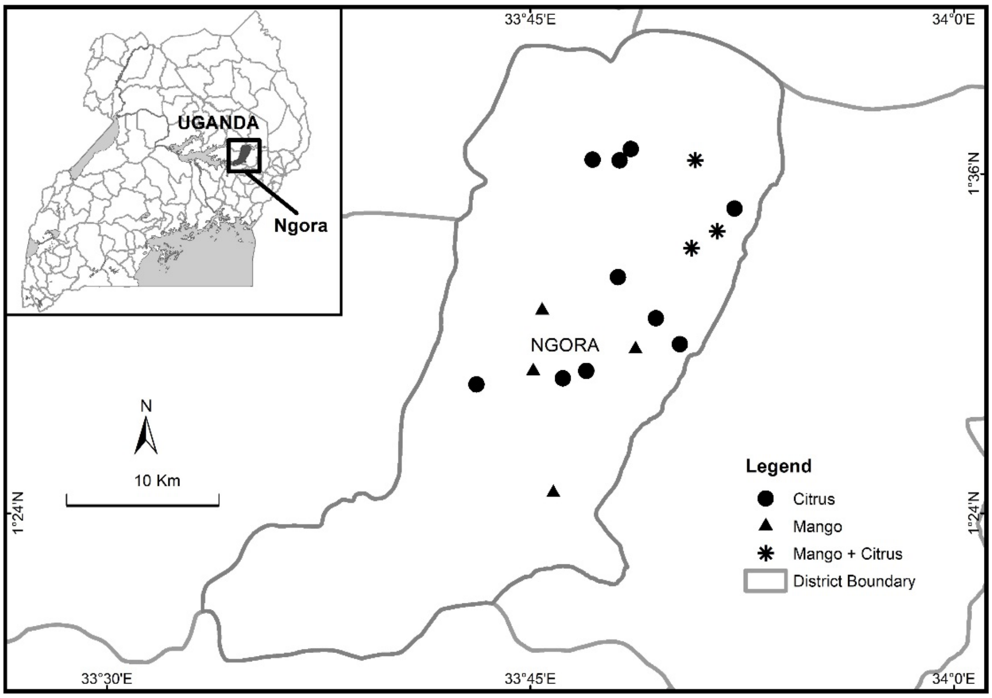

Figure 1. Location of the study area. The dots indicate the location of the fruit farm and its characteristics

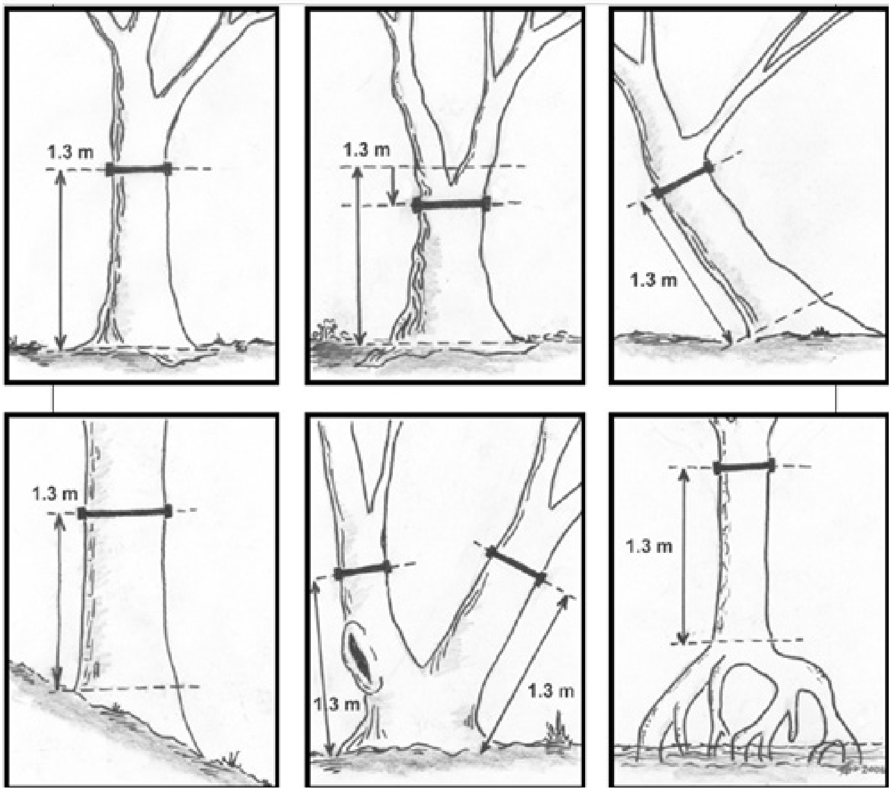

Figure 2. Measurement of DBH for irregularly shaped trees (Pearson et al., 2013)

ground biomass being the largest carbon pool. For each of the trees sampled, data was collected on the height, diameter at breast height (DBF), spacing, and age. Measurement of height was done on standing trees using a graduated stick, while the tree age was provided by farmers. The coordinates of the sampled plots were recorded using a GPS receiver and used to map the sampled points (Figure 1). Also, management practices on the respective farms were documented and the distance between individual trees was measured using a metric tape to determine the cropping density.

DBH measurements were taken at 1.3m from the soil surface; for the trees with multiple stems and branching below 1.3m, individual stem diameters were measured separately (Figure 2), and an equivalent diameter computed using the formula.

$$DBH_{equivalent} = SQRT(\Sigma(DBH_{forked})^2 \quad (2)$$

Estimation of above-ground biomass and carbon stocks

Above-ground biomass for mango was computed using the allometric equation.

$Y = \exp\{-2.134 + 2.530\ln(D)\}$ .... (Eqn 3) (Brown, 1997)

and for Citrus use.

$Y = \exp\{-1.996 + 2.32\ln(D)\}$ .... (Eqn 4) (FAO, 2004).

Where: Y = Aboveground biomass (Kg) and D = diameter at breast height (1.3 m)

Each selected tree's above-ground biomass (AGB) was then used to calculate the total AGB for each plot. The carbon stocks for the plots were consequently computed by multiplying with the biomass to a carbon conversion factor of 0.5 (IPCC, 2003; Chave et al., 2014). The carbon stocks for individual plots were extrapolated to an area (in hectares) using expansion factors based upon the computation of the proportion of a hectare occupied by individual plots (1 ha = 10,000 m^2).

This standardization was intended to allow comparison with related studies.

Data Analysis

Upon completion of the tree properties assessment, an independent t-test was used to test for differences in above-ground carbon stocks between the two species. Descriptive statistics (mean and standard deviation) and regression analysis between dependent variables (biomass) and independent variables (height and DBH) were carried out for individual species and for all the species combined. Also, Analysis of Variance (ANOVA) was used to assess effects of land management practices (independent factor) on carbon stock at a 95% confidence level. This was followed by Tukey's HSD for pairwise comparison. All analyses were done using R, 4.0.1 Statistical Software (R Core Team, 2017).

3. Results and Discussions

Tree growth parameters

The tree growth parameters that were considered in this study included the age of the trees in years, the height of the fruit tree in meters, diameter at breast height (DBH) in meters and the carbon in the fruit trees (ton/ha). The results are presented in table 1. It can be observed that although the average age for the two fruit tree species does not differ so much, there were some noticeable differences in height, DBH and carbon concentrations. Whereas the average height for the citrus trees was 4.32 meters, that of mango trees was 6.46 meters. This indicated a difference in the size of 49% between Citrus and mango trees. In relation to this growth parameter, mango trees were more efficient than citrus trees of the same age in sequestering carbon.

In relation to DBH growth parameter, on average, the citrus trees recorded 9.47m, while mangoes trees recorded an average of 13.49m. This means that mangoes were 42% better than Citrus in relation to this variable. As far as the carbon

Figure 3. Sampled fruit tree species; a) citrus and b) mangoes and measurement of the distance between individual citrus trees (c), and DBH of mango (d).

Table 1. Summary statistics (Mean ± s.e) for the two species

Species	Age (years)	Height (m)	DBH (m)	Distance between trees (m)	Carbon (ton/ha)
Citrus	11.44 ± 0.15	4.32 ± 0.04	9.47 ± 0.3	5.08 ± 0.04	13.52 ± 1.25
Mangoes	11.35 ± 0.14	6.49 ± 0.04	13.49 ± 1.45	6.77 ± 0.03	74.57 ± 14.95

DBH = diameter at breast height

variable is concerned, the citrus fruit trees registered 13.52 tons/ha., while mangoes registered 74.57 tons/ha on average. This means mango fruit trees performed 451% better than citrus fruit trees. It's noticeable that on all growth parameters that were considered in the study, the mango trees performed better than the citrus fruit trees

Increasing carbon stocks with tree age resulted from a combination of increasing DBH and height for both species. Regression analysis confirmed the strong relationship between DBH of the two species and carbon stocks ($R^2 > 0.9$) for both mangoes and Citrus as individual species and for the two species combined on one farm i.e. mixed farms. This is an indication that variability in the carbon stocks is a function of =differences in the DBH (Fig. 3). Citrus with an average height of 4.32m and DBH of 9.47m had a carbon stock of 13.52 ton/ha as compared to mangoes with an average height of 6.49m and DBH of 13.49m having a carbon stock of 74.57 ton/ha (Table 1 and Fig. 3). Further, figure.3 indicates that irrespective of species, carbon stocks increase with an increase in the DBH of the trees.

Comparison of carbon stocks, DBH and height with plantation age

Although the results in table 1 indicated variation in the growth parameters of fruit tree between the two species, an analysis of individual fruit trees between age and growth parameters indicated that there is increasing carbon stocks with tree age ($P < 0.001$), resulted from a combination of increasing DBH and height for both species. Regression analysis confirmed the strong relationship between the DBH of the two species and carbon stocks ($R^2 > 0.9$) for both combined and individual species, an indication that variability in the carbon stocks is mostly explained by differences in the DBH (Fig. 3). This means that the age of fruit trees determines the amount of carbon concentrated. However, this concentration varies between the Citrus and mangoes. The mangoes are more efficient than the citrus fruit trees. The increase in mangoes per year is more exponential than in Citrus. Nonetheless, it is also noticeable that tree age has a significant relationship with the amount of carbon sequestered (Figure 4), especially in mango trees. The increase for Citrus is not significant after the age of 10 years.

Relationship between carbon and management practices

The management practices identified in this study included; use of inorganic fertilization, intercropping, mono-cropping, organic fertilization and irrigation. Of these, only monocropping and intercropping applied to mango farms, while all five applied to orange/citrus farms. A note must be taken that the Intercrop here means fruit trees with other crops. Results of ANOVA coupled with Turkey's HSD test indicate that management practices have a significant effect on carbon stocks ($P<0.05$). The level of significance is indicated by the letter (*a, b, c*) as indicated by the THSD test at 5% confidence level (Table 2). The management practices with the highest carbon stocks for

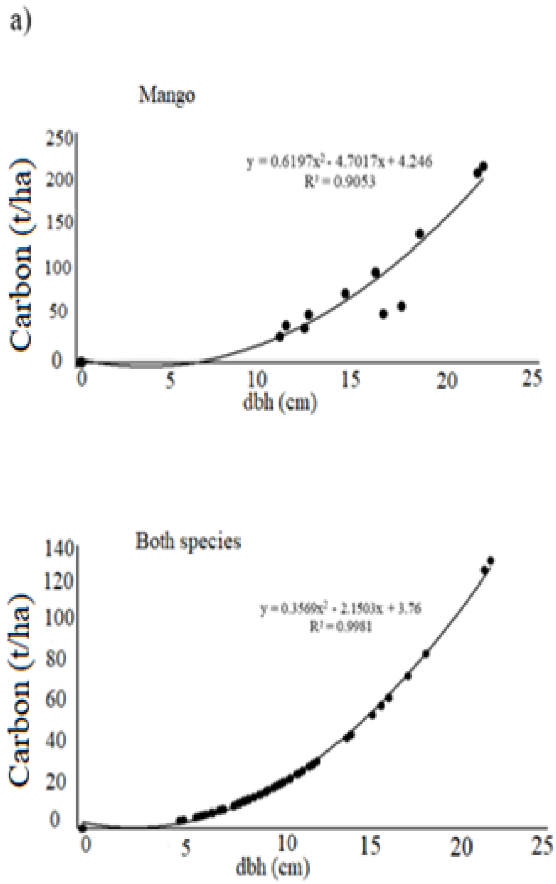

Figure 3. Bivariate relationships between carbon and DBH

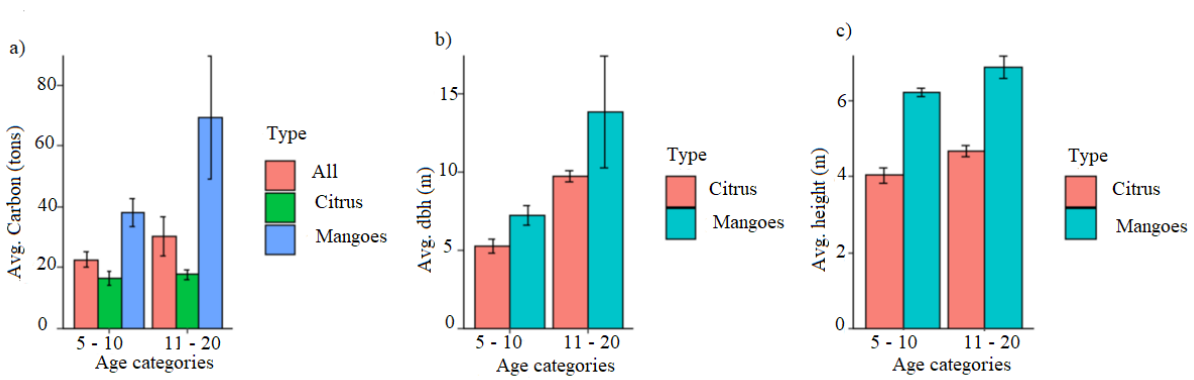

Figure 4. Carbon estimates (a), average DBH (b) and average height (c) by tree age categories among Citrus & mangoes.

Table 2: Results of one-way analysis of variance (ANOVA) with Tukey's HSD test for management practices (Mean±se) for the different species.

Management practices	Citrus	Mangoes
Inorganic fertilizer	20.21 ± 6.98ᵃ	-
Intercrop	13.53 ± 1.89ᵇ	134.41 ± 34.36ᵃ
Intercrop and inorganic fertilizer	10.6 ± 3.39ᶜ	-
Monocrop	13.49 ± 2.13ᵇ	49.64 ± 9.45ᵇ
Organic fertilizer and irrigation	10.74 ± 2.81ᶜ	-

***Notes**: Different management practices with different letters (a, b, c) in the same column indicate significant differences at 5%.*

Citrus are; inorganic fertilizer (letter a), followed by Intercrop (letter b), and lastly, organic fertilizer and irrigation (letter c). Of the two management practices found under mangoes, Intercrop had the highest carbon stocks (letter a) as compared to monochrome (letter b). There is a statistical difference between Intercrop and monocrop in citrus trees. Relatedly, there exists no significant difference between Intercrop and inorganic fertilizer and organic fertilizer and irrigation. As such, overall, inorganic fertilizer and Intercrop yielded the highest carbon stocks for both species (20.21 ± 6.98[a] and 134.41 ± 34.36[a]) for Citrus and mangoes, respectively.

The estimation of the above-ground biomass in the selected fruit tree species was performed based on estimates derived using tree growth parameters, i.e., tree height, DBH, and age. These were used to determine carbon in the fruit trees.

Tree growth parameters

Sequestration by plants is a factor of tree height, age, and diameter at breast height (Chavan & Rasal, 2012). This is so because tree store carbon in the trunks, foliage, branches, roots, and soil. The results from this study indicated a general increase in both diameter and height with age for both species, although it was higher for mango. (Figure 2). These findings are broadly consistent with Janiola & Marin (2016) and Pandya et al. (2013), who reported increasing photosynthetic activity in trees with age and, consequently, higher biomass accumulation. As the diameter of species increases with an increase in age, its biomass and carbon storage capacity increase, which also enhances carbon sequestration. Patil & Kumar (2017) further notes that mature tree sequesters more carbon since as the tree grows, there is more activity in the flowers, barks, twigs, fruits, stems, etc. The differences in species can be explained in part by tree spacing. Mangoes are often widely spaced, arguably due to their growth form. The wider spacing allows for better use of plant nutrients, water, and light (Gaikwad et al., 2017). The difference between Citrus and mango can also be explained by the growth pattern of Citrus, which tends to cease increasing in height but rather a canopy density, as noted earlier by (Liguori et al., 2009).

Carbon estimates of the two species

The allometric equations used in this study to compute carbon stocks showed varying amounts across the farms. This could be due to factors related to morphology and site productivity. Although functional trait differences of tree species are documented in community ecology, the effects of such differences on stand level carbon stocks, is rarely emphasized. The higher carbon stocks observed in mango farms as compared to Citrus can be explained by higher tree height and diameter ranges as compared to Citrus (Tom-Dery et al., 2015). This finding is in agreement with (Patil & Kumar, 2017), who reported mango as having higher carbon stocks. This, he attributed to the relatively wider tree canopy of the mango trees. Overall, the carbon stocks of the fruit trees were lower than that reported for other forest trees. This can be attributed to the fact that forest trees have wider diameter ranges which greatly relates with total stocks (Kongsager et al., 2013). Further, fruit trees are pruned and harvested periodically, which lowers their biomass and, consequently, carbon stocks (Wu. Et al., 2012). Pruning is regularly performed in a bid to remove weak branches but also to enhance productivity. In similar studies, Janiola & Marin (2017) reported lower mango stocks of 47.61 t/ha, but higher stocks of 77.14 t/ha were reported in Karnataka and 91.197t/ha in Gujarat (Ganeshamurthy et al., 2019). The stocks are, however generally low when compared to those of wild mangoes that can grow up to a height of 45m besides having slender and erect stems (Chavan & Rasel, 2012).The stocks in Citrus were also considerably lower than those reported for other forest species because citrus trees are generally small to medium trees (Scandellari et al., 2016). The study area is also frequently subjected to prolonged drought which is a limiting factor on biomass production (UBOS, 2015).

Effects of management practices on above-ground carbon stocks

The management of agricultural soils has been fronted as a partial solution to global climate change (Wairau, 2017). The practices adopted to improve tree growth and productivity in turn, influence carbon storage in the trees. The extent of carbon stored is influenced by several land management practices, including management of plant residue, manure usage, and fertilizer application (FAO, 2004; Nair et al., 2010). Because of the cost, different management practices are often adopted for better management of land. The decision is also dependent on the amount of risk and profitability of the practice, needed level of investment and any incentives for the use of the practice but with varying impacts on carbon storage. This study indicates that there is a significant relationship between carbon stocks in fruit trees and management practices. The sequence of carbon stocks under different management practices was intercrop and inorganic fertilizer < Organic fertilizer and irrigation < monocrop < Intercrop < Inorganic fertilizer. For the citrus farms, carbon stocks were highest where inorganic fertilizer had been applied. A possible explanation for this could be that the application of chemical fertilizers avails nitrogen to the soil, a useful element to crops (Robertson et al., 2007).

Additionally, intercropping was associated with higher carbon stocks as compared to monochrome, especially in mango trees. The large spacing in intercrop farms could be the reason for this outcome as farmers want to utilize the land for food crop growing. Although not statistically significant, the carbon stocks for Citrus under monochrome and Intercrop, a visual examination for the means of carbon stocks shows a slight advantage for Intercrop over monocrop. This finding is in agreement with the study done by (Jacobi et al., 2014), who found out that mixed cocoa farms had higher carbon stocks than mono crop. In relation to earlier findings, , the higher stocks in intercropped farms in comparison to monocrop, especially in the mango farms, can be attributed to several benefits associated with a diversity of crops on intercropped farms. The different crops contribute unique root structures and residues to the soil, and the diversity of soil organisms created helps to control pest populations and reduce weed pressures (Martin-Guay et al., 2018, Jacobi et al., 2014)). The findings provide support to the conceptual premise that management practices impact the rates of carbon storage (Kane & Solutions, 2015, Okullo et al., 2014; Patil & Kumar, 2017)) and this would go a long way to mitigate climate change. Since some plant resources are adapted to given environments, there is needed to further interrogate management practices that can increase carbon reserves in different landscapes.

The study found no farmers using fertilizers and irrigation for mango trees (Table 2). The possible reason for the reluctance of farmers to apply fertilizers to mangoes is the leafy nature of mango trees that ensures sufficient natural mulch and leaf litter, which decomposes into organic matter for the soil. This finding is in agreement with a study conducted by (Bentley et al., 2004), who found farmers applying no fertilizer and pesticide on leafy trees like mangoes in Bahia, Brazil. Hammad et al. (2020) also note in his study conducted in the arid region of Pakistan that mango orchards need less irrigation. Hence, for farmers who can't afford to buy fertilizers and irrigation equipment, mango trees are a better choice.

4. Conclusion

The study revealed that fruit trees are an important carbon pool. Fruit tree growing may hence be a viable alternative for future mitigation agreements under a revised Clean Development Mechanism. In so doing, the fruit farmers would earn carbon credits, consequently improving their income. It has been shown that fruit trees sequester substantial amounts of carbon, which is quite comparable to forest stocks. Besides, fruit plantations also provide both fruits and firewood, thus reducing pressure on forests and improving farmers' livelihoods and food security. There is a need to encourage more communities to plant fruits either as monocultures or as a component of agroforestry. However, intercropping should be encouraged more since it yielded higher carbon stocks and allows farmers to grow food crops alongside fruit trees, ensuring food security and resilience to climate change impacts. It is also necessary that we obtain information on the carbon stocks of the study species in other regions of the country to facilitate comparison. Attempts should also be made to disseminate findings on the contribution of fruit trees, particularly mangoes and Citrus to carbon sequestration and used to claim carbon credits. The country needs further research to identify preferred fruit tree species for maximum sequestration potential. The study further revealed that maximum stocks could be harnessed from the fruit trees irrespective of the management practice. A comprehensive study based on destructive methods is also needed to be able to develop area or country-specific allometric equations, which can be used to facilitate studies in other parts of the country.

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