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Quantifying the Carbon Potential of Carbon Capture Cubes in Kenya

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ABSTRACT

As climate change intensifies, African nations, despite contributing minimally to global greenhouse gas emissions, bear the brunt of its devastating consequences. To improve the resilience of these countries against climate change while reducing atmospheric carbon dioxide concentrations, we can adopt carbon capture cubes. Carbon capture cubes merges agroforestry and biochar to enhance crop yields in arid regions while sequestering carbon for long-term storage. Artificial intelligence (AI) is implemented for better monitoring of the cubes' conditions, but we lack the methodology to use AI to assess the carbon sinking potential of these integrated practices. Tracking the amount of carbon sequestered from carbon capture cubes would allow us to better support farmers in vulnerable regions to climate change and enable farmers to benefit from carbon offset programs. This research focuses on developing a method to calculate the carbon potential of farms in Kenya employing carbon capture cubes. To establish the baseline carbon stock of farms, spatial data from the Innovative Solutions for Decision Agriculture Ltd. (iSDA) and Food and Agriculture Organization of the United Nations (FAO)'s Water Productivity through Open access of remotely sensed derived data (WaPOR), To determine the carbon increase of agroforestry, relevant literature was referenced to calculate the carbon content of three trees grown in Kenya: *Grevillea robusta*, *Azadirachta indica*, and *Persea americana*. As for biochar, carbon inputs from biochar were calculated based on feedstock readily available in Kenya by using established conversion factors. The outcome is a basic web app calculator for assessing the carbon potential of a carbon capture cube.

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Chapter 1

Introduction

Climate Change and Sub-Saharan Africa

As climate change intensifies, African nations, despite contributing minimally to global greenhouse gas emissions, bear the brunt of its devastating consequences. To improve the resilience of these countries against climate change while reducing atmospheric carbon dioxide concentrations, countries must utilize biological carbon sequestration practices. Climate change is attributed to greenhouse gas (GHG) emissions, the majority of which come from anthropogenic sources. Carbon dioxide is one of these gases, with levels of 412 parts per million in the atmosphere (Buis, 2019). While the common direction being taken is to decrease emissions, it is necessary to also remove GHGs from the atmosphere to reverse the effects of climate change. The rate at which climate change worsens necessitates expedient solutions. Established, biological-based practices are easier to adopt in comparison to coming solutions, such as direct air capture. Especially as countries with high climate risk are often facing additional economic troubles, promoting accessible solutions alleviates part of their burdens.

Sub-Saharan Africa is considered one of the most susceptible regions to climate change. Poverty and the lack of resources in the region creates an environment where it is difficult to adapt to the changing climate (Ofori et al., 2021). With increasing frequency of droughts, land degradation in the region intensifies. As a result, smallholder farmers within the region are negatively impacted by the lack of arable land to support their livelihoods. Due to how valuable land is, land degradation exacerbates community conflict, with increased land grabbing (Deen-Swarray et al., 2020). Crop production and livestock in the region has and is expected to suffer in the region as climate change worsens. By 2050, it is possible that growing periods in Western and Southern Africa would decrease by 20% (Ofori et al., 2021). Due to the region's sensitivity to climate change, it is crucial to provide the necessary adaptation tools to support Sub-Saharan Africa. In 2020, there was an estimated 110.8 million farms in Sub-Saharan Africa, with an average farm size of 9.2 hectares (Erenstein et al., 2021). With the region's reliance on agriculture to support much of their rural population's livelihoods, we must implement practices that can improve the resilience of farms while counteracting the effects of climate change.

Artificial Carbon Sequestration

Carbon sequestration is the process of removing carbon dioxide from the atmosphere and moving it into stable storage, such as forests, soil, and the ocean. The process has been done biologically, but with the urgency of the climate crisis, artificial methods have been in development. Three of these methods include bioenergy with carbon capture and storage (BECCS), direct air capture, and enhanced weathering. While the research into each of these methods is valuable in addressing the excess amount of carbon dioxide in the atmosphere, each have their own drawbacks and divert attention away from implementing timely and effective means of carbon sequestration.

BECCS stores carbon in geological sinks while generating energy from biomass. BECCS is often portrayed in climate mitigation models due to its potential in decreasing emissions as well as offsetting carbon emissions in sectors such as transportation by providing bioenergy as fuel (Creutzig et al., 2014). However, BECCS faces a problem that all other biomass-based mitigation strategies face, which is land use change. To support bioenergy development, lands in tropical regions of the world must be utilized as 84% of available arable land is located there (Rhodes & Keith, 2008). However, this would force developing countries within this region to sacrifice food production for the sake of biomass production, raising ethical issues.

Another form of artificial carbon sequestration being considered in climate change mitigation is direct air capture. There are various methods of direct air capture but the two methods with the most development are liquid solvent and solid sorbent direct air capture (McQueen et al., 2021). In the case of solid sorbent direct air capture, carbon dioxide molecules bind to the surface of a solid sorbent, removing it from the atmosphere. As for liquid solvent direct air capture, carbon dioxide gas binds to a liquid solvent, taking carbon dioxide out of the atmosphere and trapping it in a liquid form. The main drawback to these methods is the need for large quantities steel and concrete when constructing direct air capture plants (McQueen et al., 2021). In addition to those materials, solid sorbent direct air capture faces problems in terms of disposal of solid sorbents at the end of their life. The solid sorbent direct air capture process would result in 10 to 46 g of carbon dioxide emissions per kg of carbon dioxide captured, depending on the type of solid sorbent used (McQueen et al., 2021). As for liquid solvent direct air capture, Smith (2016) claims that it can require moderate to high water use, with 10 to 300 km^3 used per year.

Enhanced weathering is another method of atmospheric carbon removal. This method focuses on a natural aspect of the global carbon cycle, where about 1.1 Gt of carbon dioxide is removed from the atmosphere during the weathering of silicate and carbonate rocks, later being stored as bicarbonate in the ocean (Strefler et al., 2018). By accelerating this weathering process, more carbon dioxide could be removed. enhanced weathering involves grinding rocks into grains to increase specific surface area and spreading them over warm and humid regions so that they dissolve with the help of water and carbon dioxide (Strefler et al., 2018). After the rocks are dissolved, they would be washed away and deposited into the ocean, where it will be stored (Strefler et al., 2018). The main concern with enhanced weathering is the type of rock used for weathering. Dunite rock has a high weathering efficiency due to the presence of olivine, but as olivine contains toxic elements such as nickel and chromium, it can present a potential environmental risk (Strefler et al., 2018). Though the exploration of alternatives, such as basalt, which is less efficient but has less hazardous elements, could address this issue (Strefler et al., 2018). While each of these methods are valuable to research for future carbon sequestration efforts, biological carbon sequestration is a method proven to work that can provide additional services in its implementation today.

Agroforestry

Agroforestry, the integration of trees in an agricultural system, promotes the storage of terrestrial carbon. Trees sequester carbon dioxide through photosynthesis, reallocating carbon into sugar used for growing woody biomass. The carbon is then permanently stored until the tree dies or is cut down. Agroforestry provides additional benefits apart from sinking carbon. For areas suffering from soil erosion, growing trees in between crops or around fields can increase the stability of soil through their roots. The trees themselves also act as a wind barrier, decreasing the amount of soil displacement due to high winds. With decreased erosion, the soil structure necessary to support crops would be protected from intense rainfall and wind events. Additionally, trees provide shade for crops, lowering the water demand for plants.

Countries with large arid regions, such as Kenya, can greatly benefit from integrating agroforestry into their farming systems, especially as climate change increases the length and severity of droughts in the area. Depending on the type of trees used, it can also act as another source of income for farmers. For instance, farmers can sell fruit from trees such as avocado trees, a common tree used in agroforestry. This benefit would especially aid farmers in regions who suffer from economic hardships.

Biochar

Biochar is a soil amendment used in improving soil fertility that can also act as a stable carbon sink. By burning organic material, in a process called pyrolysis, into a charcoal-like state, it transforms the carbon from the feedstock into a more stable form called biochar. Lehmann (2009) explains that during the creation of biochar, while 75% of the biomass weight is lost during the process, through the loss of oxygen and hydrogen, the concentration of carbon is doubled in the final product.

Biochar production itself promotes the usage of organic waste which may otherwise be thrown away, while improving soil conditions for crops. For example, wood-based feedstocks resulted in biochar with more specific surface area, while “Crop-, grass-, and manures/biosolids-based feedstocks led to biochar containing elevated cation exchange capacity (CEC) (Ippolito et al., 2020). While CEC does not hold great importance in carbon sequestration, a high CEC is valuable in nutrient retention. On the other hand, a higher specific surface area correlates with a greater water holding capacity. In addition, high specific surface area plays an important role in the bioavailability of chemicals. Due to this, biochar can sorb herbicides and pesticides, preventing their spread throughout the environment (Sarmah et al., 2010). Similarly to agroforestry, biochar production can provide a secondary source of income for farmers. Due to biochar's beneficial properties for crops and simple creation process, farmers can easily use their excess organic waste to create biochar to sell to other farmers.

Carbon Capture Cubes

Carbon capture cubes improve crop yield and carbon sequestration to address poverty in Africa. Carbon capture cubes combine agroforestry, biochar, and mycorrhizal fungi to improve soil quality and crop production while sinking carbon. For this paper, the carbon inputs of fungi will not be explored.

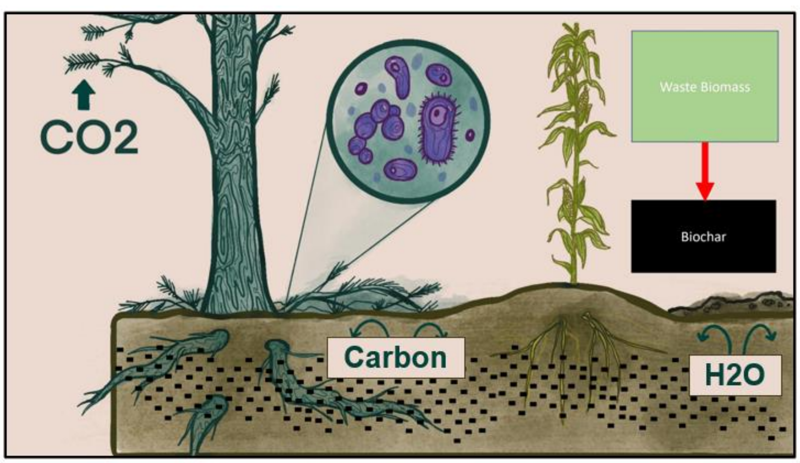

Figure 1 Illustration of a carbon capture cube and its practices (PlantVillage, 2023).

The idea of carbon capture cubes was created as part of PlantVillage's efforts to support African smallholder farmers as the region faces the effects of climate change. Sub-Saharan Africa has 33 million smallholder farms, which represents 80% of all farms in the region (Jayaram et al., 2013). In some countries, smallholder farms make up 90% of their food production (Jayaram et al., 2013). With how reliant countries are on smallholder farms, ensuring that these farms can adapt to climate change is necessary in supporting the 1.21 billion people living in Sub-Saharan Africa (O' Neill, 2024). Carbon capture cubes allow smallholder farmers to be self-sustaining and resilient against climate change.

For carbon capture cubes to be successful, it must consider the resources and conditions of the location. In the case of the agroforestry element of the cube, there is an important lesson we can learn from failed large scale tree planting projects. Merely planting trees is not enough, as only through their survival can carbon be sequestered effectively. As trees grow, their carbon sequestering capacity increases. Failed large tree planting projects often results from neglect, such as in the case of the UK's National Highways where 75% of 850,000 saplings planted alongside the highway have died during development (Heap, 2023). Integrating trees into agricultural spaces provides services to the farmers and in return trees are more likely to be maintained for years to come. Failed projects also focus more on the quantity rather than the quality of the tree. Certain trees work best under certain conditions and if that were to be ignored, either the tree's chances of survival would be slimmer, or the present environment would be harmed by the tree's introduction. This can be said in the case of Yatir Forest where short-lived nonnative pine trees are planted and expected to die within twenty to thirty years (Glausiusz, 2023). When choosing trees to plant in cubes, qualities such as drought tolerance and lifespan must be considered based on the needs of the location and the farmer.

The kinds of biochar made and used will also be location specific. The feedstock used for biochar would be sourced from the local farms' common crop waste. An additional factor to consider is the availability of each feedstock based on their preexisting uses by farmers, such as for animal fodder or mulch. Referencing these values will assume that the farmer does not need to change their current behavior to produce biochar, underscoring the ease of adoption for biochar practices. Biochar feedstock can also be sourced from surrounding vegetation. Prioritizing invasive species as biochar feedstock would provide the additional benefit of population control.

Carbon capture cubes also provide farmers an additional source of income through carbon offset schemes. However, this is only possible with proper tracking of carbon inputs based on the soil properties, trees, biochar, and crops specific to the cube. In its final product, AI would be used to monitor the conditions of the cube, but a methodology must be developed so that assessing carbon potential of the practices can be automated. This research develops a basic framework for understanding the current carbon stock of a farm and the additional carbon inputs through the advent of the carbon capture cube.

Chapter 2

Methods

Baseline Carbon Stock

Having a baseline measurement of a farm's carbon stock allows us to understand the net impact carbon capture cubes can have to the farm. To determine the soil organic carbon (SOC) stock of farms, the project referenced Equation 1.

Equation 1 Soil organic carbon stock

$$SOC_{stock} = SOC\% \times \rho b \times d \times \left(1 - \frac{GC}{100}\right)$$

SOC_{stock} is the total SOC stock in tons per hectare, SOC% is the SOC content of the soil, ρb is the bulk density of the soil in grams per cubic centimeter, d is the sampling depth in centimeters, and GC is the stone content in percent (Yigini et al., 2017).

When testing the equation, farm soil data from PlantVillage's Ag Observatory was referenced. The soil data from the Ag Observatory uses soil spatial data from iSDAsoil, a field level soil map for Africa. The map utilizes machine learning and 130,000 soil samples to generate the soil properties of the continent. By inserting the coordinates of the site of interest, the soil properties of the area would be given. Figure 2 shows the iSDAsoil map interface for an area of interest.

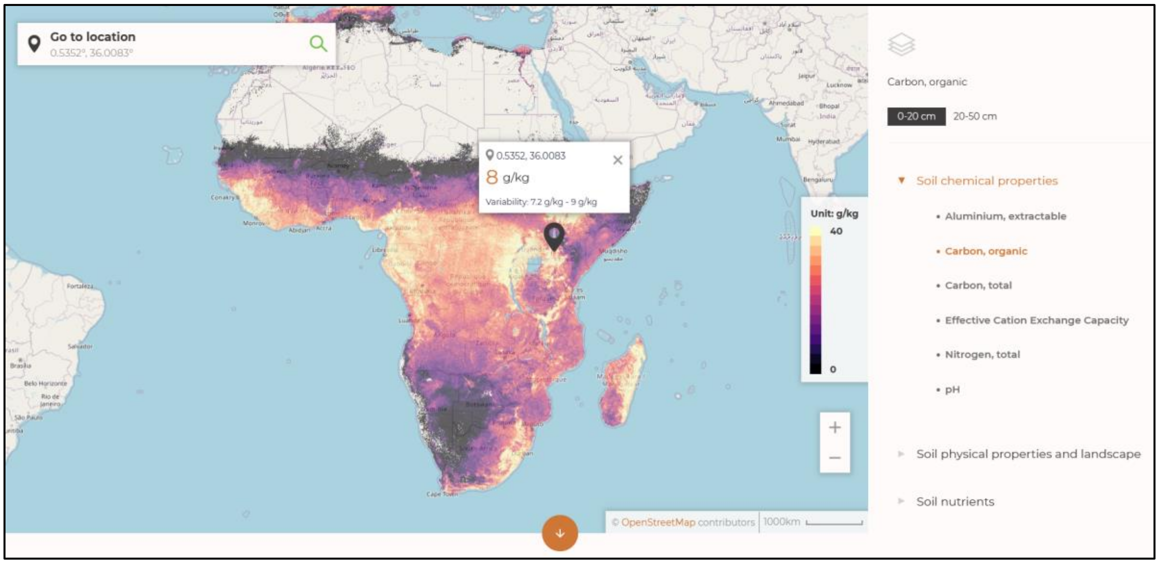

Figure 2 iSDAsoil map interface used to obtain soil properties data (iSDAsoil, 2024).

While in-person soil testing remains the most accurate method for evaluating the properties of a specific farm, iSDAsoil provides a readily available estimate of the area's conditions. For the purposes of this research, a rough estimate suffices for testing the methodology of the equation. The usage of soil spatial data also makes it possible to automate the SOC calculation process for multiple locations through using its API. Table 1 provides the soil property values for an area of interest.

Table 1. Soil property values derived from test site (0.5352°, 36.0083°) (iSDAsoil, 2023).

Variables	Soil Depth	
	0-20 cm	**20-50 cm**
Organic Carbon (g/kg) or (ppm)	8.00	5.70
Organic Carbon (%)	0.80	0.57
Bulk Density (g/cm^3)	1.30	1.32
Stone (%)	2.70	3.10
Organic Carbon Stock (t/ha)	20.24	21.87
Total Organic Carbon Stock (t/ha)	42.11	
Area (ha)	0.45	
TOTAL (ton)	19.04	

Based on a test site location in Baringo, Kenya the following properties are given: organic carbon (g/kg), bulk density g/cm^3, and stone content (%). Assuming the farm area to be 0.45 ha, the final soil carbon stock is 19.04 tons.

In addition to the SOC stock, we must consider the aboveground carbon from plants such as trees and shrubs. To do so the research used FAO's WaPOR, a map of water productivity throughout Africa to obtain the location's NPP. Using the same coordinates from before, and using a year time period from July 31st, 2022 to July 31st, 2023, Figure 3 shows the values WaPOR returns, where the average NPP value in a year is 1.60 gC/m^2/day.

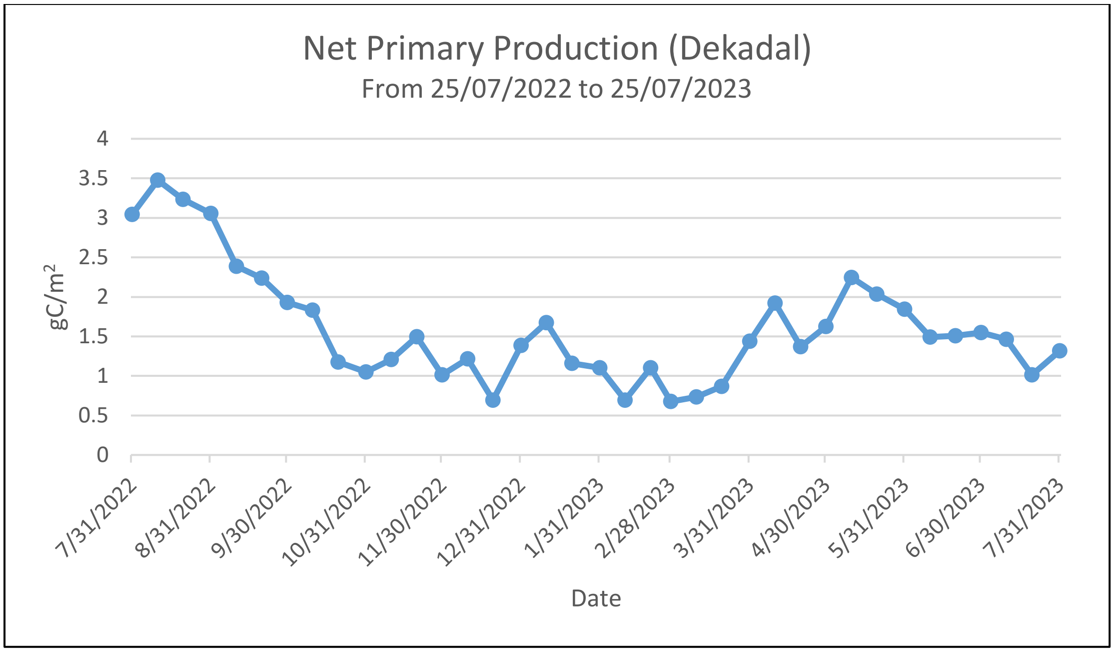

Figure 3 Dekadal net primary production values for test site (0.5352°, 36.0083°) (FAO, 2018).

The NPP value is converted to ton/ha/year and when considering the 0.45 ha farm, the total aboveground carbon is 2.90 tons. When adding the two values together, the total baseline carbon stock of the farm is 21.94 tons.

Agroforestry Calculations

To determine the potential carbon inputs from integrating trees to a farm, the allometric equation of the tree species must be used to find its biomass. As established previously, prioritizing tree species that can withstand the conditions of the area is crucial for its survival and subsequent carbon sequestration. A native tree species of the area that will be used for this purpose is the *Grevillea robusta* tree, also known as silk oak. Unlike other trees, silk oak does not lead to increased competition with the crops. This is due to how silk oak's roots are distributed, located deeper than the crop rooting zone (Lott et al., 2000). The biomass of silk oak was calculated, according to Equation 2.

Equation 2 *Grevillea robusta* allometric equation

$$TTB_G = 1.811(DBH_G)^{1.658}$$

TTB_G is the total tree biomass (kg) for silk oak and DBH_G is the diameter at breast height, assumed at 20 cm for the purpose of this paper (Owate et al., 2018). Based on this DBH, the TTB for one tree would be 260.03 kg. To convert the biomass into carbon, the conversion factor of 0.49 is used, which is the estimated carbon content for tropical trees (Thomas et al., 2012). In this paper, all tree species used for agroforestry will use the same conversion factor. This results in a final 127.42 kg or 0.14 tons of carbon per tree. For the purposes of the paper, the silk oak tree would act as a rough estimate for other native trees in the area.

Another common tree species in Kenya is the *Azadirachta indica* tree, otherwise known as neem. Neem is an evergreen tree native to India, Pakistan, and Myanmar, but is also present in African countries such as Kenya (Valery et al., 2023). Neem is often incorporated in agriculture by supplying shade for livestock, acting as a windbreak, and providing a natural pesticide for farmers. The total biomass of neem is calculated according to Equation 3.

Equation 3 *Azadirachta indica* allometric equation.

$$TTB_A = e^{-0.4568+1.6733\ln(DBH_A)}$$

TTB_A is the total tree biomass (kg) for neem and DBH_A is the diameter at breast height (Valery et al., 2023).

Another tree of interest is the avocado tree, which can operate as an additional source of income for farmers through its fruits. The *Persea americana* tree would be used, as it is one of the popular fruit trees planted by smallholder farmers in Kenya (Kuyah et al., 2024). The aboveground biomass would be calculated according to Equation 4.

Equation 4 *Persea americana* allometric equation

$$AGB = 0.0638 \times DBH^{2.5435}$$

where AGB is the aboveground biomass of the tree (kg) and DBH is the diameter at breast height (Kuyah et al., 2024). It is important to note that this equation only gives the aboveground biomass rather than the total tree biomass. Therefore, the amount of carbon would be underestimated without the carbon inputs from the belowground biomass.

To understand how long it would take for each tree species to produce a certain amount of carbon, a species' growth model with respect to the tree's DBH and age must be considered. Growth rate can vary based on species and location. Data derived from locations near Kenya or with similar climates would improve the accuracy of the assessment. Figure 4 shows the growth rate of G. robusta grown in Nandi County, Kenya (Cheruiyot, 2015).

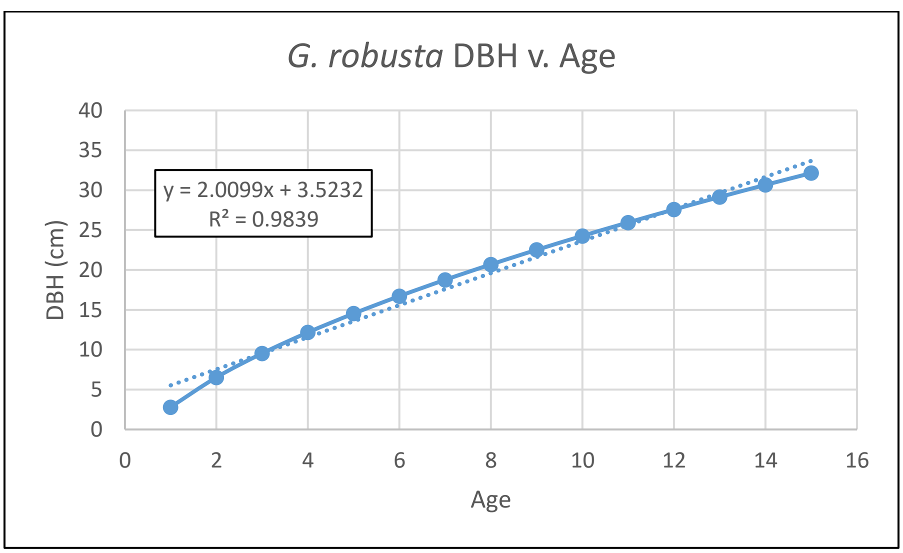

Figure 4 Grevillea robusta DBH vs. age (Cheruiyot, 2015)

The data for neem was collected in several regions in India, using forty plantations as samples for five age groups ranging from six to ten years of age (Rizvi et al., 2012). The equation for DBH vs. age in *Azadirachta indica* is seen in Figure 5.

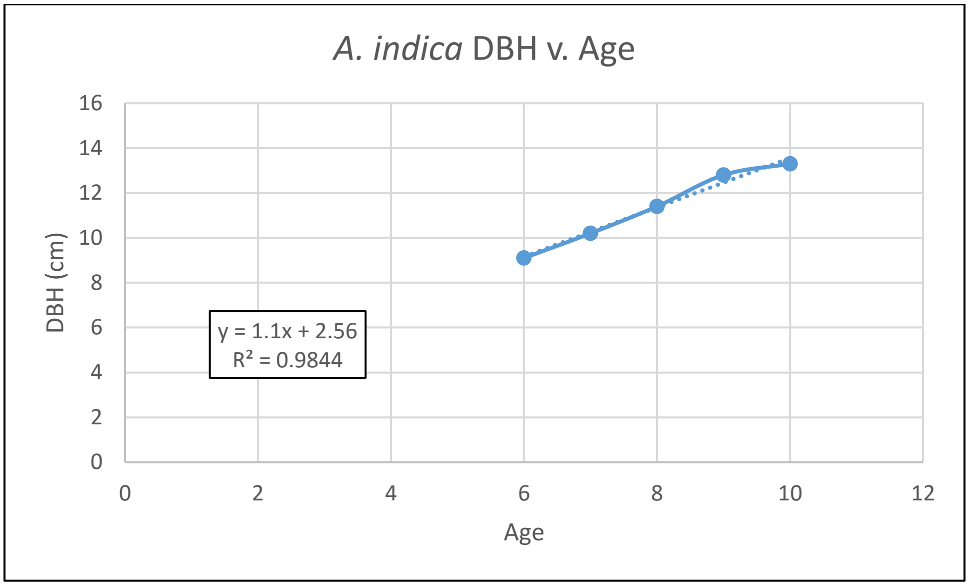

Figure 5 *Azadirachta indica* DBH vs. age (Rizvi et al., 2012)

With the limited number of age groups covered in the study, as well as the difference in region, the equation would not be completely accurate to neem grown in Kenya.

For the avocado tree, data was derived from Arraiján, Panama for a sample size of forty trees, ten for each age group: ten, fifteen, twenty, and twenty-five years old (Corella et al., 2022). *Persea americana's* growth rate for the region can be seen in Figure 6.

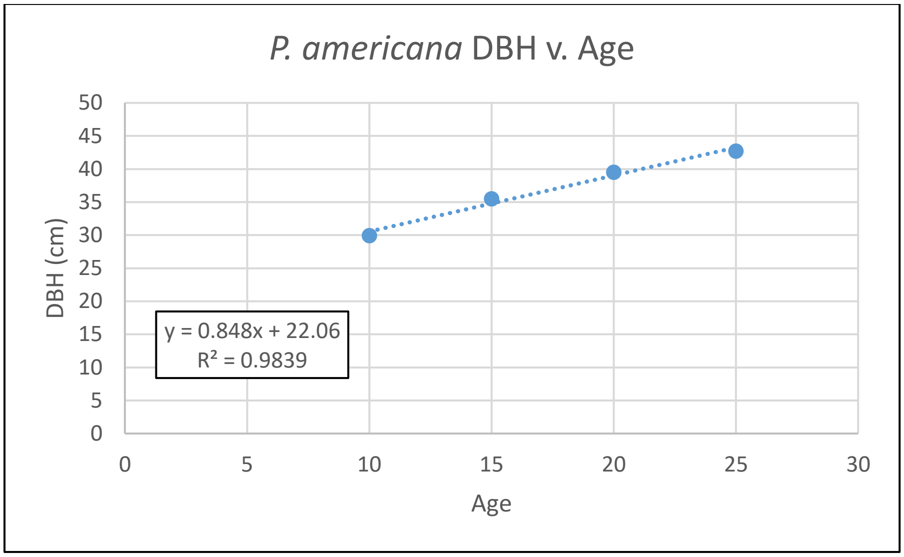

Figure 6 *Persea americana* DBH vs. age (Corella et al., 2022)

As the climate of Panama is unlike that of Kenya, as well as the smaller selection of ages, the estimated growth rate for *Persea americana* will not be as representative of avocado trees grown in Kenya.

Biochar Calculations

The amount of carbon generated by biochar is dependent on the type of feedstock used, such as the crop species and the part of the crop. Common sources of feedstock produced in the region include maize, sorghum, rice, and groundnuts. As crop residues are used for other purposes on the farm, considering their variations in availability for biochar production allows for a more accurate estimate of carbon sinkage.

Table 2 Conversion factors of different feedstocks (Roobroeck et al., 2019).

Crop Residue	Availability (%)	Biochar (%)	Fixed Carbon in Biochar (%)
Maize Straw	39.00	32.54	59.93
Maize Cob	100.00	26.05	85.75
Sorghum Straw	60.00	36.90	51.00
Rice Husks	88.00	44.45	46.96
Rice Straw	52.00	35.13	40.91
Groundnut Shells	95.0	32.00	72.90

The availability of each feedstock would be multiplied by the total crop residue produced by the farm. The final carbon amount generated by each feedstock is calculated according to Equation 5.

Equation 5 Fixed carbon stock of feedstocks.

$$C_B = R \times A \times B \times FC$$

C_B is the carbon produced from the feedstock, R is the residue amount, A is the availability for biochar, B is the biochar conversion rate, and FC is the fixed carbon conversion rate. With a known amount of crop residue produced for one of these six feedstocks, the carbon amount can be determined. In the final total carbon stock, the paper assumes that all biochar generated by the farm will be put into the soil.

Another source of feedstocks is the invasive species *Prosopsis juliflora*, also known as mesquite. Mesquite can cause harmful allergic reactions and asthma while also increasing the incidence of malaria by providing food to mosquitos (Hussain et al., 2020). One way to control the population of mesquite is to encourage its usage in biochar production. To quantify the carbon inputs of mesquite, Equation 6 was used.

Equation 6 *Prosopsis juliflora* biochar to carbon.

$$C_p = Q \times C_{org} \times Con$$

C_p is the amount of carbon sequestered, Q is the quantity of mesquite, C_{org} is the organic carbon content of mesquite, which is 50.43%, and Con is the conversion of gigatons of carbon to carbon dioxide, which is 3.664 (Biochar Life, 2022). For this paper, all final carbon amounts are converted to U.S. tons.

Chapter 3

Results and Future Studies

Web Application Results

To make the process of calculating the carbon stock of a farm more streamlined, a web application was developed using Python. From the user's end, the only information needed are the coordinates and area of the location, the species and number of trees, and the type and amount of feedstock generated by the farm. After inputting the information, the web application generates charts based on the given data. The user can view how much carbon would be added to the location and compare it to the baseline carbon stock. The interface for each calculation can be seen in Figure 7, Figure 8, Figure 9, Figure 10, and Figure 11.

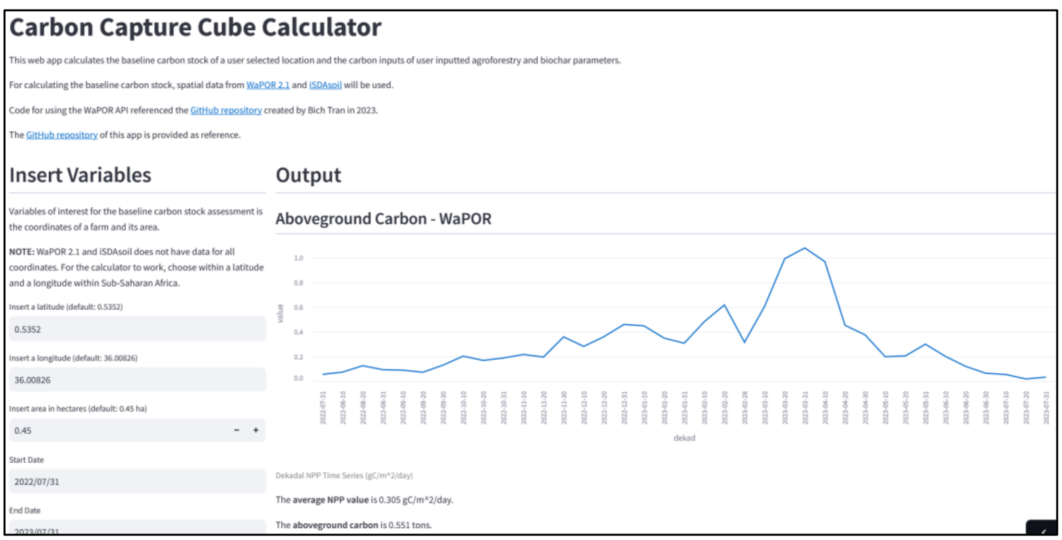

Figure 7 User interface of the carbon capture cube calculator for aboveground carbon.

Figure 8 User interface of the carbon capture cube calculator for soil organic carbon.

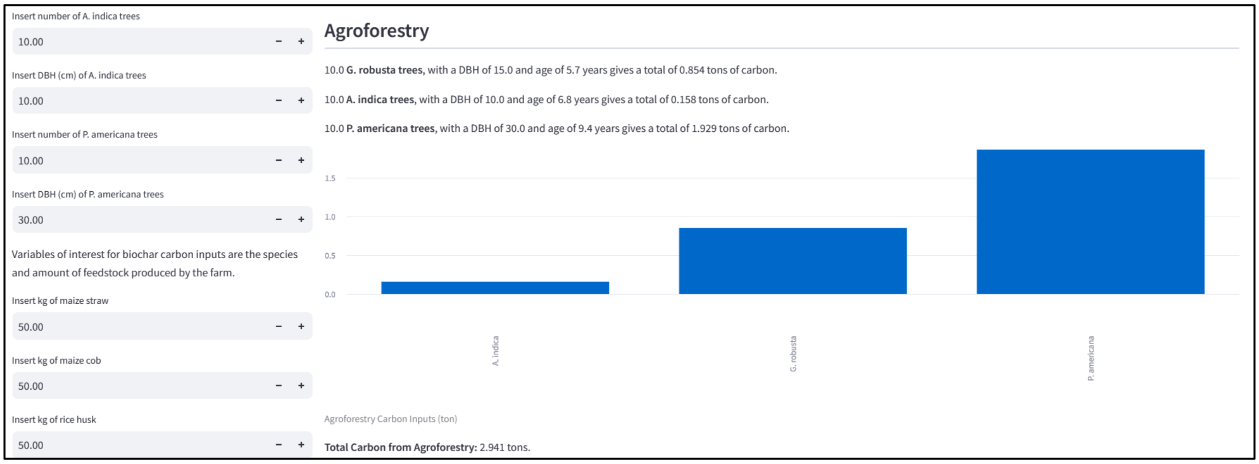

Figure 9 User interface of the carbon capture cube calculator for agroforestry.

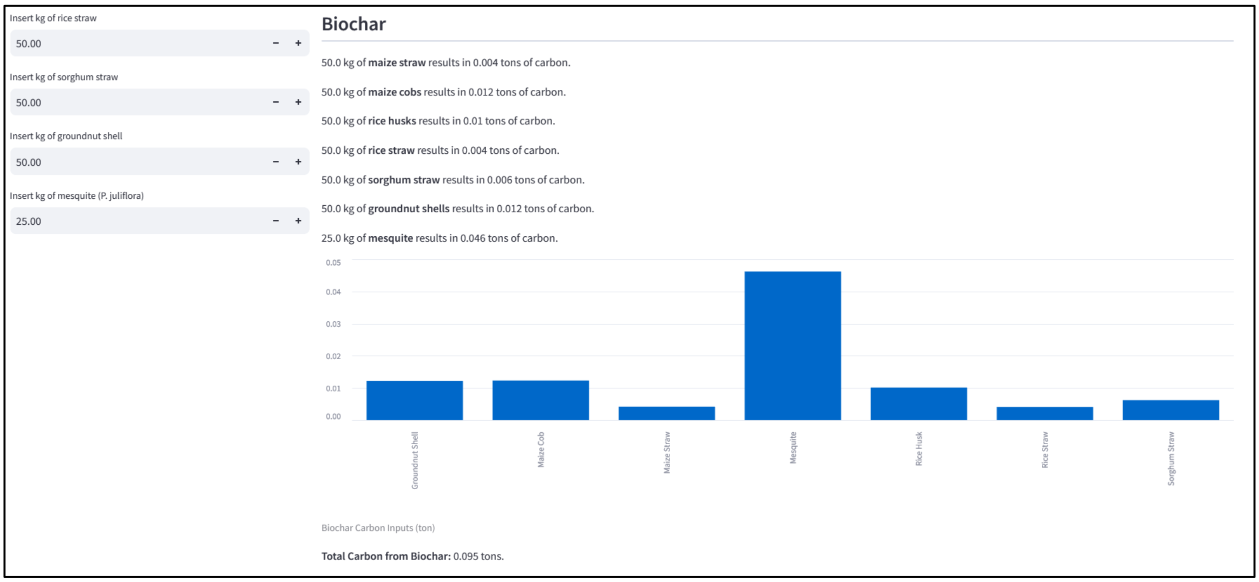

Figure 10 User interface of the carbon capture cube calculator for biochar.

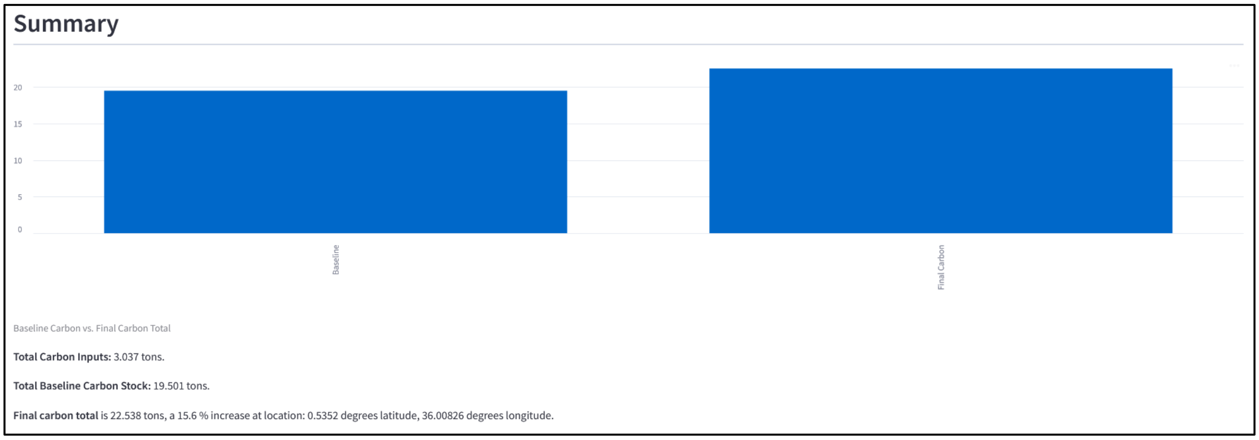

Figure 11 User interface of the carbon capture cube calculator for baseline vs. final carbon.

One of the main drawbacks of the calculator is that not all locations in Sub-Saharan Africa have spatial data. If the user inputs a coordinate outside of what WaPOR and iSDAsoil has, the calculator returns null information. Another limitation of the calculator is that it covers only the tree species and feedstocks detailed in this paper. Although silk oak is used as a substitute for other native tree species, having allometric equations dedicated to each species would improve the calculator's accuracy. Some allometric equations used are also limited, such as the *Persea americana* carbon equation, which only considers the aboveground carbon inputs rather than both above and below ground inputs. Despite this, the calculator still offers a basic assessment that the user can reference for further research into the carbon stock of the location.

Future Studies

The methodology made can be used to calculate the carbon potential of farms using their coordinates and area. However, the method can still be further refined for accuracy as more data becomes available. In the future, considering the persistence of different biochar over time rather than the immediate carbon input could allow for better planning when implementing these practices. The calculator can also benefit from taking into account emissions generated when creating and transporting biochar and saplings. Although, in the case of transportation, it is assumed that emissions would be negligible if biochar is generated nearby or at the farm itself.

Investigating the relationships between crop yield with agroforestry and biochar to create estimates on productivity would add further utility to the calculator. While carbon capture cubes aim to sequester more carbon, allowing farmers to view the additional advantages, can encourage its adoption. Calculating economic benefits from carbon capture cubes, such as harvesting fruit from trees, improved crop yield, and cost savings from reducing fertilizer purchases, would be another way to present the positives of carbon capture cubes.

Although countries in the Global North have historically contributed the most to the climate change, nations in the Global South, such as African nations, are harmed far more. With climate change, comes the degradation of arable land and increased conflict. With the current amount of greenhouse gases in the atmosphere, reducing emissions and sinking carbon must be prioritized in addressing climate change. Carbon capture cubes serve smallholder farmers in Africa by improving crop productivity with agroforestry and biochar while providing additional sources of income from sequestering carbon. As much of the farmers’ livelihoods are placed in their land, integrating practices that improve its resilience against climate change can support farmers and the people that rely on their produce. At the same time, quantifying carbon inputs can makes carbon offset schemes available to farmers and further improve their livelihoods. To aid smallholder farmers in vulnerable regions, carbon capture cubes are the solution.

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