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Total Carbon Stock and Potential Carbon Sequestration Economic Value of Mukogodo Forest-Landscape Ecosystem in Drylands of Northern Kenya

Nereoh C. Leley[1,2*], David K. Langat[1], Abdalla K. Kisiwa[1], Geoffry M. Maina[2], Meshack O. Muga[1,3]

[1]Kenya Forestry Research Institute, Nairobi, Kenya
[2]Department of Natural Resources, Egerton University, Njoro, Kenya
[3]Food and Agriculture Organization of the United Nations, Nairobi, Kenya
Email: *nereoh24@gmail.com, lnereoh@kefri.org

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Abstract

Carbon sequestration is one of the important ecosystem services provided by forested landscapes. Dry forests have high potential for carbon storage. However, their potential to store and sequester carbon is poorly understood in Kenya. Moreover, past attempts to estimate carbon stock have ignored drylands ecosystem heterogeneity. This study assessed the potential of Mukogodo dryland forest-landscape in offsetting carbon dioxide through carbon sequestration and storage. Four carbon pools (above and below ground biomass, soil, dead wood and litter) were analyzed. A total of 51 (400 m^2) sample plots were established using stratified-random sampling technique to estimate biomass across six vegetation classes in three landscape types (forest reserve, ranches and conservancies) using nested-plot design. Above ground biomass was determined using generalized multispecies model with diameter at breast height, height and wood density as variables. Below ground, soil, litter and dead wood biomass; carbon stocks and carbon dioxide equivalents (CO_{2eq}) were estimated using secondary information. The CO_{2eq} was multiplied by current prices of carbon trade to compute carbon sequestration value. Mean ± SE of biomass and carbon was determined across vegetation and landscape types and mean differences tested by one-way Analysis of Variance. Mean biomass and carbon was about 79.15 ± 40.22 TB ha^{-1} and 37.25 ± 18.89 TC ha^{-1} respectively. Cumulative carbon stock was estimated at 682.08 TC ha^{-1}; forest reserve (251.57 TC ha^{-1}) had significantly high levels of carbon stocks compared to ranches (209.78 TC ha^{-1}) and conservancies (220.73 TC ha^{-1}, $P = 0.000$). Further, closed forest significantly contributed to the overall biomass and carbon stock (58%). The carbon sequestration potential was about 19.9MTCO_{2eq} with most conservative worth of KES 39.9B (US$40M) per annum. The high carbon stock in the landscape shows the potential of dryland ecosystems as carbon sink for climate change mitigation. However, for communities to benefit from bio-carbon funds in future, sustainable landscape management and restorative measures should be practiced to enhance carbon storage and provision of other ecosystem services.

Keywords

Carbon Sequestration, Carbon Stock, Economic Value, Dryland Forest-Landscape, Kenya

1. Introduction

The main carbon pools on earth systems are atmosphere, terrestrial biosphere, ocean and Earth's crust (Hoover & Riddle, 2020). Terrestrial ecosystems (mainly forest, soil and wetland), are the major carbon pool components on earth's system (Beedlow et al., 2004; Lal et al., 2012; Xu et al., 2018) and largely contributes to the global carbon balance (IPCC, 2007; Hoover & Riddle, 2020). However, anthropogenic activities such as land-use change and combustion of biomass and fossil fuel are largely contributing to de-carbonization and accumulation of bio-spheric greenhouse gases (GHGs)—(Lal et al., 2012; Ciais et al., 2014; Friedlingstein et al., 2019). The accumulation of carbon dioxide (CO_2) and other GHGs in the upper atmosphere, has led to climate variability and associated stochastic events such as increases in the average global temperature, drought and flood events (Lal, 2004; Dabasso et al., 2014).

Since pre-industrial times, global CO_2 concentration in the atmosphere has increased by over 40% from about 277 parts per million (ppm) in 1750 to 407.38 ± 0.1 ppm in 2018 (Joos and Spahni, 2008; IPCC, 2013; Dlugokencky and Tans, 2018). Accordingly, warming from pre-industrial levels to the decade 2006-2015 was estimated to be 0.87˚C (IPCC, 2019) and reached approximately 1˚C above pre-industrial levels in 2017 (Allen et al., 2018). International efforts aim to limit the temperature increase to below 2˚C, preferably 1.5˚C above the pre-industrial level to reduce the risks and impacts of climate change (Gao et al., 2017; IPCC, 2018). According to the Nationally Determined Contribution synthesis report of 2021, to limit global warming to below 2˚C, CO_2 emissions need to decrease by about 25% from 2010 level by 2030 and reach net zero around 2070 (Chevallier, 2021). Consequently, climate mitigation strategies not only focus on reducing emissions of GHGs into the atmosphere but more on removing and stabilizing carbon concentration in the atmosphere (Gren & Aklilu, 2016).

Re-carbonization of the biosphere is important to reduce net anthropogenic carbon emissions through sequestration of CO_2 (Lal et al., 2012). Carbon sequestration is an important ecosystem service provided largely by terrestrial ecosystems. Estimates suggest that terrestrial ecosystems release about 10 to 20% of the total global CO_2 to the atmosphere due to land degradation, but also sequesters about 30% of CO_2 emissions from anthropogenic activities (Gibbs et al., 2007; Harris et al., 2012; Houghton et al., 2012; Houghton & Nassikas, 2018; Friedlingstein et al., 2019; IPCC, 2019). Accordingly, between 2009 and 2018, the terrestrial CO_2 sink increased to about 3.2 ± 0.7 GtC yr^{-1} down from 1.3 ± 0.4 GtC yr^{-1} in the 1960s (Friedlingstein et al., 2019). Despite the high potential of these ecosystems to sequester carbon, emissions from land-use changes and deforestation coupled with other carbon sources outweigh the carbon sink leading to the accumulation of greenhouse gases.

Forested landscapes are the largest carbon pool of the terrestrial ecosystem and integral in global carbon cycle (Pan et al., 2011; Abere et al., 2017; Zhao et al., 2019). The carbon pools in forest areas include; living biomass (above and below-ground biomass), dead organic matter (dead wood and litter) and soils (soil organic matter)—(Pan et al., 2011; Zhao et al., 2019; Hoover & Riddle, 2020). According to Pan et al. (2011), the carbon stock in the world's forests is estimated to be 861 ± 66 Pg C, with about 383 ± 30 Pg C (44%) in soil (1 m depth), 363 ± 28 Pg C (42%) in live biomass, 73 ± 6 Pg C (8%) in deadwood, and 43 ± 3 Pg C (5%) in litter. Out of 861 Pg C, about 471 Pg (~45%) of it is stored in tropical forests. The uptake of CO_2 from the atmosphere and storage within the forested ecosystem is one of the most practical and feasible way of reducing present and future emissions of CO_2 in the atmosphere (Trumper et al., 2008). It is also less costly since, it is natural based process and can be enhanced through restorative land-use and sustainable management (Lal et al., 2012).

Reducing carbon emissions is critical in combating climate change. Various carbon reduction mechanisms have been put in place by the United Nations Framework Convention on Climate Change (UNFCCC). These include Kyoto protocol, reducing emissions from deforestation and degradation (REDD+), the nationally determined contributions as provided for in the Paris agreement and the creation of carbon credit offset markets. Accordingly, International initiatives to offset and maintain greenhouse gases require an understanding of the existing and future potential of forest landscapes in carbon emissions and sequestration (Lal et al., 2012). Therefore, estimation of biomass (carbon stock) is pre-requisite to quantify the potential carbon sequestration in forests including the woodlands.

The estimates of biomass (and carbon) can be determined through field inventories only or a combination with various remote sensing approaches (Ubuy et al., 2018) using both direct and indirect methods. Direct methods use biomass models developed through destructive sampling of selected trees, while indirect methods involve the use of allometric volume equations, form factor and biomass expansion factors and or with wood basic density (Chave et al., 2014; Njana, 2017). The direct method although the most reliable and accurate approach, is time consuming and destructive (Vashum & Jayakumar, 2012) and may not be applicable in protected or threatened forests (Tetemke et al., 2019). Therefore, the use of allometric models is the commonly used approach (Chave et al., 2003; Ngomanda et al., 2014). Conversely, the accuracy of biomass estimated using allometric models is dependent on the appropriateness and applicability of the chosen model (Chave et al., 2014). The models can be species specific (species-site specific, species specific but from multiple sites) or general (multiple species from single site or multi-species from several sites)—(Henry et al., 2011). The general multi species-site models are appropriate for extensive forested landscapes with large number of different species (Chave et al., 2005) as is the case in this study.

Drylands occupy about 45.4% to 47.2% of the world's total land area (Lal, 2004; Lal, 2019). The dryland ecosystem contributes significantly to land-based carbon sink and negative feedback to global carbon cycle given its expansiveness (Lal, 2019) and stores about one third of the global carbon stock (Trumper et al., 2008). The drylands of Kenya cover about 80% of the total landmass in the Country (Githae & Mutiga, 2021). These drylands are mostly utilized for pastoral systems. The potential of rangelands and dryland forests to store carbon is well documented globally (Lal, 2004; IPCC, 2007; Trumper et al., 2008; Lal, 2019) and is influenced by its response to communal grazing effects (Perez-Quezada et al., 2011). However, the potential of these pastoral ecosystems to sequester and store carbon is poorly understood in Kenya. Moreover, attempts to estimate carbon stock in such ecosystems have not considered heterogeneity of these landscapes.

This study was undertaken in the heterogeneous pastoral environments of Mukogodo forest landscape, in the drylands of Northern Kenya. The objectives of the study were to assess the potential of Mukogodo forest landscape to store and sequester carbon, and equivalent economic value of carbon sequestration. The study covered the woodlands (ranches and conservancies) and dry forest (Mukogodo forest reserve). The study sites were classified into three landscape types (forest reserve, conservancy and ranch) and six vegetation categories (closed forest, open forest, grassland, shrubland, bare land and Opuntia dominated areas) depending on vegetation life forms and canopy cover to capture landscape variability in drylands of Northern Kenya. The study applied the commonly used tree variables (Diameter at Breast Height—DBH, total tree height and wood density)—(Chave et al., 2014) to estimate above ground biomass carbon and analyzed four main carbon pools of forest landscapes (living biomass, soil, deadwood and litter). The purpose of this study therefore, was to understand the capacity of dryland ecosystems to offset carbon and combat climate change by estimating the carbon stock and carbon sequestration potential and worth. The findings can contribute to the development of conservation policies for these fragile ecosystems as carbon sinks and for understanding the potential for carbon credits and associated economic benefits to the society in future.

2. Materials and Methods

2.1. Materials

Description of Study Area

Mukogodo forest landscape is composed of forest reserve, group ranches and conservancies and traverses Laikipia and Isiolo Counties of Kenya. It lies approximately between longitude 37˚05'E to 37˚23'E and at latitude 0˚18'N and 0˚32'N. In Laikipia County, the landscape encompasses the Mukogodo forest reserve (30,189 ha) and four surrounding group ranches namely; Ilngwesi (9470 ha) in the southeast, Makurian (5390 ha) in the southwest, Kurikuri (3340 ha) in the northwest and Lekuruki (15,872 ha) in the northeast of the forest (KIFCON, 1994; Kagombe et al., 2006; Kagombe and Owuor, 2007). The landscape also extends to two conservancies in Isiolo County (Oldonyiro 52,500 ha and Leparua 34,200 ha)—**Figure 1**.

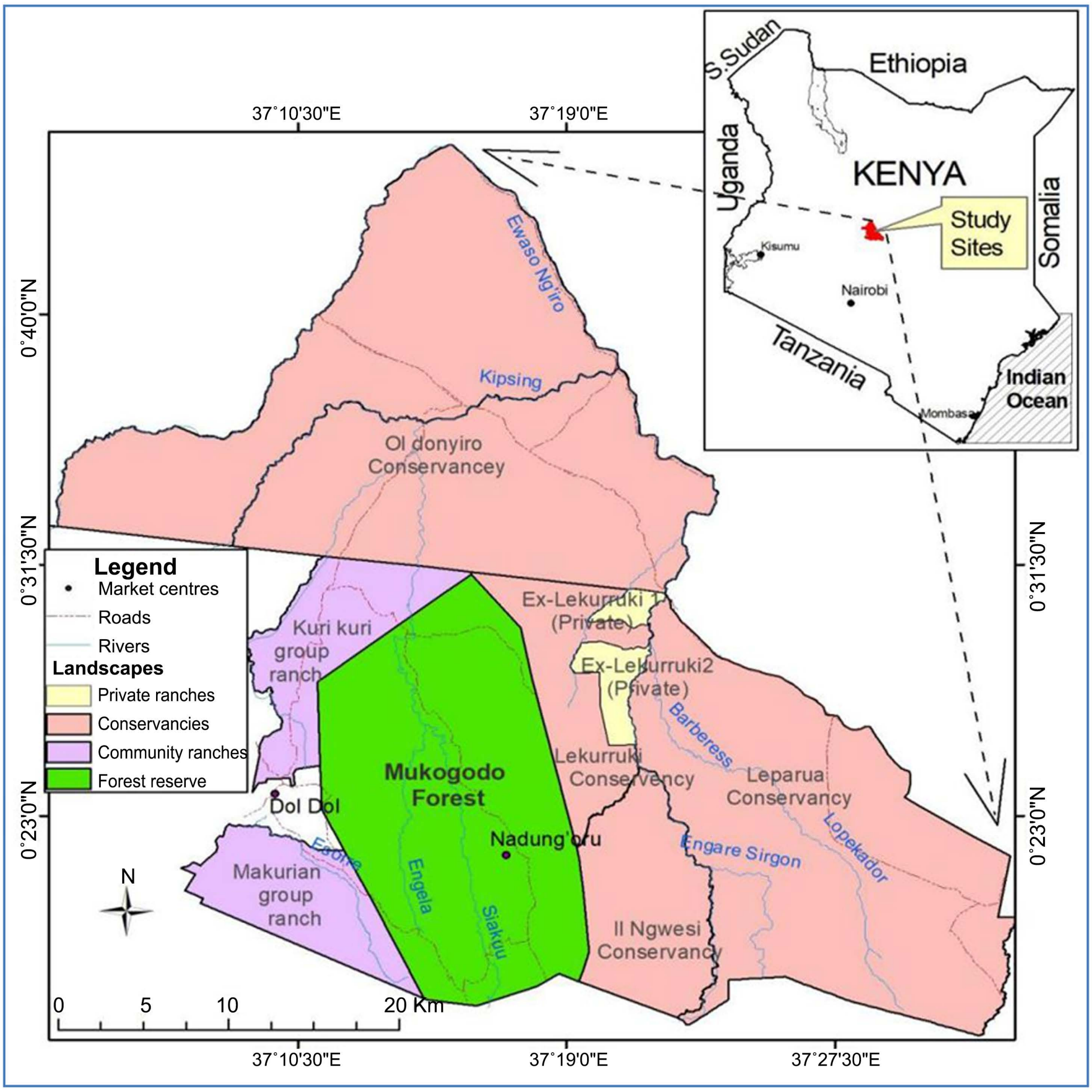

Figure 1. Map showing the location of Mukogodo forest landscape (Source: Authors).

The landscape is found in agro-climatic zone V, (semi-arid), thus an ecologically sensitive ecosystem (World Bank, 1993; KFS, 2008). It is characterized by rugged terrains with hilly masses of between 10% and 40% slope (Muchiri and Gachathi, 2006; KFS, 2008). The elevation ranges between 1600 to 2100 m. The mean annual rainfall ranges between 400 and 600 mm. The rainfall distribution is bimodal with long rains in March-April and short rains in October-December. The daily temperatures range from 18˚C to 29˚C. The landscape is drained by seasonal rivers, the main ones being Sieku and Kipsing (KFS, 2008).

Mukogodo landscape is characterized by seven broad vegetation types: Closed forest, closed woodland, open forest, open grassland, open scattered trees, very open scattered trees, and degraded grassland. The most abundant trees in the landscape are *Olea europaea* ssp. africana, *Acacia tortilis* and *Juniperus procera* (Muchiri and Gachathi, 2006; KFS, 2008). The forest landscape is a habitat for 209 species of birds, 11 small mammals, and 34 large mammal species. The large mammal species include Elephant (*Loxodonta africana*), Buffalo (*Syncarus caffer*), Lion (*Panthera leo*), Leopard (*Panthera pardus*) and endangered grevy's Zebra (*Equus grevyi*) (KFS, 2008).

The Mukogodo landscape is inhabited by the Laikipia Maasai and the indigenous hunter-gatherer community Yaaku. The two Isiolo conservancies are mainly occupied by Samburu and Turkana in Oldonyiro conservancy, Turkana, Somali, Borana, and Samburu in Leparua conservancy. The main economic activity in the landscape is semi-sedentary pastoralism where cattle, sheep, goats and camels are kept in communal grazing lands (Ng'ethe et al., 1997; M'mboroki et al., 2018). Eco-tourism and nature-based enterprises are emerging economic activities in the landscape. Despite the significant importance of the Mukogodo ecosystem to the communities' livelihoods, forests and lands are threatened by degradation. The driving factors of degradation include forest fires, deforestation, charcoal production, and grazing pressure, which have reduced forest cover over the years (Webala et al., 2006; M'mboroki et al., 2018). For instance, between 1984 and 2014, the forested landscape in Mukogodo reduced by 3071 ha (24%)-(M'mboroki et al., 2018). This increases the pressure on existing landscape to provide vital ecosystem services such as carbon storage and sequestration.

2.2. Methods

2.2.1. Sampling and Data Collection

Primary data for estimating above ground biomass and carbon stock were collected through vegetation assessment in accordance with National forest inventory sampling framework (Hyvönen et al., 2016; Ndambiri et al., 2020). Multi-stage stratified random sampling technique was used to collect vegetation data. The landscape was first stratified into three types: forest reserve, group ranches and conservancies. In each of the landscape class, the vegetation was further divided into six classes/types: closed forest, open forest, grassland, shrubland, bare land and Opuntia dominated areas and area (ha) under each vegetation type was estimated using GIS and remote sensing technologies (**Figure 2**).

The number of plots sampled in each landscape type was proportional to the area under each vegetation type. The field sampling plots were pre-determined by randomly selecting coordinates points from a list generated through GIS techniques along six transects parallel to each other. The selected points were then loaded in a hand held GPS. The GPS coordinates were used to locate the first corner of the plots whereby the other plot corners were laid in North-West direction. Nested plot design was applied in the vegetation assessment. The main plot measuring 400 m^2 was used to assess trees and shrubs with DBH ≥ 5 cm. Sub-plot of 25 m^2 was nested at the first corner of the main plot was used to assess woody regenerates (≥1 cm but <5 cm DBH). Within the plots, plants were identified to species level in local and botanical names with assistance from Para-taxonomist and a Botanist. The DBH and height of regenerates and trees were measured at 1.3 m above ground using a diameter tape and Suunto clinometer respectively. A total of fifty one (51) sample plots were established and assessed across the six vegetation classes in the three landscapes types. Secondary data and

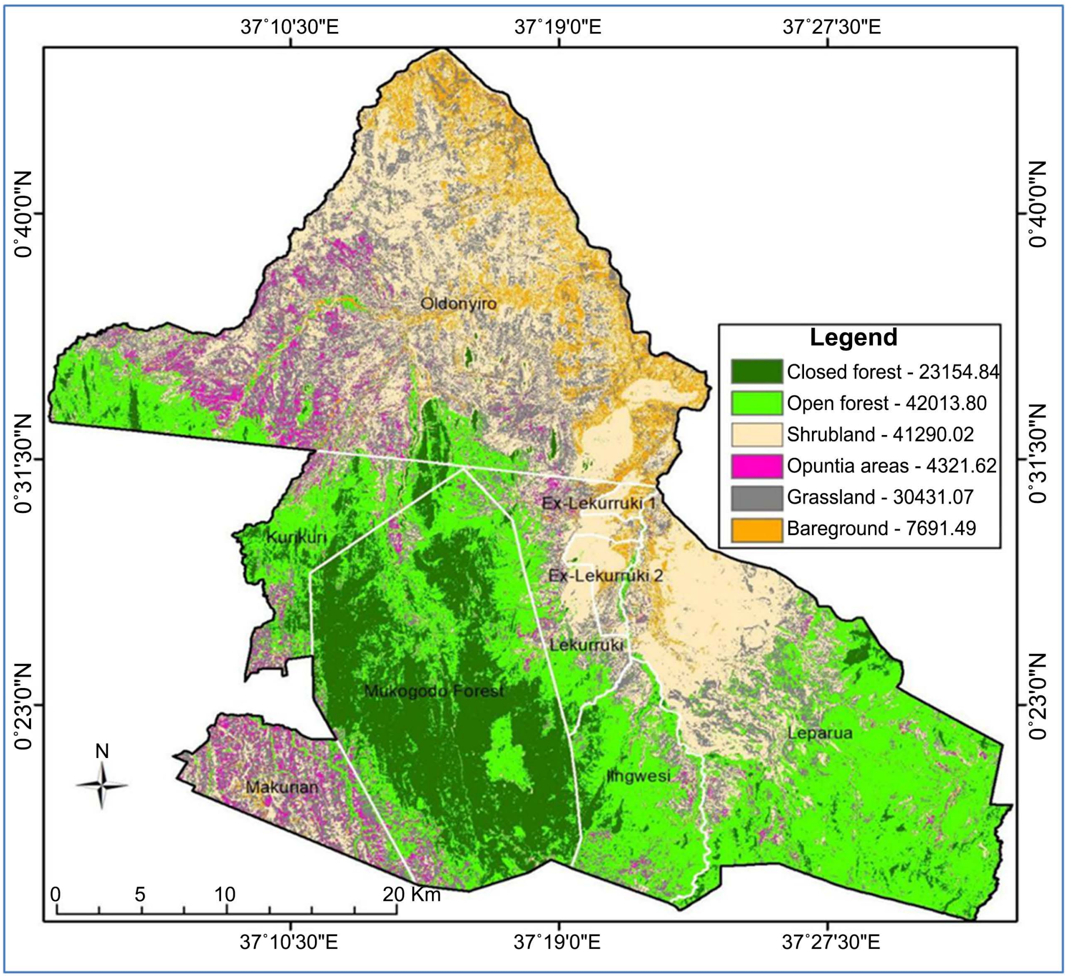

Figure 2. Map showing Mukogodo landscape vegetation types and respective area (Ha) (Source: Authors).

information on wood density, productivity of Opuntia and models for estimating biomass were obtained from intensive review of literature from scientific articles with emphasis on biomass and carbon stock in dryland tropical montane forests and range lands.

2.2.2. Data Processing and Analysis

Four main carbon pools were identified for estimation of the total carbon stock in the landscape: living biomass (Above Ground Biomass—(AGB) and Below Ground Biomass—(BGB), soil, litter and dead wood (MacDicken, 1997; Marklund and Schoene, 2006; Pan et al., 2011). First, AGB of trees was determined using generalized multispecies linear allometric equation for tropical dryland forest of Ethiopia (Tetemke et al., 2019) as described in Equation (1).

$$Y = 0.327 d^{2.016} h^{0.055} \rho^{0.505}. \quad (1)$$

where Y is AGB (kg/ha), d is Diameter at Breast Height (cm), h is the total tree height (m) while ρ is the wood density ($g \cdot cm^{-3}$).

The above equation was selected due similarity in species harvested to develop the model with those sampled in this study and the similarity in eco-climatic conditions with Mukogodo landscape. Moreover, the model applied more than one parameter (DBH, height and wood density) which tend to give reliable results (Chave et al., 2005; Nam et al., 2016; Aabeyir et al., 2020).

Secondly, BGB was estimated as a fraction of the above ground biomass by multiplying with a shoot root ratio of 0.28 (MEF, 2019) and comparing with values from other studies (Cairns et al., 1997; MacDicken, 1997; IPCC, 2003; Marklund & Schoene, 2006; Mokany et al., 2006). Dead wood biomass was estimated based on dead-live ratios of 0.12 (Marklund & Schoene, 2006). Litter biomass was assumed to be 5% of the total biomass (Marklund & Schoene, 2006; Pan et al., 2011; Sun and Liu, 2020). The soil carbon was assumed to account for 32% of the biomass (Pan et al., 2011) based on assumption that both AGB and BGB account for 56% of the total carbon pool (Pan et al., 2011). The total biomass of *Opuntia stricta* was assumed to be 63.52 TB ha^{-1} based on proxy of mean productivity of *Opuntia ficus-indica* found in several studies (Nobel, 1995; Nefzaoui et al., 2014; Dubeux Jr. et al., 2015; Fouche & Coetzer, 2015; Iqbal et al., 2020). Respective carbon stock in each carbon pool was estimated by multiplying biomass by a coefficient of 0.475 (Raghubanshi, 1991; Singh and Chand, 2012). This study assumed that soil carbon accounted for 100% of total carbon stocks for bare land in accordance with Solomon et al. (2018). Accordingly, the carbon stock of bare land was assumed to be the average of grassland and shrubland soil carbon, since most bare lands in the landscape are within the two vegetation types.

The mean ± SE of biomass and carbon stock was determined for each carbon pool, landscape category and vegetation type. Mean total biomass and carbon were estimated by multiplying the mean carbon per vegetation type and respective area. To estimate carbon sequestration capacity, carbon dioxide equivalent

(CO_{2eq}) was calculated by multiplying the total carbon stock by a factor of 3.67 (Petersson et al., 2012). The CO_{2eq} was then multiplied by the current prices of carbon trade to obtain potential carbon sequestration economic value as per Equation (2):

$$V_C = E_{CO_2eq}\rho \tag{2}$$

where Vc is the value of carbon sequestration (US$), E_{CO2eq} is the estimated carbon dioxide equivalent, while ρ is the price of carbon (US$).

According to the World Bank (2020), Carbon prices ranged from less than US$1 T^{-1} CO_{2eq} to US$119 T^{-1} CO_{2eq}, with almost half of the covered emissions priced at less than US$10 T^{-1} CO_{2eq}. This study used a conservative value of 2 US$ T^{-1} CO_{2eq}, the global average carbon price provided by IMF (2019)—to demonstrate the lowest case scenario, a mean of 20.46 US$ T^{-1} CO_{2eq} to show moderate scenario adopted from IHS Markit's Global Carbon Index 2020, which is made up of prices from the California Compliance Allowance, Regional Greenhouse Gas Initiative (RGGI), and European Allowance prices, with the weighted global price on carbon equivalent of US$20.81 T^{-1} CO_{2eq} and the World Bank's data with a similar price across its 61 jurisdictions at US$20.11 T^{-1} CO_{2eq} (Carbon Credit Capital, 2020). The highest case scenario used a price of 80 US$ T^{-1} CO_{2eq} as suggested by the high-level commission on carbon prices estimated that carbon prices of at least US$40 - 80 T^{-1} CO_{2eq} by 2020 are required to cost-effectively reduce emissions in line with the temperature goals of the Paris Agreement (World Bank, 2020).

One way Analysis of Variance (ANOVA) was used to test the differences in biomass and carbon stocks across the carbon pools, landscape categories (forest reserve, community ranches and conservancies) and among the six vegetation types using MINITAB version 19.1.1.0 at 95% confidence level. The means with significant differences were separated by Tukey's honestly significant difference post hoc test.

3. Results

3.1. Biomass and Carbon Stocks

The mean biomass both (living and dead) in the landscape was about 79.15 ± 40.22 TB ha^{-1} while the mean carbon was found to be 37.25 ± 18.89 TC ha^{-1}. The disaggregation of the above carbon stocks for various carbon pools indicates that 56.15% was stored in both above and below ground biomass, 32.09% was stored in the soils, 6.74% in the dead wood and 5.02% in the litter. Significant variation existed in mean biomass and carbon stocks across the different carbon pools ($DF_{3, 200} = 18.95$, $P = 0.000$)—**Table 1**. The closed forest contributed the most to all the carbon pools compared to the other vegetation categories. The contribution of (Opuntia vs. open forest) and (shrubland vs. grassland) was comparable. The bare land contributed marginally to the carbon pools through soil carbon pool only (**Figure 3**).

Table 1. Overall biomass and carbon stocks in Mukogodo forest landscape.

Carbon pool	Mean biomass (T ha^{-1})	Mean carbon (T ha^{-1})
Below and above ground	$47.12^{a} \pm 8.03$	$22.15^{a} \pm 3.77$
Soil	$26.93^{b} \pm 4.59$	$12.66^{b} \pm 2.16$
Dead wood	$5.65^{c} \pm 0.97$	$2.66^{c} \pm 2.16$
Litter	$4.21^{d} \pm 0.72$	$1.98^{d} \pm 0.34$
Landscape type	**Mean biomass (T ha^{-1})**	**Mean carbon (T ha^{-1})**
Mukogodo forest reserve	$209.00^{a} \pm 31.00$	$98.20^{a} \pm 14.60$
Laikipia group ranches	$13.17^{b} \pm 4.38$	$6.19^{b} \pm 2.06$
Isiolo conservancies	$26.50^{b} \pm 4.94$	$12.46^{b} \pm 2.32$
Vegetation type	**Mean biomass (T ha^{-1})**	**Mean carbon (T ha^{-1})**
Closed	$273.82^{a} \pm 30.50$	$128.70^{a} \pm 14.30$
Open	$72.92^{b} \pm 19.50$	$34.27^{b} \pm 9.15$
Shrubland	$23.7^{b} \pm 3.75$	$11.14^{b} \pm 1.76$
Grassland	$32.43^{b} \pm 16.70$	$15.24^{b} \pm 7.86$
Opuntia	63.52	30.17
Bare land	8.49	3.99

Note: Means with different superscript letters are significantly different at 95% confidence level. Also, Opuntia dominated areas and bare land does not contain error bars of means because their total carbon pools estimates were derived from secondary data.

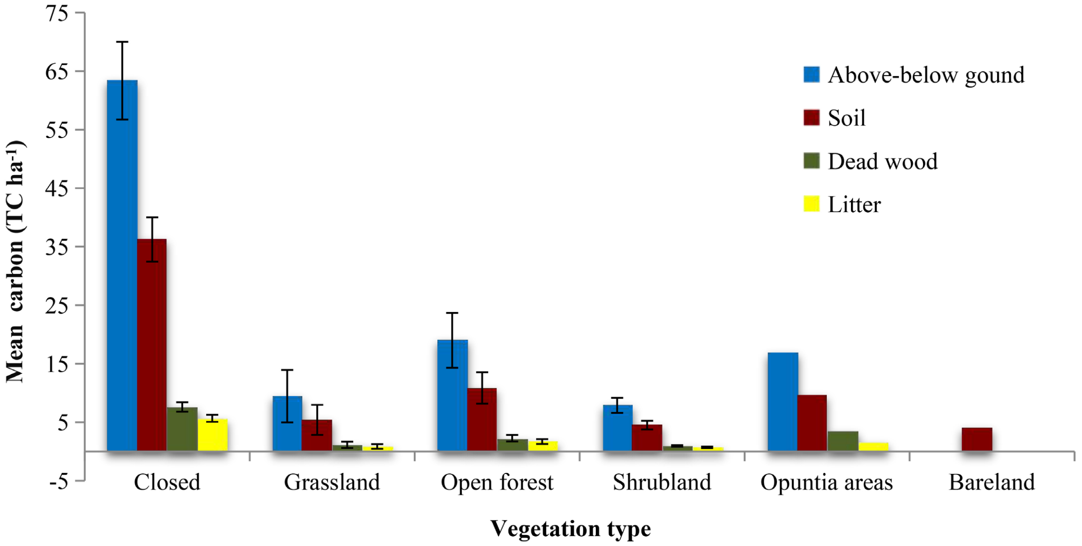

Figure 3. Carbon pools across the vegetation types in Mukogodo forest landscape. Note: Opuntia dominated areas and bare land does not contain error bars of means because their total carbon pools estimates were derived from secondary data.

Generally, the forest reserve had significantly high quantities (~84%) of the total biomass and carbon stocks (209.00 ± 31.00 TB ha^{-1} and 98.20 ± 14.60 TC ha^{-1} respectively) compared to the group ranches and conservancies ($DF_{2, 48}$ =

31.69, $P = 0.000$). Although not significant, the group ranches showed less capacity of carbon storage by 50.31% compared to the conservancies. Further, the closed forest areas significantly contributed to the overall biomass and carbon stock (273.82 ± 30.50 TB ha^{-1} and 128.70 ± 14.30 TC ha^{-1} respectively) in the Mukogodo forest landscape in relation to the other vegetation types by about 58% ($DF_{5, 45} = 51.83$, $P = 0.000$). Notably, the conversion of intact forest to open forest has the potential carbon loss of about 73.37%. As expected, the bare land had the least capacity of carbon storage with about 3.99 TC ha^{-1}. Opuntia dominated sites showed high capacity to store carbon than grasslands and shrubland by 49.95% and 62.69% respectively (**Table 1**). However, being an invasive species, it is associated with negative effect on the ecosystem functionality.

The mean total biomass and carbon storage was estimated at 14,449 TB ha^{-1} and 682.08 TC ha^{-1} respectively (**Table 3**). Of this carbon stock quantities, 251.57 TC ha^{-1} were stored in the forest reserve while, 209.78 and 220.73 TC ha^{-1} were stored in the group ranches and conservancies respectively (**Table 2**). The total biomass and carbon stock in Mukogodo forest landscape were estimated at 11,552,768.98 TB and 5,431,309.0 TC respectively (**Annex**).

3.2. The Value of Carbon Sequestration

The carbon sequestration potential in the landscape was about 19,932,905.70 T CO_{2eq} per year worth between US$39,865,811.39 and 1,594,632,455.78 annually or (US$260.37 and 10,414.97 ha^{-1} $year^{-1}$ respectively). The most conservative estimate of carbon sequestration worth for the landscape was KES 3.99 billion with KES 2.0 billion, 670 million and 1.4 billion for Mukogodo forest reserve, group ranches and community conservancies respectively (**Table 3**). The forest reserve contributed nearly half (49.30%) of the total carbon sequestration value, hence underpins the need for its conservation. The ranches and conservancies contributed about 16.92% and 33.78% respectively.

Table 2. Biomass and carbon stock across the landscape and vegetation types in Mukogodo.

Landscape type vs vegetation type biomass and carbon stocks		
Mukogodo forest reserve	**Mean biomass (TB ha^{-1})**	**Mean carbon (TC ha^{-1})**
Closed forest	273.82	128.70
Open	72.92	34.27
Grassland	92.13	43.30
Shrubland	23.70	11.14
Opuntia	63.52	30.17
Bare land	8.49	3.99
Total	**534.58**	**251.57**
Laikipia group ranches		
Shrubland	12.05	5.66

Continued

Grassland	14.87	6.99
Closed forest	273.82	128.70
Open	72.92	34.27
Opuntia	63.52	30.17
Bare land	8.49	3.99
Total	**445.67**	**209.78**
Isiolo conservancies		
Shrubland	27.59	12.97
Grassland	22.61	10.63
Closed forest	273.82	128.70
Open	72.92	34.27
Opuntia	63.52	30.17
Bare land	8.49	3.99
Total	**468.95**	**220.73**
Grand total	**1449.20**	**682.08**

Table 3. Carbon sequestration potential and worth in Mukogodo forest landscape.

Category	a) Carbon (TC ha^{-1})	b) Total area (ha)	c) Total Carbon (T)	d) CO$_{2eq}$ (T)	e) Lowest value (US$)	f) Moderate value (US$)	g) Highest value (US$)
			$=a^{x}b$	$=c^{x}3.67$	$=d^{x}2$ US$	$=d^{x}20.46$ US$	$=d^{x}80$ US$
Forest reserve	251.57	29,537.80	2,677,641.45	9,826,944.14	19,653,888.28	201,059,277.06	786,155,531.01
Group ranches	209.78	31,964.40	918,727.73	3,371,730.78	6,743,461.57	68,985,611.81	269,738,462.61
Conservancies	220.73	91,607.40	1,834,940.27	6,734,230.78	13,468,461.55	137,782,361.70	538,738,462.16
Total	**682.08**	**153,109.60**	**5,431,309.45**	**19,932,905.70**	**39,865,811.39**	**407,827,250.57**	**1,594,632,455.78**

4. Discussion

Biomass, Carbon Stock and Carbon Financing

International efforts are in place to stabilize GHGs emissions and climate such as the Kyoto protocol, compliance and voluntary carbon trading markets, clean development mechanisms (REDD+) and the nationally determined contribution. According to the United Nations Framework Convention on Climate Change (UNFCCC) Bali conference in 2007, resolutions were made regarding strategies to combat climate change by the ratified countries. They include; developed countries should adopt national emission reduction targets and provide developing countries with mitigation financing and capacity building; while developing countries should undertake mitigation actions (Carpenter, 2008). Further, the Paris agreement in 2015 reaffirmed that developed countries should take the lead in providing financial assistance to party countries that are less endowed and more vulnerable, and commitment of voluntary contributions by all ratified countries (Gao et al., 2017). By 2020, party countries were to submit their plans for climate action—the nationally determined contributions (NDCs). Kenya committed to abate GHGs emissions by 32% by 2030 relative to the business as usual scenario of 143 $MTCO_{2eq}$ (MEF, 2021). The total emission reduction potential for the country is about 86 $MTCO_{2eq}$. The remaining 40 $MTCO_{2eq}$ is secured for carbon credits/trading. Out of 86 $MTCO_{2eq}$, forestry is expected to meet about 24% (20.8 $MTCO_{2eq}$) of the total emissions. This underscores the need for reliable estimates of carbon sequestration potential of forested landscapes in the country. In this study, Mukogodo forest alone in the current state has the potential to sequester about 19 $MTCO_{2eq}$ without consideration of carbon emission through land use change and degradation. Sustainable management and implementation of carbon reduction interventions in Mukogodo landscape have the potential to sequester carbon worth about US$40M annually through carbon trading.

To effectively participate in carbon market, reliable estimation of total biomass carbon storage is essential (Weiskittel et al., 2015). The robust estimate is also critical for sustainable forest management decision making, for monitoring status of the forest and reporting carbon stock dynamics as required by Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism (Ubuy et al., 2018). Further, the international negotiations on offsetting greenhouse gases require reliable current and potential estimates of forested areas to emit and sequester carbon (Pan et al., 2011). Therefore, valuing of the forest areas for their carbon storage potential may influence their protection through development of financial incentives for carbon storage.

Results from the study, indicate that, most of the carbon pools were contributed by living biomass carbon (~56%), followed by soil (~32%), deadwood and litter carbon by about 7% and 5% respectively. The litter and deadwood carbon were within the range reported by other studies (Tiessen et al., 1998; Pan et al., 2011). The high contribution of living biomass over soil to overall carbon were in agreement with Meena et al. (2019) who reported that living plant biomass contribute about 40% to 49% and Simegn et al., 2014 who reported about 57% of the total carbon from living biomass. Abere et al. (2017) and Atsbha et al. (2019) also reported findings that were within the range found in the study. This was, however contrary to the findings by other studies undertaken in nearly similar dry ecosystems (Dabasso et al., 2014; Solomon et al., 2018; Gebeyehu et al., 2019) who found soil to contribute the greatest carbon storage potential than the other carbon pools.

The variation in soil and living biomass carbon stock may have risen from the use of different biomass model, the application of empirical vs. secondary data and information in estimating carbon pools and methodological difference. Further, Zhao et al. (2019) indicated that the variation in data sources, estimation methods, scope of study area and environmental variables with different biotic and abiotic conditions and response to climate change may lead to significant variation in carbon storage estimates. Moreover, Keiluweit et al. (2015) reported that livestock grazing affect soil physico-chemical properties and nutrient cycling which result to soil organic carbon loss. The persistent grazing in Mukogodo forest landscape may have affected carbon storage potential of the soil carbon pool. The fact that majority of the carbon stock is stored in the living biomass suggests that any anthropogenic disturbances that might adversely affect the vegetation will have significant implication on carbon stock and sequestration potential of Mukogodo forest landscape.

The mean carbon stock from this study was slightly lower compared to those reported for nearly similar landscape in northern Kenya and Ethiopia (Dabasso et al., 2014; Gebeyehu et al., 2019), but was within the reported range in other dry forest-landscapes (Tiessen et al., 1998; Glenday, 2008; Simegn et al., 2014; Abere et al., 2017; Atsbha et al., 2019; Srinivas and Sundarapandian, 2019). The effects of vegetation and landscape type were significant on carbon stocks. The forest reserve stored most carbon within the landscape than the group ranches and conservancies. Furthermore, the high biomass carbon stock in closed forest than other vegetation types is in agreement with the findings of other studies in nearly similar ecosystems (Rajput et al., 2017; Solomon et al., 2017). In this study, the conversion of intact forest to open forest showed the potential carbon loss of about 73.37%, which is within the range reported by Wekesa et al. (2016). The observed variation in biomass carbon across the landscape and vegetation types may be due to variation in tree density, height, diameter size and low litter which facilitate decomposition of plant material for soil carbon formation. The large diameter, heights and density of trees in the forest reserve may have contributed to high carbon stock (Gibbs et al., 2007; Solomon et al., 2017; Dibaba et al., 2019; Srinivas and Sundarapandian, 2019) and their removal will impact largely on biomass dynamics in the landscape. The slightly high potential of conservancies to store carbon compared to the ranches is an indication that unsuitable land use practices such as intensive grazing have high potential of enhancing carbon emission and reducing the capacity of rangelands as carbon sink.

Sustainable management of forest areas and rehabilitation can enhance carbon stock. According to Mendelsohn et al. (2012), about 42% of carbon storage could be achieved through reduced deforestation, 3% from forest management, and estimated 27% from afforestation. Contrary, poor management coupled with deforestation and degradation can significantly reduce carbon storage (Dibaba et al., 2019). The existence of high carbon stock in the forest shows the potential of the area for climate change mitigation. The landscape should therefore be sustainably managed through reduction of deforestation and land degradation, promotion of sustainable landscape management to enhance *in-situ* carbon storage and carbon sequestration potential to mitigate effects of climate change and ensure continued provision of other ecosystem services.

5. Conclusion and Recommendation

5.1. Conclusion

This study estimated the biomass, total carbon stock, carbon sequestration potential and equivalent carbon storage economic value of Mukogodo forest landscape in drylands of Northern Kenya. The study approach accounted for the spatial and landscape-vegetation heterogeneity. The findings indicated that mean biomass both (living and dead) in Mukogodo forest landscape was about 79.15 ± 40.22 TB ha^{-1} with carbon storage potential of 37.25 ± 18.89 TC ha^{-1}. The mean total biomass and carbon storage for the landscape was estimated at 14,449 TB ha^{-1} and 682.08 TC ha^{-1} respectively. Of these carbon stock quantities, forest reserve (251.57 TC ha^{-1}) contributed significantly to the total carbon stock compared to 209.78 and 220.73 TC ha^{-1} from the group ranches and conservancies respectively. Furthermore, living biomass (~56%) and closed forest significantly (58%) contributed to the overall biomass carbon stock in the landscape compared to the other vegetation types. The carbon sequestration potential in the landscape was about 19,932,905.70 CO_{2eq} per year worth between US$39,865,811.39 and 1,594,632,455.78 $year^{-1}$ or (260.37 and 10,414.97 US$ ha^{-1} $year^{-1}$ respectively). The high carbon storage potential underscores the importance of the landscape as carbon sink and contribution to the global carbon cycle. Further, the large proportion of carbon in the landscape is stored in living biomass and closed forest, thus, a slight disturbance through deforestation and land use change may significantly reduce the carbon storage potential. The persistent exposure of group ranches to grazing had reduced their carbon storage potential by about 50.31% compared to the conservancies. The finding of this study will inform policy formulation on access of carbon funds through Clean Development and REDD+ mechanisms which will boost conservation and further enhance the carbon stocks.

5.2. Recommendation

Efforts should be enhanced to sustainably manage the landscape through restoration practices to reduce emissions associated with degradation and enhance carbon storage potential and flow of other ecosystem services. Continuous monitoring of carbon stock is also important to estimate net carbon storage and sequestration. To achieve this, the use of primary data in estimating carbon storage is highly recommended to give precise results. More research would be necessary to assess the impact of land use on carbon storage potential and feasibility of carbon credit investment in such pastoral ecosystems.

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Conflicts of Interest

The authors declare that they have no competing interests with regard to the publication of this paper.

References

Aabeyir, R., Adu-Bredu, S., Agyare, W. A., & Weir, M. J. (2020). Allometric Models for Estimating Aboveground Biomass in the Tropical Woodlands of Ghana, West Africa. *Forest Ecosystems, 7,* 1-23. https://doi.org/10.1186/s40663-020-00250-3

Abere, F., Belete, Y., Kefalew, A., & Soromessa, T. (2017). Carbon Stock of Banja Forest in Banja District, Amhara Region, Ethiopia: An Implication for Climate Change Mitigation. *Journal of Sustainable Forestry, 36,* 604-622. https://doi.org/10.1080/10549811.2017.1332646

Allen, M. R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S. et al. (2018). Framing and Context in Global Warming of 1.5˚C. In V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla et al. (Eds.), *An IPCC Special Report on the Impacts of Global Warming of 1.5˚C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (pp. 41-91). (In Press)

Atsbha, T., Desta, A. B., & Zewdu, T. (2019). Carbon Sequestration Potential of Natural Vegetation under Grazing Influence in Southern Tigray, Ethiopia: Implication for Climate Change Mitigation. *Heliyon, 5,* e02329. https://doi.org/10.1016/j.heliyon.2019.e02329

Beedlow, P. A., Tingey, D. T., Phillips, D. L., Hogsett, W. E., & Olszyk, D. M. (2004). Rising Atmospheric CO_2 and Carbon Sequestration in Forests. *Frontiers in Ecology and the Environment, 2,* 315-322. https://doi.org/10.1890/1540-9295(2004)002[0315:RACACS]2.0.CO;2

Cairns, M. A., Brown, S., Helmer, E. H., & Baumgardner, G. A. (1997). Root Biomass Allocation in the World's Upland Forests. *Oecologia, 111,* 1-11. https://doi.org/10.1007/s004420050201

Carbon Credit Capital (2020). *The Value of Carbon Market Update 2020.*

Carpenter, C. (2008). *The Bali Action Plan: Key Issues in the Climate Negotiations. Summary for Policy Makers.* An Environment and Energy Group Publication, UNDP.

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Yamakura, T. et al. (2005). Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests. *Oecologia, 145,* 87-99. https://doi.org/10.1007/s00442-005-0100-x

Chave, J., Condit, R., Lao, S., Caspersen, J. P., Foster, R. B., & Hubbell, S. P. (2003). Spatial and Temporal Variation of Biomass in a Tropical Forest: Results from a Large Census Plot in Panama. *Journal of Ecology, 91,* 240-252. https://doi.org/10.1046/j.1365-2745.2003.00757.x

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. et al. (2014). Improved Allometric Models to Estimate the Aboveground Biomass of

Tropical Trees. *Global Change Biology, 20,* 3177-3190. https://doi.org/10.1111/gcb.12629

Chevallier, R. (2021). *The Urgent Race to Net Zero: Exploring African Priorities for COP 26.* https://www.africaportal.org/publications/urgent-race-net-zero-exploring-african-priorities-cop-26

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J. et al. (2014). Carbon and Other Biogeochemical Cycles Supplementary Material. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 465-570). Cambridge University Press.

Dabasso, B. H., Taddese, Z., & Hoag, D. (2014). Carbon Stocks in Semi-Arid Pastoral Ecosystems of Northern Kenya. *Pastoralism, 4,* 1-8. https://doi.org/10.1186/2041-7136-4-5

Dibaba, A., Soromessa, T., & Workineh, B. (2019). Carbon Stock of the Various Carbon Pools in Gerba-Dima Moist Afromontane Forest, South-Western Ethiopia. *Carbon Balance and Management, 14,* Article No. 1. https://doi.org/10.1186/s13021-019-0116-x

Dlugokencky, E., & Tans, P. (2018). *Trends in Atmospheric Carbon Dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL).* http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html

Dubeux Jr., J. C. B., dos Santos, M. V. F., de Mello, A. C. L., Vieira da Cunha, M., de Ferreira, M. A., dos Santos, D. C., de Lira, M. A., & da Silva, M. C. (2015). Forage Potential of Cacti on Drylands. *Acta Horticulturae, 1067,* 181-186. https://doi.org/10.17660/ActaHortic.2015.1067.24

Fouche, H. J., & Coetzer, G. M. (2015). Response of Cactus Pear (Opuntia spp.) Biomass Production to Fruit Load. *Acta Horticulturae, 1067,* 199-204. https://doi.org/10.17660/ActaHortic.2015.1067.27

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P. et al. (2019). Global Carbon Budget 2019. *Earth System Science Data, 11,* 1783-1838. https://doi.org/10.5194/essd-11-1783-2019

Gao, Y., Gao, X., & Zhang, X. (2017). The 2˚C Global Temperature Target and the Evolution of the Long-Term Goal of Addressing Climate Change—From the United Nations Framework Convention on Climate Change to the Paris Agreement. *Engineering, 3,* 272-278. https://doi.org/10.1016/J.ENG.2017.01.022

Gebeyehu, G., Soromessa, T., Bekele, T., & Teketay, D. (2019). Carbon Stocks and Factors Affecting Their Storage in Dry Afromontane Forests of Awi Zone, Northwestern Ethiopia. *Journal of Ecology and Environment, 43,* Article No. 7. https://doi.org/10.1186/s41610-019-0105-8

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and Estimating Tropical Forest Carbon Stocks: Making REDD a Reality. *Environmental Research Letters, 2,* Article ID: 045023. https://doi.org/10.1088/1748-9326/2/4/045023

Githae, E. W., & Mutiga, I. M. (2021). Ecological Restoration of Pastoral Landscapes in the Drylands of East Africa. *Journal of Dryland Agriculture, 7,* 34-41. https://doi.org/10.5897/JODA2020.0061

Glenday, J. (2008). Carbon Storage and Emissions Offset Potential in an African Dry Forest, the Arabuko-Sokoke Forest, Kenya. *Environmental Monitoring and Assessment, 142,* 85-95. https://doi.org/10.1007/s10661-007-9910-0

Gren, M., & Aklilu, A. Z. (2016). Policy Design for Forest Carbon Sequestration: A Review of the Literature. *Forest Policy and Economics, 70,* 128-136. https://doi.org/10.1016/j.forpol.2016.06.008

Harris, N. L., Brown, S., Hagen, S. C., Saatchi, S. S., Petrova, S., Salas, W., Lotsch, A. et al. (2012). Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science, 336,* 1573-1576. https://doi.org/10.1126/science.1217962

Henry, M., Picard, N., Trotta, C., Manlay, R., Valentini, R., Bernoux, M., & Saint-André, L. (2011). Estimating Tree Biomass of Sub-Saharan African Forests: A Review of Available Allometric Equations. *Silva Fennica, 45,* 477-569. https://hal.inrae.fr/hal-02651041 https://doi.org/10.14214/sf.38

Hoover, K., & Riddle, A. A. (2020). *Forest Carbon Primer.* Congressional Research Service. https://fas.org/sgp/crs/misc/R46312.pdf

Houghton, R. A., & Nassikas, A. A. (2018). Negative Emissions from Stopping Deforestation and Forest Degradation, Globally. *Global Change Biology, 24,* 350-359. https://doi.org/10.1111/gcb.13876

Houghton, R. A., House, J. I., Pongratz, J., Van Der Werf, G. R., Defries, R. S., Hansen, M. C., Ramankutty, N. et al. (2012). Carbon Emissions from Land Use and Land-Cover Change. *Biogeosciences, 9,* 5125-5142. https://doi.org/10.5194/bg-9-5125-2012

Hyvönen, P., Heikkinen, J., Haakana, H., Balazs, A., Muchiri, M. N., Kirongo, B. B., Ojuang, F. et al. (2016). *Technical Report on Sampling Design Simulations for National Forest Resources Assessment in Kenya.*

IMF (2019). Putting a Price on Pollution. *Finance & Development, 56,* 16-19.

Intergovernmental Panel on Climate Change (IPCC) (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Institute for Global Environmental Strategies.

Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (104 p.). IPCC.

Intergovernmental Panel on Climate Change (IPCC) (2013). Summary for Policymakers. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung et al. (Eds.), *Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3-29). Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC) (2018). Summary for Policymakers. In *Global Warming of 1.5˚C. An IPCC Special Report on the Impacts of Global Warming of 1.5˚C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (pp. 3-24). (In Press)

Intergovernmental Panel on Climate Change (IPCC) (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.*

Iqbal, M. A., Hamid, A., Imtiaz, H., Rizwan, M., Imran, M., Sheikh, U. A. A., & Saira, I. (2020). Cactus Pear: A Weed of Dry-Lands for Supplementing Food Security under Changing Climate. *Planta Daninha, 38,* e020191761. https://doi.org/10.1590/s0100-83582020380100040

Joos, F., & Spahni, R. (2008). Rates of Change in Natural and Anthropogenic Radiative Forcing over the Past 20,000 Years. *National Academy of Sciences, 105,* 1425-1430.

https://doi.org/10.1073/pnas.0707386105

Kagombe, J. K., & Owour, B. (2007). Community Managed Forests: A Case of Mukogodo Forest, Laikipia. In *Proceedings of the 1st National Participatory Forest Management Conference* (pp. 21-28). Kenya Forestry Research Institute, Nairobi.

Kagombe, J. K., Karriuki, J. G., & Luvanda, A.M. (2006). *Socio-Economic and Natural Resources Baseline Survey in Mukogodo Landscape, Laikipia District*. FORREMS Project Report. (Unpublished)

Keiluweit, M., Nico, P., Harmon, M. E., Mao, J., Pett-Ridge, J., & Kleber, M. (2015). Long-Term Litter Decomposition Controlled by Manganese Redox Cycling. *National Academy of Sciences, 112,* E5253-E5260. https://doi.org/10.1073/pnas.1508945112

Kenya Forest Service (KFS) (2008). *Integrated Forest Management Plan for Mukogodo forest.*

Kenya Indigenous Forest Conservation Programme (KIFCON) (1994). *Forest Inventory Report No. 15. Kenya Indigenous Forest Conservation Programme.* Mukogodo Forest.

Lal, R. (2004). Carbon Sequestration in Dryland Ecosystems. *Environmental Management, 33,* 528-544. https://doi.org/10.1007/s00267-003-9110-9

Lal, R. (2019). Carbon Cycling in Global Drylands. *Current Climate Change Reports, 5,* 221-232. https://doi.org/10.1007/s40641-019-00132-z

Lal, R., Lorenz, K., Hüttl, R. F., Schneider, B. U., & von Braun, J. (2012). Terrestrial Biosphere as a Source and Sink of Atmospheric Carbon Dioxide. In *Recarbonization of the Biosphere* (pp. 1-15). Springer. https://doi.org/10.1007/978-94-007-4159-1_1

M'mboroki, K. G., Wandiga, S., & Oriaso, S. O. (2018). Climate Change Impacts Detection in Dry Forested Ecosystem as Indicated by Vegetation Cover Change in Laikipia, of Kenya. *Environmental Monitoring and Assessment, 190,* 1-19. https://doi.org/10.1007/s10661-018-6630-6

MacDicken, K. G. (1997). *A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects.* Winrock International Institute for Agricultural Development.

Marklund, L. G., & Schoene, D. (2006). *Global Assessment of Growing Stock, Biomass and Carbon Stock*. Forest Resources Assessment Programme Working Paper 106, Food and Agriculture Organization of the United Nations Publication.

Meena, A., Bidalia, A., Hanief, M., Dinakaran, J., & Rao, K. S. (2019). Assessment of Above- and Belowground Carbon Pools in a Semi-Arid Forest Ecosystem of Delhi, India. *Ecological Processes, 8,* 1-11. https://doi.org/10.1186/s13717-019-0163-y

Mendelsohn, R., Sedjo, R., & Sohngen, B. (2012). Forest Carbon Sequestration. In *Fiscal Policy to Mitigate Climate Change* (pp. 89-102). International Monetary Fund.

Ministry of Environment and Forestry (MEF) (2019). *The National Forest Reference Level for REDD+ Implementation, Kenya.*

Ministry of Environment and Forestry (MEF) (2021). *Kenya's Updated Nationally Determined Contribution (NDC) and JCM Activities.*

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical Analysis of Root: Shoot Ratios in Terrestrial Biomes. *Global Change Biology, 12,* 84-96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Muchiri, M. N., & Gachathi, F. N. (2006). *Tree Inventory and Vegetation Survey of Mukogodo Landscape, Laikipia District.* FORREMS Project Report, Kenya. (Unpublished)

Nam, V. T., Van Kuijk, M., & Anten, N. P. (2016). Allometric Equations for Aboveground and Belowground Biomass Estimations in an Evergreen Forest in Vietnam. *PLoS ONE, 11,* e0156827. https://doi.org/10.1371/journal.pone.0156827

Ndambiri, J., Ngugi, J., & Maina, E. (2020). *Monitoring of Woodlands Biomass in Kenya:*

Technical Guide for Establishing Permanent Sample Plots for Monitoring above Ground Biomass in Kenya's Woodlands.

Nefzaoui, A., Louhaichi, M., & Ben Salem, H. (2014). Cactus as a Tool to Mitigate Drought and to Combat Desertification. *Journal of Arid Land Studies, 24,* 121-124.

Ng'ethe, R., Kariuki, A., & Opondo, C. (1997). Some Experience on Adaptive Research Input on Natural Resource Use: The Case of Gums and Resins in Mukogodo Rangelands, Laikipia District, Kenya. *Aidgum, 9,* 45.

Ngomanda, A., Obiang, N. L. E., Lebamba, J., Mavouroulou, Q. M., Gomat, H., Mankou, G. S., Picard, N. et al. (2014). Site-Specific versus Pantropical Allometric Equations: Which Option to Estimate the Biomass of a Moist Central African Forest? *Forest Ecology and Management, 312,* 1-9. https://doi.org/10.1016/j.foreco.2013.10.029

Njana, M. A. (2017). Indirect Methods of Tree Biomass Estimation and Their Uncertainties. *Southern Forests: Journal of Forest Science, 79,* 41-49. https://doi.org/10.2989/20702620.2016.1233753

Nobel, P. S. (1995). Recent Eco-Physiological Findings for *Opuntia ficus-indica* and Other Cacti. *Journal of the Professional Association for Cactus Development,* 1-11.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Hayes, D. et al. (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science, 333,* 988-993. https://doi.org/10.1126/science.1201609

Perez-Quezada, J. F., Delpiano, C. A., Snyder, K. A., Johnson, D. A., & Franck, N. (2011). Carbon Pools in an Arid Shrubland in Chile under Natural and Afforested Conditions. *Journal of Arid Environments, 75,* 29-37. https://doi.org/10.1016/j.jaridenv.2010.08.003

Petersson, H., Holm, S., Ståhl, G., Alger, D., Fridman, J., Lehtonen, A., Mäkipää, R. et al. (2012). Individual Tree Biomass Equations or Biomass Expansion Factors for Assessment of Carbon Stock Changes in Living Biomass—A Comparative Study. *Forest Ecology and Management, 270,* 78-84. https://doi.org/10.1016/j.foreco.2012.01.004

Raghubanshi, A. S. (1991). Dynamics of Soil Biomass C, N, and P in a Dry Tropical Forest in India. *Biology and Fertility of Soils, 12,* 55-59. https://doi.org/10.1007/BF00369388

Rajput, B. S., Bhardwaj, D. R., & Pala, N. A. (2017). Factors Influencing Biomass and Carbon Storage Potential of Different Land Use Systems along an Elevational Gradient in Temperate Northwestern Himalaya. *Agroforestry Systems, 91,* 479-486. https://doi.org/10.1007/s10457-016-9948-5

Simegn, T. Y., Soromessa, T., & Bayable, E. (2014). Forest Carbon Stocks in Lowland Area of Simien Mountains National Park: Implication for Climate Change Mitigation. *Science, Technology and Arts Research Journal, 3,* 29-36. https://doi.org/10.4314/star.v3i3.5

Singh, K., & Chand, P. (2012). Above-Ground Tree outside Forest (TOF) Phytomass and Carbon Estimation in the Semi-Arid Region of Southern Haryana: A Synthesis Approach of Remote Sensing and Field Data. *Journal of Earth System Science, 121,* 1469-1482. https://doi.org/10.1007/s12040-012-0237-z

Solomon, N., Birhane, E., Tadesse, T., Treydte, A. C., & Meles, K. (2017). Carbon Stocks and Sequestration Potential of Dry Forests under Community Management in Tigray, Ethiopia. *Ecological Processes, 6,* 20. https://doi.org/10.1186/s13717-017-0088-2

Solomon, N., Pabi, O., Annang, T., Asante, I. K., & Birhane, E. (2018). The Effects of Land Cover Change on Carbon Stock Dynamics in a Dry Afromontane Forest in Northern Ethiopia. *Carbon Balance and Management, 13,* 14. https://doi.org/10.1186/s13021-018-0103-7

Srinivas, K., & Sundarapandian, S. (2019). Biomass and Carbon Stocks of Trees in Tropical Dry Forest of East Godavari Region, Andhra Pradesh, India. *Geology, Ecology, and*

Landscapes, 3, 114-122. https://doi.org/10.1080/24749508.2018.1522837

Sun, W., & Liu, X. (2020). Review on Carbon Storage Estimation of Forest Ecosystem and Applications in China. *Forest Ecosystems, 7,* 4. https://doi.org/10.1186/s40663-019-0210-2

Tetemke, B. A., Birhane, E., Rannestad, M. M., & Eid, T. (2019). Allometric Models for Predicting Aboveground Biomass of Trees in the Dry Afromontane Forests of Northern Ethiopia. *Forests, 10,* 1114. https://doi.org/10.3390/f10121114

Tiessen, H., Feller, C., Sampaio, E. V. S. B., & Garin, P. (1998). Carbon Sequestration and Turnover in Semiarid Savannas and Dry Forest. *Climatic Change, 40,* 105-117. https://doi.org/10.1023/A:1005342932178

Trumper, K., Ravilious, C., & Dickson, B. (2008). *Carbon in Drylands: Desertification, Climate Change and Carbon Finance.* A UNEP-UNDP-UNCCD Technical Note for Discussions at CRIC 7, Istanbul, Turkey, 3-14 November, 2008.

Ubuy, M. H., Eid, T., Bollandsås, O. M., & Birhane, E. (2018). Aboveground Biomass Models for Trees and Shrubs of Exclosures in the Drylands of Tigray, Northern Ethiopia. *Journal of Arid Environments, 156,* 9-18. https://doi.org/10.1016/j.jaridenv.2018.05.007

Vashum, K. T., & Jayakumar, S. (2012). Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests—A Review. *Journal of Ecosystem & Ecography, 2,* 1-7. https://doi.org/10.4172/2157-7625.1000116

Webala, P. W., Muriuki, G., Lala, F., & Bett, A. (2006). The Small Mammal Community of Mukogodo Forest, Kenya. *African Journal of Ecology, 44,* 363-370. https://doi.org/10.1111/j.1365-2028.2006.00634.x

Weiskittel, A. R., MacFarlane, D. W., Radtke, P. J., Affleck, D. L., Temesgen, H., Woodall, C. W., Coulston, J. W. et al. (2015). A Call to Improve Methods for Estimating Tree Biomass for Regional and National Assessments. *Journal of Forestry, 113,* 414-424. https://doi.org/10.5849/jof.14-091

Wekesa, C., Leley, N., Maranga, E., Kirui, B., Muturi, G., Mbuvi, M., & Chikamai, B. (2016). Effects of Forest Disturbance on Vegetation Structure and Above-Ground Carbon in Three Isolated Forest Patches of Taita Hills. *Open Journal of Forestry, 6,* 142. https://doi.org/10.4236/ojf.2016.62013

World Bank (1993). *Ecologically Sensitive Sites in Africa. Volume II: Eastern Africa.* Compiled by the World Conservation Monitoring Centre for The World Bank. https://doi.org/10.5962/bhl.title.52367

World Bank (2020). *State and Trends of Carbon Pricing 2020.* World Bank.

Xu, L., Yu, G., He, N., Wang, Q., Gao, Y., Wen, D., Ge, J. et al. (2018). Carbon Storage in China's Terrestrial Ecosystems: A Synthesis. *Scientific Reports, 8,* Article No. 2806. https://doi.org/10.1038/s41598-018-20764-9

Zhao, M., Yang, J., Zhao, N., Liu, Y., Wang, Y., Wilson, J. P., & Yue, T. (2019). Estimation of China's Forest Stand Biomass Carbon Sequestration Based on the Continuous Biomass Expansion Factor Model and Seven Forest Inventories from 1977 to 2013. *Forest Ecology and Management, 448,* 528-534. https://doi.org/10.1016/j.foreco.2019.06.036

Annex

Overall biomass, carbon stocks and respective value in forest reserve, group ranches and conservancies in Mukogodo forest landscape under different vegetation types

Vegetation type	Biomass (TB ha^{-1})	Carbon (TC ha^{-1})	Total area (ha)	Total biomass (T)	Total Carbon (T)	CO$_{2eq}$ (T)	Lowest value (US$)	Moderate value (US$)	Highest value (US$)
1. Mukogodo forest reserve									
Closed forest	273.82	128.70	17,625.06	4,826,093.93	2,268,345.22	8,324,826.96	16,649,653.93	170,325,959.70	665,986,157.18
Open	72.92	34.27	9167.67	668,506.50	314,176.05	1,153,026.11	2,306,052.21	23,590,914.15	92,242,088.54
Grassland	92.13	43.30	1817.55	167,450.88	78,699.92	288,828.69	577,657.38	5,909,434.96	23,106,295.04
Shrubland	23.70	11.14	593.01	14,054.34	6606.13	24,244.50	48,489.00	496,042.52	1,939,560.18
Opuntia	63.52	30.17	323.89	20,573.49	9771.76	35,862.36	71,724.73	733,743.97	2,868,989.12
Bare land	8.49	3.99	10.62	90.16	42.37	155.51	311.02	3181.77	12,440.95
Total	534.58	251.57	29,537.80	5,696,769.30	2,677,641.45	9,826,944.14	19,653,888.28	201,059,277.06	786,155,531.01
2. Laikipia ranches									
Shrubland	12.05	5.66	6996.60	84,309.03	39,600.76	145,334.77	290,669.55	2,973,549.49	11,626,781.96
Grassland	14.87	6.99	7931.52	117,941.70	55,441.32	203,469.66	406,939.32	4,162,989.28	16,277,572.96
Closed forest	273.82	128.70	2832.93	775,712.89	364,598.09	1,338,074.99	2,676,149.99	27,377,014.38	107,045,999.52
Open	72.92	34.27	11,834.64	862,981.95	405,573.11	1,488,453.32	2,976,906.65	30,453,755.01	119,076,265.92
Opuntia	63.52	30.17	1683.09	106,909.88	50,778.83	186,358.29	372,716.58	3,812,890.59	14,908,663.11
Bare land	8.49	3.99	685.62	5820.91	2735.62	10,039.74	20,079.48	205,413.07	803,179.15
Total	445.67	209.78	31,964.40	1,953,676.36	918,727.73	3,371,730.78	6,743,461.57	68,985,611.81	269,738,462.61
3. Isiolo conservancies									
Shrubland	27.59	12.97	33,700.59	929,799.28	437,096.65	1,604,144.71	3,208,289.43	32,820,800.85	128,331,577.12
Grassland	22.61	10.63	20,682.09	467,622.05	219,850.62	806,851.76	1,613,703.53	16,508,187.08	64,548,141.06
Closed forest	273.82	128.70	2672.46	731,773.00	343,945.60	1,262,280.36	2,524,560.72	25,826,256.15	100,982,428.75
Open	72.92	34.27	20,990.25	1,530,609.03	719,335.87	2,639,962.63	5,279,925.27	54,013,635.49	211,197,010.70
Opuntia	63.52	30.17	2314.71	147,030.38	69,834.80	256,293.72	512,587.44	5,243,769.48	20,503,497.49
Bare land	8.49	3.99	11,247.30	95,489.58	44,876.73	164,697.59	329,395.18	3,369,712.65	13,175,807.05
Total	468.95	220.73	91,607.40	3,902,323.32	1,834,940.27	6,734,230.78	13,468,461.55	137,782,361.70	538,738,462.16
Grand total	1449.20	682.08	153,109.60	11,552,768.98	5,431,309.45	19,932,905.70	39,865,811.39	407,827,250.57	1,594,632,455.78