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Research Article

Estimating above-ground biomass and carbon stock of a date palm (*Phoenix dactylifera* L.) tree using Sentinel 2 imagery in Afambo district, Northern Ethiopia

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Abstract

Accurate estimation of forest aboveground biomass (AGB) and carbon stocks is crucial for sustaining forest management and mitigating climate change, supporting REDD+ (reducing emissions from deforestation and forest degradation, plus the sustainable management of forests and the conservation and enhancement of forest carbon stocks) processes. The main objective of this study was to estimate the aboveground biomass and carbon stock of a date palm tree using Sentinel-2 imagery in Afambo District, Northern Ethiopia. Five variables, two vegetation indices, i.e., IRICI and NDVI, and three biophysical variables, i.e., FVC, FPAR, and LAI, were extracted from Sentinel-2 imagery and used to construct the AGB prediction model. Forest stand parameters, such as DBH and tree height, were collected on July 15, 2022, at 20×20 m within 88 plots and used to determine in situ AGB using an allometric equation. The correlations between the AGB measured in each plot and the variables extracted from the Sentinel-2 images were assessed using Pearson correlation analysis and were used to estimate AGB. A strong correlation was observed between the field AGB and predictor variables, with a coefficient of determination (R^2) ranging from 0.47 to 0.89. Among the overall variables, vegetation indices were strongly correlated ($R^2 = 0.84-0.89$) with aboveground biomass. Relatively good correlations ($R^2 = 0.47-0.57$) were recorded between the 2 sentinel-extracted biophysical variables and AGB. The model has a coefficient of determination value of 0.79, and overall, the Sentinel 2 variables performed better in estimating AGB. Integrating field data with remote sensing methods increases the accuracy of estimating forest AGB and carbon stocks.

Keywords: Aboveground biomass, Sentinel imagery, Carbon stock, Vegetation indices, Biophysical variables

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1. INTRODUCTION

Greenhouse gas emissions are aggravated by land use/land cover changes (LU/LCC), which account for 14% of all anthropogenic causes and have a significant influence on human living conditions (Badgley 2003). Different LU/LC types store carbon in vegetation and soil, as well as release or absorb greenhouse gases such as carbon dioxide from the atmosphere (Gitarskiy 2019). Tropical rainforests, in particular, have a considerable impact on the global carbon cycle, storing nearly 40% of the globe's terrestrial carbon(Issa et al., 2019; Pandey et al., 2019). Also, date palm forests are critical for regulating CO_2 levels in the atmosphere (Betemariyam and Kefalew 2022; Pandey et al. 2019).

Aboveground biomass data of date palm tree (AGB) play an important role in mitigating climate change by sequestering a significant amount of carbon in aboveground biomass, which in turn reduces climate change. It's also the data of above-ground biomass data of date palms favor REDD+ (reducing emissions from deforestation and forest degradation), as well as the protection and maintenance of forest carbon reserve processes, which play a vital role in reducing sequestered carbon(Issa et al., 2019; Pandit et al., 2018). As a result, investigating and evaluating AGB at various geographical and temporal scales is crucial for reducing variability in carbon stock assessments and adds value to forest management strategies that address greenhouse gas emissions (Taddese et al. 2020). Ethiopia plans to use remote sensing data to gather information for forest service management, monitoring, reporting, and confirmation of forest stand volume and biomass (Shiferaw, Kassawmar, and Zeleke 2022).

Biomass measurements are being used to determine forest carbon sinks and other factors using modelling and scientific methods. (Pandit et al. 2018). Sentinel-2 recorded an image with a 290-kilometer swath width in 13 spectral bands extending from visible and near-infrared (NIR) wavelengths to shortwave infrared wavelengths with fine (10, 20 m) and coarse (60 m) spatial resolutions (Ali et al. 2018). Furthermore, the occurrence of four bands located at 705 (band 5), 740 (band 6), 783 (band 7), and 865 nm (band 8a) within the red-edge region gives the sensor considerable potential for mapping major vegetation properties (Mauya and Madundo, 2022). For instance, the potential of Sentinel-2 MSI red-edge bands for estimating grass nutrients has been successfully demonstrated (Mauya and Madundo, 2022). Similarly, a study in rural Burkino Faso used Landsat 8 and Sentinel-2 data for mapping LU/LC and discovered that Sentinel-2 red-edge bands alone delivered better results than did Landsat 8 and comparable results to those of other Sentinel-2 bands (*i.e.*, visible, NIR, and SWIR) (Forkuor et al. 2018).

This study estimates the AGB of date palm forests in Ethiopia's Afar area using a correlation and regression approach. A typical way to construct AGB estimation models is through regression analysis (Lu 2006). If linear regression somehow does not appear to indicate a substantial correlation between AGB and retrieved variables after determining the link, multilinear regression must be used to model AGB (McRoberts, Næsset, and Gobakken 2013). Remote sensing images have become efficient data sources for AGB estimation (Li et al., 2021).

This study presents the first spatial estimation and mapping of aboveground biomass and carbon stock for date palm plantations in the Afambo district using Sentinel-2 imagery. While remote sensing has been widely applied for biomass estimation in various ecosystems, challenges remain in selecting appropriate sensors, variables, and algorithms across different ecological settings (Issa et al., 2019). To address this gap, we developed a predictive model based on vegetation indices and biophysical variables derived from Sentinel-2 data. The primary objective was to estimate and map aboveground biomass and carbon stocks, thereby providing a baseline for sustainable management and serving as a reference for similar dryland ecosystems.

2. MATERIALS AND METHODS

2.1. Study area

Four districts in Afar have experienced cultivating date palms, namely, Afambo, Aysaita, Gewane,and Amibara (Takele, Tsegaw, and Indracanti 2021). Because it is close to the end of the Awash River (Lake Abe) and has an extended period of community experience in date cultivation (Hussen 2010; Lemlem, Alemayehu, and Endris 2018, 2019). The Afambo district was purposively selected for this study. As part of administrative zone one, Afambo is situated in the eastern part of the region and shares international boundaries with Djibouti in the east and regional boundaries with Dubti in the west, Aysaita in the north, and the Ethiopian Somali region in the south. Geographically, the Afambo district is situated between 41^0 24” and 41^0 43” in the east and 10^0 57” and 11^0 33” in the north, as shown in Figure 1. The Awash River is the main gift of the district, and its final destination is Lake Abe in this district. It serves as the main water source for people (Betemariyam and Kefalew 2022).

The major crops grown in the districts were maize, and vegetables, fruits, oil crops, and date palms are cultivated in a limited range as sources of food and income (Alemu and Taye 2020). The average temperature of the area is approximately 38°C, and the rainfall is bimodal with an erratic distribution, with the long rainy season (*Kerma*) occurring between mid-June and mid-September and the short rainy season (*Sugum*) occurring between March and April, and the average annual rainfall is between 110 and 200 mm (Lemlem et al. 2019).

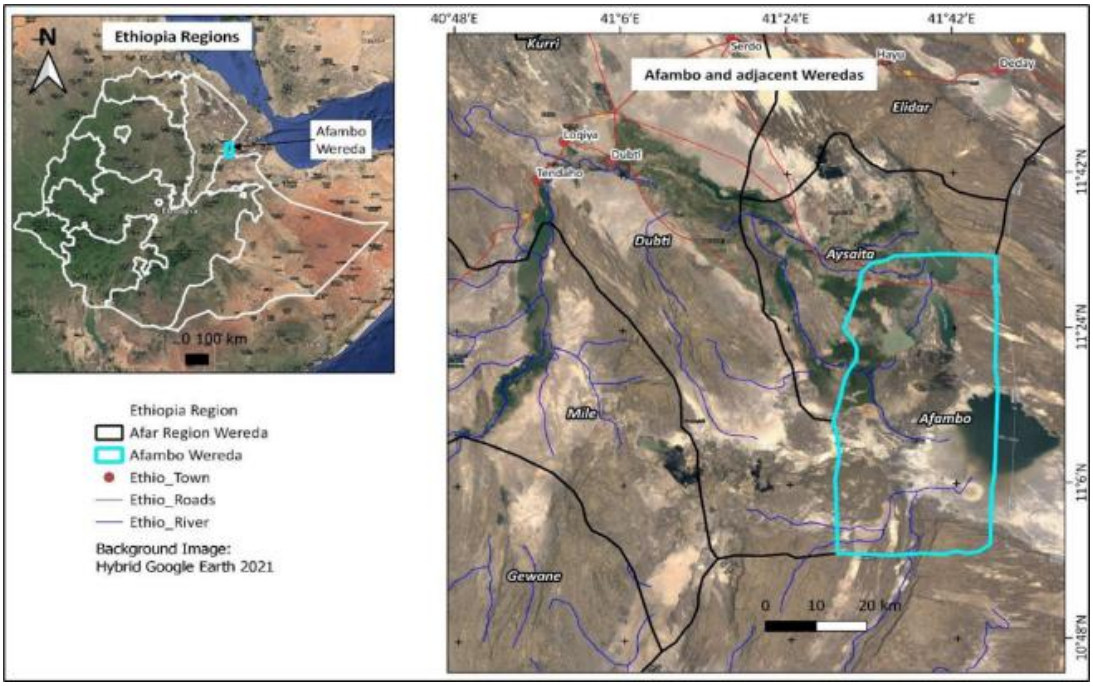


Figure 1. Map of study area

2.2. Data and Sources

The data sources for estimating the above AGB of the date palm tree and carbon stock were the Sentinel 2 images downloaded from ESA (European Space Agency), and in situ (field) measurements were taken. The final maps and statistics were analysed using statistical software for social science (SPSS) and ArcMap 10.8 software, as shown in Table 1 below.

Table 1. Lists of data with their purpose and source

Data	Purpose	Sources
Sentinel-2 MSI	Image for extracting biophysical variables and vegetation indices	ESA (European Space Agency)
Forest DBH and Height	Used to compute in situ AGB using an Allometric equation	An allometric equation and field measurement
Coordinate points (latitude, longitude, and elevation)	By creating coordinates first and then navigating to the point's location, plot locations in the field.	Co-ordinate created on ArcMap

2.3. Data analysis and sampling design

The study's field sample plots were 88 in total, rectangular in shape, and 20 × 20 (400 m^2) in size. Primarily, transect lines reaching the border of the date orchard were established, and

20x20 m sampling plots were laid out. Here, a nested plot design was used to collect data on biomass. Based on the size of the date orchard, the distance between (parallel) transect lines was adjusted to 50 to100 m. The goal of the fieldwork was to determine the aboveground biomass in the study area. This information was used as the ground truth for both the estimation and validation of biomass prediction. However, when performing a forest inventory, we must establish a correlation between directly measurable tree or stand characteristics and other forest stand factors, such as volume or biomass, which cannot be directly measured. Biomass estimation equations, also known as allometric equations or regression models, were used to estimate the aboveground biomass of tree components based on DBH and total tree height data.

Date diameter at breast height (DBH), crown diameter (CD), and trunk height (Ht) were measured at Alasabolo Kebele. The sphere equation (Eq. 1) was used to compute the crown area (CA) of each date palm tree.

$$CA = ¼\ \pi CD^2 \qquad \text{Equ. 1}$$

where CA= crown area and CD= crown diameter

2.4. Date palm biomass and carbon stock analysis using an allometric equation

2.4.1. Biomass data analysis

The aboveground biomass (AGB) was estimated using the allometric equation (Eq. 2) developed for date palm in the United Arab Emirates (UAE) (Issa et al. 2018). Although this equation was not originally developed for Ethiopia, it was selected owing to the lack of locally developed, species-specific allometric models for date palm in the study area. The UAE and Afambo district share some comparable arid to semi-arid biophysical conditions, including high temperatures, low annual rainfall, and similar dryland vegetation characteristics, which partially support its application(Issa et al. 2018).

$$AGB = CB + TB \qquad \text{Equ. 2}$$

$$\text{Crown Biomass (CB)} = 14.034 \times e^{0.0554 \times CA} \qquad \text{Equ. 3}$$

$$\text{Trunk Biomass (TB)} = 40.725 \times Ht^{0.9719} \qquad \text{Equ. 4}$$

where AGB is the aboveground biomass (ton/pixel), CB is the crown biomass (ton/pixel), TB is the trunk biomass (ton/pixel), CA is the crown area (m^2), and Ht is the height (m).

2.4.2. Carbon stock estimation

The organic carbon content is the dry weight organic content of all components of the date palm (Cierjacks et al., 2012). The conversion factor from date biomass to organic carbon stock is expressed in Equation 5.

Aboveground carbon stock (ton/pixel) = 0.5387 × AGB Equ. 5

where AGB is the aboveground biomass (ton/pixel), and the overall flow chart of the study is shown in Figure 2.

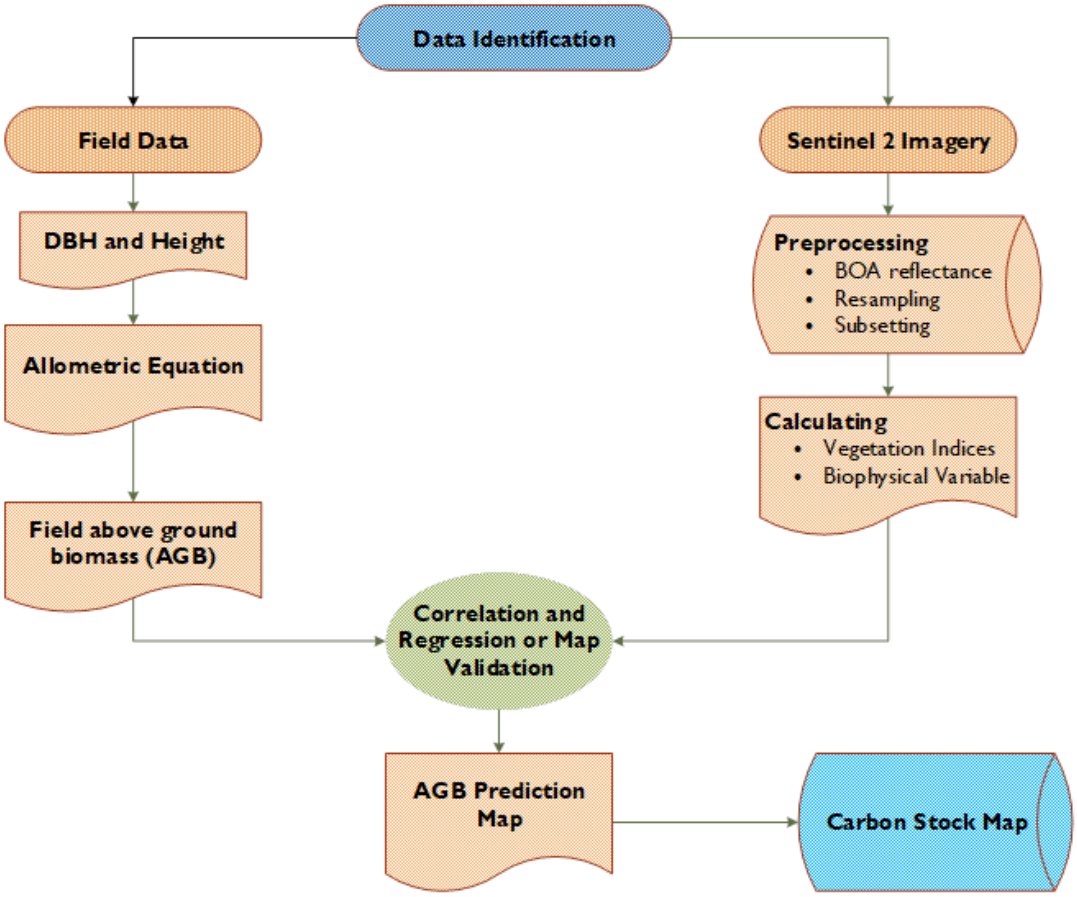


Figure 2. Flow chart of the study

3. RESULTS

3.1. Field aboveground biomass

The aboveground biomass from the field forest parameter was computed using an allometric equation for the 88-sample plot. The aboveground biomass for each plot was converted from kg to tons to correlate with variables extracted from the Sentinel imagery. The highest above-ground biomass was 0.26 ton/pixel, which included dense and large date palm trees, followed by 0.25 ton/pixel and 0.24 ton/pixel, respectively. The lowest AGB was 0.10 ton/pixel, which was relatively short of trees. The plots with large and dense date palm trees had greater AGB than the plots with relatively short trees, as shown in Table 2.

Table 2. The maximum, minimum, mean, and std. deviation of the above-ground biomass of the date palm tree

Parameters	N	Min	Max	Mean	Std. Deviation
AGB	88	0.10	0.26	0.4087	0.09793
NDI	88	0.25	0.10	0.4194	0.09663
IRICI	88	0.10	0.26	0.3906	0.08982
FPAR	88	0.08	0.35	0.4659	0.10019
FVC	88	0.10	0.27	0.4388	0.10957
LAI	88	0.10	0.27	0.4364	0.42367

3.2. Correlation of the Sentinel-2 variable with the field AGB

Pairwise correlations between Sentinel-2-derived predictors and field-measured AGB were evaluated using scatter plots (Figuress. 3&4). Coefficient of determination (R^2) values ranged from 0.47 to 0.89, indicating moderate to strong linear relationships. Among vegetation indices, NDVI exhibited the strongest correlation with AGB ($R^2 = 0.89$), followed by IRECI ($R^2 = 0.83$) and FVC ($R^2 = 0.56$). Overall, vegetation indices demonstrated superior explanatory capacity ($R^2 = 0.56–0.89$) compared to biophysical variables ($R^2 = 0.47–0.57$), which included LAI and FAPAR (Figure 4). These findings confirm the utility of both spectral and biophysical metrics for AGB estimation, with vegetation indices showing comparatively stronger predictive potential.

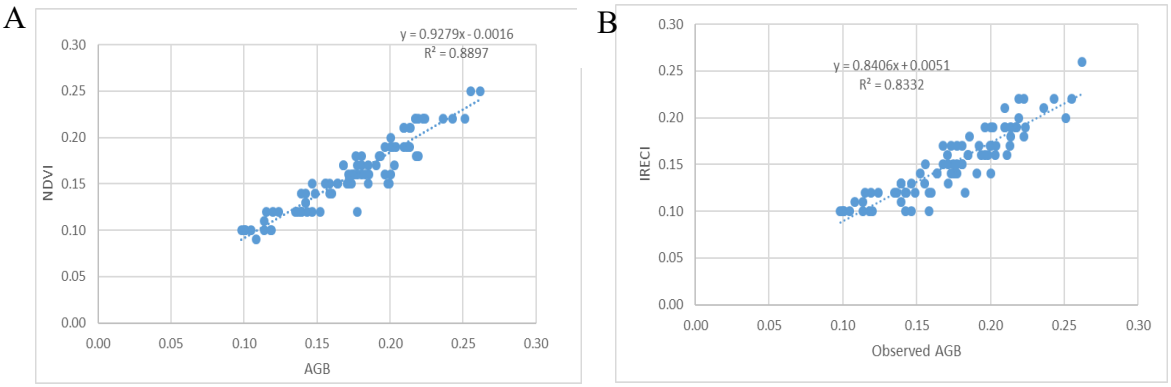


Figure 3 (A) Scatter plot showing the correlation between NDVI and field-measured aboveground biomass (AGB); (B) scatter plot showing the correlation between IRECI and field-measured aboveground biomass (AGB).

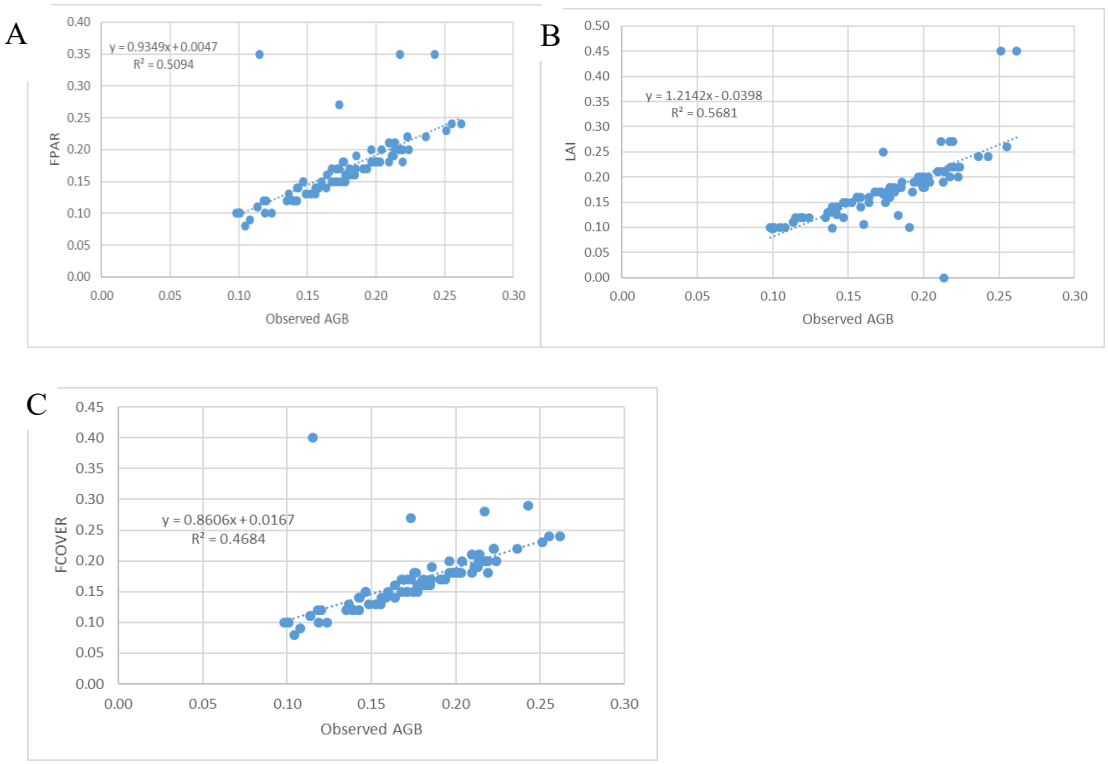


Figure 4. (A) Scatter plot showing the correlation between FPAR and field-measured aboveground biomass (AGB); (B) scatter plot showing the correlation between LAI and field-measured AGB; and (C) scatter plot showing the correlation between FCOVER and field-measured AGB.

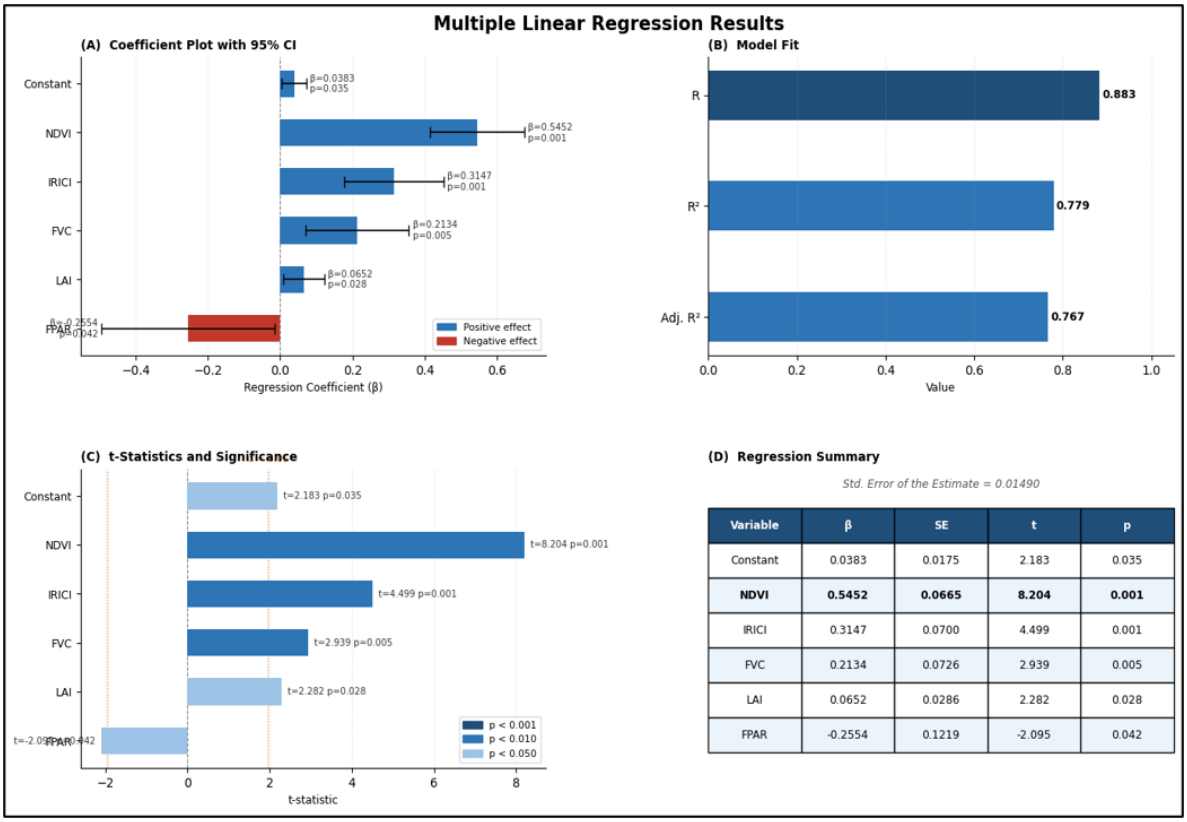
3.3. Model development for AGB prediction

A stepwise multiple linear regression model was developed in SPSS to predict aboveground biomass (AGB) using five variables significantly correlated with field measurements: NDVI, IRICI, FVC, LAI, and FAPAR. Variable selection was guided by correlation strength, coefficient of determination, and multicollinearity diagnostics. The final model exhibited strong predictive performance ($R = 0.883$, $R^2 = 0.779$, adjusted $R^2 = 0.767$) with a low standard error of the estimate (0.01490), indicating that approximately 77% of AGB variability was explained while minimizing overfitting risk (Figure 5). All predictors were statistically significant ($p < 0.05$). NDVI was the dominant predictor ($\beta = 0.545$, $p < 0.001$), followed by IRICI ($\beta = 0.315$, $p < 0.001$), FVC ($\beta = 0.213$, $p = 0.005$), LAI ($\beta = 0.065$, $p = 0.028$), and FAPAR ($\beta = -0.255$, $p = 0.042$). Notably, while NDVI, IRICI, FVC, and LAI showed positive effects, FAPAR exhibited a significant negative relationship with AGB, suggesting that increased radiation absorption may not directly translate to biomass accumulation, potentially due to vegetation structural constraints or environmental stress.

Finally, Equation 6 was developed to predict aboveground biomass using Sentinel-extracted variables.

$$AGB = 0.0383 - 0.2554(FPAR) + 0.3147(IRICI) + 0.5452(NDVI) + 0.2134(FVC) + 0.0652(LAI) \quad \text{Equ. 6}$$

Where, LAI=Leaf area index, IRECI= inverted red-edge chlorophyll index, FAPAR= Fraction of Absorbed Photosynthetically Active Radiation, NDVI= Normalized Difference Vegetation Index, and FVC= Fractional Vegetation Cover.



Variable	β	SE	t	p
Constant	0.0383	0.0175	2.183	0.035
NDVI	**0.5452**	**0.0665**	**8.204**	**0.001**
IRICI	0.3147	0.0700	4.499	0.001
FVC	0.2134	0.0726	2.939	0.005
LAI	0.0652	0.0286	2.282	0.028
FPAR	-0.2554	0.1219	-2.095	0.042

Figure 5. Scatter plot of biophysical variables with observed AGB (A) Regression coefficient estimates with 95% confidence intervals; (B) model fit; (C) t-statistics and significance levels; and (D) regression model summary.

3.4. Assessment of the accuracy of the estimated aboveground biomass

The predicted aboveground biomass (AGB) values for 22 independent validation pixels were extracted at the corresponding field plot locations and compared with the measured field AGB values from 22 plots. The relationship between observed and predicted AGB showed a strong positive correlation, with a coefficient of determination (R^2) of 0.78 (Figure 6), indicating good predictive performance of the developed model. Although the validation dataset consisted of only 22 plots, these plots were independently reserved from the model calibration process and represented the range of biomass conditions within the study area. The satisfactory agreement between predicted and observed AGB suggests that the model is suitable for spatial estimation of AGB and carbon stock across the study area. Nevertheless, the relatively small number of

validation plots may limit the statistical robustness of the assessment, and future studies should incorporate larger validation datasets, cross-validation techniques, and independent external datasets to further evaluate model reliability and generalizability. Based on the achieved validation accuracy, the model was subsequently applied to generate the final AGB and carbon stock maps.

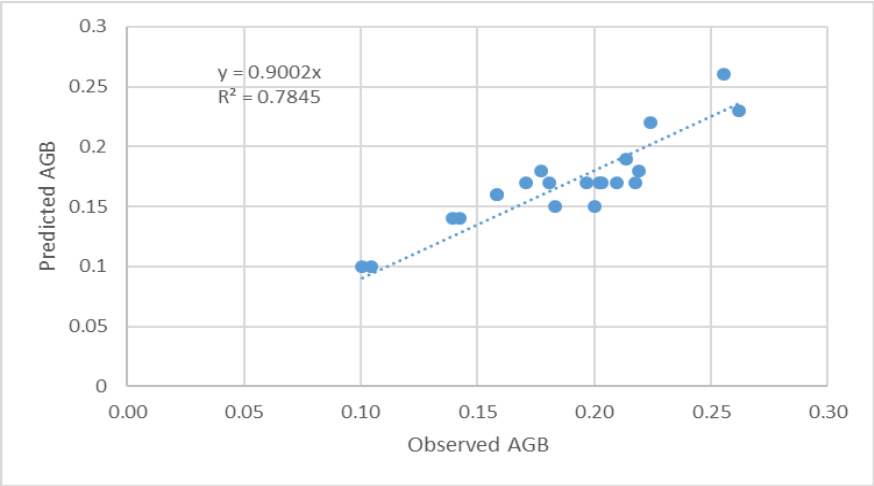


Figure 6. Scatter plot showing model validation of observed and predicted aboveground biomass

3.5. Mapping forest aboveground biomass and carbon stock

The developed AGB model, which achieved a satisfactory validation accuracy ($R^2 = 0.78$), was applied to generate a spatially explicit aboveground biomass (AGB) map of the date palm forest using the raster calculator in ArcGIS (Figure 7). The resulting map revealed considerable spatial variation in biomass distribution across the study area. Three AGB classes were identified, ranging from low biomass (-0.20–0.18 ton/pixel), moderate biomass (0.18–0.44 ton/pixel), to high biomass (0.44–1.01 ton/pixel). The low-biomass class (red) dominated a large proportion of the study area, indicating sparse vegetation cover or non-date-palm land-cover types. Areas with moderate biomass (yellow) were scattered throughout the forest landscape and likely represent transitional zones with intermediate vegetation density and productivity.

The highest AGB values (green) were concentrated mainly in the northwestern part of the study area, suggesting the presence of relatively dense and mature date palm stands with greater carbon storage potential. These areas may benefit from favorable environmental conditions, reduced disturbance, or better management practices compared to other parts of the study area. The observed spatial heterogeneity in AGB highlights differences in vegetation density and forest condition across the landscape. Since aboveground biomass is directly related to carbon storage, areas with high biomass are expected to contribute substantially to carbon sequestration

and should therefore be prioritized for conservation and sustainable management. The generated biomass map provides valuable information for forest resource assessment, carbon stock estimation, and future monitoring of date palm forest dynamics.

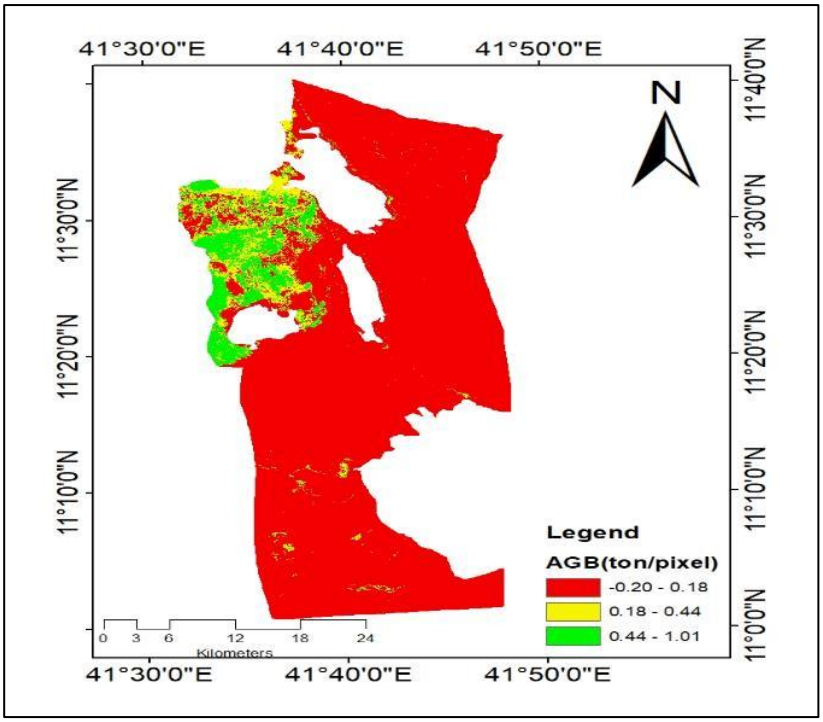


Figure 7. Aboveground biomass map of the date palm forest in Afambo District

The carbon stock map was derived from the estimated aboveground biomass (AGB) using the standard biomass-to-carbon conversion factor (Figure 8). The spatial distribution of carbon stocks exhibited substantial variability across the date palm forest landscape, reflecting the heterogeneous distribution of biomass within the study area. Carbon stock values ranged from approximately −0.11 to 0.54 ton/pixel, and were categorized into three classes: low carbon stock (−0.11–0.10 ton/pixel), moderate carbon stock (0.10–0.23 ton/pixel), and high carbon stock (0.23–0.54 ton/pixel). The low carbon stock class (red) occupied the largest proportion of the study area, indicating areas with sparse vegetation cover, low biomass accumulation, or degraded forest conditions. Moderate carbon stock areas (yellow) were distributed in fragmented patches and represented zones with intermediate biomass density and carbon sequestration capacity. Areas with high carbon stock values (green) were concentrated primarily in the northwestern portion of the study area, corresponding to locations where high AGB values were observed. These areas likely contain relatively dense and mature date palm stands that contribute significantly to carbon storage and sequestration. The concentration of carbon-rich areas in

specific locations suggests that carbon storage potential is not uniformly distributed throughout the forest ecosystem. The spatial pattern of carbon stocks demonstrates a strong relationship between vegetation density and carbon sequestration potential. Areas exhibiting higher carbon stocks are ecologically important because they act as significant carbon sinks, helping to mitigate atmospheric carbon dioxide concentrations. Consequently, these high-carbon areas should be prioritized for conservation and sustainable management to maintain their ecosystem services and climate-regulation functions.

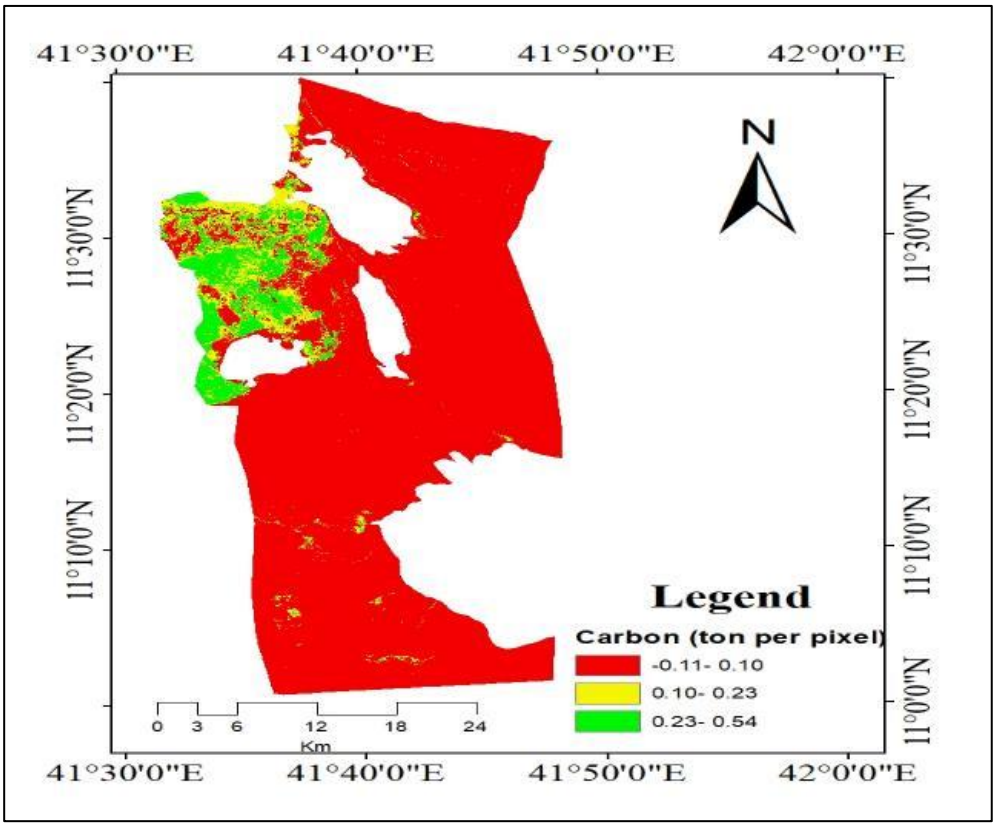


Figure 8. Carbon stock map of the date palm plantation in Afambo District.

4. DISCUSSION

4.1. Correlation of measured forest aboveground biomass and Sentinel-2-extracted variables

According to our study results, the AGB in the region ranged largely from 0.10 to 0.25 ton/pixel. Due to human activity, it decreased to less than 0.10 ton/pixel in areas of landscapes that are close to roads and other types of land cover, particularly in areas close to agricultural lands. Only a small portion of the forest in the core zone, which is distant from anthropogenic activity, less degraded, and more difficult to reach, had an AGB value higher than 0.26 ton/pixel. Figure 7 presents the map of carbon stocks in the date palm forest; thus, the area with the highest

carbon stocks, exceeding 7.05 tons/pixel, was the most difficult to access. The area that was easily accessible and close to the road and other land cover types contained carbon stocks that were less than 2.82 ton/pixel. This study showed the potential advantages and viability of replacing conventional field measurements and widely used remote sensing techniques with a quick, low-cost method for increasing biomass.

According to Chen et al., (2021) The potential of Sentinel-2 data for estimating pasture biomass using machine learning was highly accurate (R^2=0.81 and RMSE=0.25 ton/pixel). Vegetation indices and forest AGB were strongly correlated in the present research. This demonstrates the value of the improved spectral resolution of the Sentinel-2 data and that the strongest associations between field biomass and all vegetation indices and biophysical factors were estimated from the Sentinel-2 data. Compared to biophysical variables (R^2 = 0.47 0.57), vegetation indicators performed better (R^2= 0.56-0.89).

According to Muhe, (2019) vegetation indices, and biophysical variables of Sentinel-2 were the most relevant and important predictors for explaining the observed variability in AGB. Compared with other open-source sensor data products, the Sentinel-2A product has comparatively extensive spatial coverage and high resolution for efficient estimation of biomass (Belloli et al. 2022). Liang et al. (2019) stated that the estimation of the aboveground biomass of horticultural crops and forests depends critically on optical sensors of Sentinel 2 images that are sensitive to leaf features and linkages with the woody component of the vegetation.

In line with our study Belloli et al., (2022), demonstrated that the carbon stock of oil palm plantations in Malaysia was 440.09 kg palm^{-1}. Aboveground carbon stocks for oil palm plantations ranged from 0.31 to 0.62 ton/pixel for young plantations of 10 years and 0.96–1.01 ton/pixel for stands aged 14 and 19 years (Siarudin et al. 2021). In Sumatra, Indonesia, aboveground carbon stocks reached 0.09 ton/pixel in 3-year-old plantations and 0.35, 0.42, and 0.55 ton/pixel in 10-, 20-, and 30-year-old plantations, respectively (Novita et al. 2021). In the DPF, date palm trees stored more than 98% of the total biomass carbon. The mean biomass carbon stock of the DPF in this study was relatively greater than the biomass carbon stocks reported for home gardens (0.08 ton/pixel), parklands (0.08 ton/pixel), woodlots (0.31 ton/pixel), and boundary plantations (0.04 ton/pixel) in the lowlands, midlands, and highlands of Tigray, Ethiopia. These differences may be attributed to variations in the selected variables and biomass estimation equations, as well as limitations in integrating field measurements and remote sensing data (Dereje 2021). A study conducted in northeastern Brazil also reported greater biomass

carbon stocks than those of oil palm plantations (0.35 ton/pixel). Due to discrepancies in satellite-derived data across diverse land-cover types, the developed biomass estimation equation was recommended only for application within the study region (Belloli et al. 2022).

5. CONCLUSION

This study demonstrated the potential of Sentinel-2-derived vegetation indices and biophysical parameters for estimating aboveground biomass (AGB) and carbon stock of date palm trees in the Afambo district. The results show a generally strong relationship between field-measured biomass and remotely sensed variables, with correlation coefficients ranging from 0.47 to 0.89. Among the tested predictors, NDVI, IRICI, LAI, FPAR, and FVC showed the highest explanatory power and collectively provided a reliable basis for biomass estimation.

The final multilinear regression model achieved a moderate predictive performance ($R^2 = 0.78$), indicating that Sentinel-2 data can reasonably capture spatial variability in biomass under semi-arid plantation conditions. Despite these encouraging results, the model's performance suggests some limitations. The moderate R^2 indicates that a portion of biomass variation remains unexplained, likely due to the relatively sparse vegetation structure in the study area, mixed pixel effects, and limited field sample size. In addition, optical indices alone may not fully capture structural differences in tree height and canopy volume, which are important for improving biomass estimation accuracy. From a practical perspective, the findings support the use of Sentinel-2-based biomass estimation as a cost-effective tool for supporting REDD+ initiatives, particularly in monitoring carbon stock changes and guiding land management decisions in data-scarce dryland environments.

The approach can assist policymakers in identifying areas of low and high carbon storage, supporting restoration planning and sustainable land-use strategies in the Afambo district and similar agro-ecological settings. Future research should focus on integrating additional data sources such as LiDAR or SAR (e.g., Sentinel-1) to better capture vegetation structure and reduce uncertainty. Expanding field sample size and incorporating machine learning algorithms could also improve model robustness and transferability to other regions.

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