Biomass And Carbon Sequestration Capacity Of FSC-Certified Acacia Plantations In Quang Nam Province, Vietnam

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**Abstract:** Forests play a crucial role in mitigating climate change, with tropical forests storing approximately 50% of global carbon. Accurate biomass estimation is vital for understanding the global carbon cycle, guiding forest management, and addressing energy needs. The study focuses on the Acacia hybrid, a dominant species with short harvesting cycles, necessitating an extension to meet the growing demand for FSC-certified wood. Assessing carbon reserves is essential for informed decision-making, and aligning economic and environmental interests. The methodology involves secondary data collection and primary data from sample plots, considering factors like diameter, height, volume, and existing density. The results shown that total fresh biomass gradually increased from 23.578 to 242.852 tons/ha and the dry biomass increased from 9.874 to 118.428 tons/ ha for age 1 to age 7 forest. On average, forests absorb 7.632 tons of C/ha/year, equivalent to 28 tons of CO2/ha/year.The relationship between diameter and forest age can be used the equation: D = 3.1077A0.7535. Meanwhile, the relationship between density and forest age is N = 4426.3 – 1152.Ln(A) Regression analysis aids in forecasting forest productivity, emphasizing the optimal rotation cycle of 9 to 10 years for economic and environmental sustainability.

**Keywords:** Carbon sequestration, FSC-certified, Acacia plantations, Forest density, Sustainable Forestry

1. INTRODUCTION

Forests play an important role in combating climate change due to their impact on the global carbon cycle. Tropical forests store about 50% of carbon volume in vegetation and 50% in soil [1,2]. Accurately estimating the biomass of trees and forests is important in assessing the global carbon cycle, especially in forest management, planning and use, and energy use in forest biomass [3-5]. Emissions of CO2 and other greenhouse gases have increased over the past century [6]; thus, raising environmental problems and leading to concerns about climate change and development strategies of countries around the world [7]. Carbon sequestration is considered a pathway to mitigate climate change [1,8]. Forests can maintain carbon balance through significant carbon sequestration. Forest ecosystems play an irreplaceable role in minimizing atmospheric CO2 accumulation and maintaining global climate stability [9, 10]. Planted forests are considered an effective tool to combat climate change because of their ability to absorb carbon, and they also play an increasingly important role in regulating future climate. Some studies also show that the ability of short-term rotation plantations to remove carbon from the atmosphere is highly effective if there is a suitable impact method.

In Quang Nam province, the Acacia hybrid grows rapidly and dominates the province's forestry species structure, especially among households. However, Acacia hybrid forests are mostly planted and harvested with short cycles, mainly providing wood chips. Meanwhile, with the increasing demand for roundwood, especially FSC-certified wood, it is necessary to keep Acacia hybrid forests for longer rotation (at least 8 years) and achieve FSC certification. One way to encourage households to extend the rotation of Acacia hybrid forests to reach roundwood products is to receive support or shares from the above-ground carbon storage of FSC-certified forests, not only increasing high economic efficiency from Roundwood products but also accumulating carbon to contribute to minimizing climate change. Assessing carbon reserves for Acacia hybrid forests in Quang Nam province is necessary to help forest growers know the carbon reserve capacity of Acacia hybrid forests to make business decisions for both economic and environmental effectiveness.

2. METHODOLOGY

**2.1. Secondary data collection**

In order to assess the amount of carbon sequestered by acacia plantations, a comprehensive review of relevant secondary data and available documents has been conducted. This review encompasses reports on assessment methods employed for determining carbon sequestration, both in a general context and specifically within the project area. The examination focuses on the implementation of methodologies aimed at quantifying the carbon sequestered by acacia plantations. Additionally, a thorough analysis has been undertaken to gather data pertaining to changes in forest resources within the Tien Phuoc, Hiep Duc, Nong Son, Phuoc Son, Dai Loc, Nam Giang, and Bac Tra My districts during the year 2023. The aim is to provide a comprehensive understanding of the carbon sequestration dynamics in the specified regions and contribute to informed decision-making regarding sustainable forestry practices.

**2.2. Method of collecting primary data on sample plots**

The determination of planted forest areas by each age group is facilitated through the analysis of data collected from households participating in the FSC group certification program. This data is systematically updated on an annual basis by key entities including QNAFOR (Quang Nam Forestry Investment and Development Joint Stock Company), Thien Hoang Forestry Company, and Hiep Thuan Cooperative. Employing a typical sampling method, sample plot areas measuring 500m2 (20m x 25m) were established. A total of 42 sample plots were selected for QNAFOR, 21 for Hiep Thuan Cooperative, and 30 for Thien Hoang Forestry Company. These plots were strategically distributed using a stratified sampling method based on the respective areas of each forest age.

Within each sample plot, measurements were conducted, including Diameter at Breast Height (DBH) and Total Height, to estimate the average carbon stocks. The outcomes of this investigation serve as input data for calculating and estimating the average carbon stock for each age of the plantation, determining the average annual increase in carbon stock, and evaluating the overall carbon stock of FSC-certified plantations throughout the entire project cycle. This comprehensive approach ensures a robust understanding of carbon dynamics within different age groups of plantations, contributing valuable insights for sustainable forestry management and FSC certification compliance.

**2.3 Criteria to evaluate forest stand growth**

\* Existing density:

N = n x 10,000/ (sample plot area) (trees/ha) (1)

In which: N: average density of the forest stand (trees/ha)

n: number of investigated trees in the sample plot (tree/plot)

\* Average density of forest stands in each forest age:

Na = (N1 +N2+N3.... +Nm)/m (2)

In which: Na: Average density of forest stands in each forest age (trees/ha)

N1, N2, N3, Nm: Average density of forest stands 1,2, 3, m of the same age forest

m: number of the surveyed sample plots of the same age forest stands

DBH, total height (H), and volume (M):

Average DBH, H, and M of each standard plot:

 (3)

: The average of D or H or M of the sample plot

: The value of D or H or volume of the ith tree in the sample plot

n: Number of investigated trees in the sample plot (tree/plot)

Average D, H, and M of forest stands by each forest age

 (4)

: Average D or H or M value of the same age forest stands

: Average D or H or M value of sample plots of the same age forest stands

m: Number of surveyed sample plots of the same age forest stands (plots/age class)

Average annual growth of diameter, height, and volume

 (5)

: Average annual growth of D or H or M

X: Average D or H or M value of the same age forest stands

A: Forest age (years)

The reserves of each standard plot are determined by two methods:

Standing tree trunk volume using the formula:

V = 0.0002 x DBH^2.4174 (6) [11]

DBH: diameter at breast height (D) of tree (Cm)

Or calculate according to the popular formula:

V = GHF (7)

G: tree basal (m2)

H: tree height (m)

F: shape fraction, usually choose F = 0.5

Determine the volume of the surveyed sample plot (m3/plot): is the total volume of trees in the surveyed plots:

M (m3/plot) = V1 + V2 + V3 +.... + Vn (8)

Determine average volume (m3/ha):

M (m3/ha) = M (m3/plot) x (10,000 /(plot area (500m2))

= M (m3/plot) x 20 (9)

Reserves (M) can be determined through average tree volume and existing density.

M (m3/ha) = Vbq (m3/tree) x existing density (10)

Determine the average growth amount (m3/ha/year)

Average growth (m3/ha/year) = M (m3/ha) / forest age (years) (11)

**2.4 Calculate carbon stocks**

Utilizing the average Diameter at Breast Height (DBH) values derived from all representative sample plots within each age class, the calculation of the average carbon reserve per hectare for each age class was undertaken. The determination of fresh and dry biomass, as well as carbon reserves for individual trees, was accomplished through specific equations. These equations were employed to compute the fresh and dry biomass, and subsequently, the carbon reserves of each tree. This meticulous approach ensures accurate assessments of the average carbon reserve per hectare for each age class, providing crucial information for understanding the carbon dynamics within different stages of plantation development. The utilization of standardized equations enhances the precision and reliability of the estimates, contributing to a comprehensive evaluation of carbon stocks across diverse age groups within the plantation area.​

Fresh biomass (FB) of each tree [12]

FB = exp [–0.567118 + 2.03792 × ln(D)] (Kg/tree) (12)

In which: FB: Fresh biomass (Kg/tree)

D: Diameter at breast height (Cm)

The average total fresh biomass of forests (TFB) by age is determined:

TFB = FB x N/1000 (Ton/ha) (13)

In which: TFB: Total fresh biomass (Ton/ha)

N: average density of forest stands (Trees/ha)

Dry biomass (DB) of each tree [12]:

DB = exp [–1.56325 + 2.15274 × ln(DBH)] (Kg/tree) (14)

In which: DB: Dry biomass (Kg/tree)

The average Total Dry Biomass of the forest (TDB) by age is determined:

TDB = DB x N/1000 (Ton/ha) (15)

In which TDB: Total dry biomass (Ton/ha)

Carbon (C) content in dry biomass was determined by applying the default coefficient of 0.5 according to IPCC 2003 [12; 13; 14]:

CS = 0.5 × TDB (Ton/ha) (16)

In which: CS (Carbon Stock): Carbon stock/reserves (tons/ha)

The amount of CO2 absorbed is determined based on the conversion factor: 1C = 3.67 CO2.

CO2S = CS x 3.67 (Ton/ha) (17)

In which: CO2S (CO2 Stock): Absorbed CO2 reserves (tons/ha)

The annual amount of CO2 absorbed by the forest stand is determined based on the amount of CO2 absorbed divided by the age of the forest.

ΔCO2S = CO2S/A (Ton/ha/year) (18)

In which: ΔCO2: Annual CO2 absorbed (tons/ha/year)

A: Forest age (years)

All calculations and data analysis were used and performed using Excel software.

**2.5 Carbon stock forecast for current and desired project cycle**

The regression correlation between average diameter (D) and forest age (A), as well as between existing density (N) and forest age (A), was explored utilizing four commonly employed regression forms in Excel (Table 1).

**Table 1: Common Regression Forms and Corresponding Equation Forms**

|  |  |  |
| --- | --- | --- |
| **No.** | **Regression form** | **Equation form** |
| 1 | Linear | Y = a + b.X |
| 2 | Logarithmic | Y = a + b. lnX |
| 3 | Power | Y = a. Xb |
| 4 | Exponential | Y = a. ebX |

These regression analyses aimed to establish the statistical relationship and correlation between the variables. Specifically, regression models were applied to examine the dependence of average diameter on forest age and the relationship between existing density and forest age. The utilization of four common regression forms in Excel provided a comprehensive evaluation of the data, enabling a nuanced understanding of how average diameter and existing density vary in relation to forest age. This analytical approach enhances the capacity to make informed predictions and draw meaningful insights regarding the interdependencies within the studied parameters, contributing to a more robust comprehension of the dynamics within the forest ecosystem.

Then we select the best equation based on the R and R2 values of each equation.

Forecast D and N for the following years based on the selected equation and forest age.

Following the thorough analysis of the collected data, an assessment of the carbon accumulation cycle and carbon reserves within FSC-certified planted forests for the entire project cycle (spanning 5-7 years) was conducted. This evaluation aimed to comprehend the dynamic patterns of carbon sequestration over the initial phase of the project. Moreover, a forecast of carbon reserves for an extended project cycle, encompassing a timeline of 12-15 years, was undertaken. This forward-looking analysis provides insights into the expected trends and potential fluctuations in carbon reserves over a more extended period. The comprehensive assessment contributes valuable information for understanding the long-term carbon dynamics and sustainability of the FSC-certified planted forests, aiding in informed decision-making for future forestry management strategies.

3. RESULTS AND DISCUSSIONS

**3.1. The growth of forest stands**

3.1.1. The existing density of forest stands

Density is one of the factors that affect forest reserves, especially the factor that affects the nutritional space of trees in the forest stand. The planting density of FSC forest stands in Quang Nam province often fluctuates greatly from 1650 trees/ha to 6500 trees/ha depending on the business purpose of the forest owners. However, for most small timber business purposes, the planting density of most forest stands is very high (over 3000 trees/ha). After a period of growth, the current density by forest age of FSC forest stands in Quang Nam is as follows:

**Table 2: Existing density of FSC Acacia forest stands in Quang Nam province**

|  |  |  |  |
| --- | --- | --- | --- |
| **Forest age**  **(planting year)** | **N average**  **(Tree/ha)** | **N Min.**  **(Tree/ha)** | **N Max.**  **(Tree/ha)** |
| 1 (2022) | 4461 | 3450 | 6100 |
| 2 (2021) | 3704 | 2250 | 5250 |
| 3 (2020) | 3029 | 2300 | 3800 |
| 4 (2019) | 2695 | 1250 | 4150 |
| 5 (2018) | 2575 | 550 | 2600 |
| 6 (2017) | 2517 | 2400 | 2650 |
| 7 (2016) | 3275 | 3200 | 3350 |

(Source: Analysis from field survey in 2023)

The average density of forest stands gradually decreases with age from age 1 to age 6. However, with age 7 forests, the density of these forest stands is still very high (3275 trees/ha) greater than the density of the age 6 forest (2517 plants/ha). This may be because the forest is planted at a very high density and there are no thinning processes. Besides, this forest stand has many trees with 2-3 trunks, so the remaining density is very high.

In general, the existing density of forest stands is very high with the average density at age 1 being 4461 trees/ha and decreasing at age 6 to still 2517 trees/ha (over 2500 trees/ha). The highest remaining density is at age 1 with 6100 trees/ha and the lowest remaining density is at age 4 with 1250 trees/ha. The variation in density is due to different planting densities, depending on the business purpose of the forest owner, in addition to the factor of the survival ability of the tree species.

3.1.2. Diameter growth situation

Tree trunk diameter is the most important indicator that characterizes the structure of the forest stand as well as determines the forest yield and carbon reserves of the forest stand. Through investigation results in forest stands from age 1 to 7 in FSC-certified planted forests in Quang Nam province, growth in diameter is shown as follows

**Table 3: Growth in DBH by the age class of FSC Acacia forest stands in Quang Nam province**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Forest age**  **(planting year)** | **D/DBH (Cm)** | **ΔD**  **(Cm/year)** | **Dmin**  **(Cm)** | **Dmax**  **(Cm)** |
| 1 (2022) | 2.99 | 2.99 | 1.21 | 4.51 |
| 2 (2021) | 5.18 | 2.59 | 3.81 | 7.70 |
| 3 (2020) | 7.73 | 2.58 | 6.53 | 9.26 |
| 4 (2019) | 9.53 | 2.38 | 7.71 | 12.62 |
| 5 (2018) | 10.02 | 2.00 | 9.72 | 10.33 |
| 6 (2017) | 11.19 | 1.87 | 10.88 | 11.61 |
| 7 (2016) | 10.93 | 1.56 | 10.81 | 11.05 |

(Source: Analysis from field survey in 2023)

Table 3 shows that the average diameter of the forest stands increases with age from age 1 to age 6. However, with age 7 forests, it shows that the diameter of these forest stands does not grow well, the average diameter value of the 7-year-old forest but smaller than the 6-year-old forest stands. This may be because this forest was planted on a bad site or the care process was not good so the diameter growth was not as expected. The interview with forest owners also showed that the forest is not growing well, so it has not been harvested for trading as other forest owners with the same forest age. Most forest owners in the area often harvest (clear-cut) forests at age 5 or 6 when they can make a profit from small timber forest businesses (selling for wood chips or pellets) without any solutions or method to preserve forests for longer cycles to produce the large timber products. The average diameter of age 1 forest is about 3 cm and gradually increases until age 6 reaching about 11 cm. This shows that, with growth in diameter like forest stands, by age 6, the rate of wood utilization for large timber products (with the smallest diameters of 13Cm or more) will be very low. Therefore, to increase the utilization rate of large timber, it is necessary to take measures to keep the forest for a longer cycle so that the diameter value increases.

The average annual growth in diameter follows the rule of gradually decreasing from age 1 forest to age 7 forest. The overall average growth in diameter is about 2.3 Cm/year, of which the highest at age 1 is 2.99 Cm/year and the smallest at age 7 is only 1.56 Cm/year.

When the forest is young (from age 1 to age 4), the variation in diameter is still quite high, reflected in the smallest and largest average diameter values, with a variation range of 3 - 5 Cm. Meanwhile, in forests over 4 years old, the average diameter variation is smaller, only about 0.3-0.8 Cm. This is because when the forest is over 4 years old, the poorly growing trees are naturally eliminated or pruned during the forest care process.

3.1.3. The height growth situation

The total height of the tree is an important growth indicator for forest stand structure. The investigation results in forest stands from age 1 to age 7 in FSC-certified planted forests of Quang Nam province show the growth in height as in table 4.

Table 4 shows that the average height of forest stands increases with age from age 1 to age 6. However, with age 7 forests, it shows that the total height of the forest stands does not grow well, the total height of age 7 forests (only 10.35m) is lower than that of age 6 forests (reaching 12.76m). This may be because the forests are planted on bad sites or the care process is not good, so the height growth is not as expected. The Interview with forest owners showed that the forest is not growing as well as expected, so it has not been harvested for selling like other forest owners have the same forest age.

**Table 4: The height growth by age class in Quang Nam province**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Forest age**  **(planting year)** | **Htb**  **(m)** | **ΔH**  **(m/year)** | **Hmin**  **(m)** | **Hmax**  **(m)** |
| 1 (2022) | 3.46 | 3.46 | 2.00 | 5.30 |
| 2 (2021) | 6.06 | 3.03 | 2.50 | 9.75 |
| 3 (2020) | 9.12 | 3.04 | 7.13 | 11.90 |
| 4 (2019) | 11.66 | 2.91 | 8.19 | 15.67 |
| 5 (2018) | 12.15 | 2.43 | 10.70 | 14.80 |
| 6 (2017) | 12.76 | 2.13 | 10.32 | 16.00 |
| 7 (2016) | 10.35 | 1.48 | 10.00 | 12.70 |

(Source: Analysis from field survey in 2023)

The average height of the age 1 forest is about 3.5 m and gradually increases until age 6 reaching about 12.8 m. The tree with the lowest average height surveyed was 2m height in the age 1 forest while the tree with the highest height was 16m in the age 6 forest.

The average annual growth in height follows the regulation of decreasing from age 1 forest to age 7 forest. The overall average growth in height is about 2.6 m/year, of which the highest at age 1 is 3.46 m/year and the lowest at age 7 is only 1.48 m/year.

**3.1.4. The reserves of forest stands**

The reserve is a comprehensive growth indicator of the forest management and protection process as well as environmental factors other than the genetic resources of forested tree species.

The average reserves of forest stand increase with age from age 1 to age 6. However, with 7-age forests, it shows that the reserves of these forest stands have a low average reserve (165,805 m3/ha) lower than other 6-age forests (reaching 170,694 m3/ha). Although the density of 7-year-old forest stands is greater than that of 6-year-old forest stands, the growth in diameter and height is much lower than that of 6-year-old forests, so its reserves are still lower. This is also the reason why 7-year-old forest stands have not been harvested for selling as same-age forest stands from other forest owners (Table 5).

**Table 5:** Reserves of forest stands by forest age (by using equation V= GHF)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Forest age**  **(planting year)** | **M**  **(m3/ha)** | **ΔM**  **(m3/ha/year)** | **Mmin**  **(m3/ha)** | **Mmax**  **(m3/ha)** |
| 1 (2022) | 7.618 | 7.618 | 0.620 | 19.844 |
| 2 (2021) | 26.694 | 13.347 | 8.423 | 61.299 |
| 3 (2020) | 72.523 | 24.174 | 40.159 | 127.003 |
| 4 (2019) | 113.060 | 28.265 | 64.099 | 172.782 |
| 5 (2018) | 115.617 | 23.123 | 110.878 | 120.356 |
| 6 (2017) | 170.694 | 28.449 | 138.452 | 224.895 |
| 7 (2016) | 165.805 | 23.686 | 160.630 | 170.980 |

(Source: Analysis from field survey in 2023)

The average reserve of age 1 forest is about 7.6 m3/ha and gradually increases until age 6 reaching about 170.7 m3/ha. The forest stands with the lowest average reserve is 0.6 m3/ha in age 1 forests while the largest average reserve is 224.9 m3/ha in age 6 forests.

The average annual growth in reserves has no specific rules. The overall average growth in reserves is about 21,237 m3/ha/year, of which the lowest is at age 1 reaching 7.6 m3/ha/year and the highest is at age 6 reaching 28.5 m3/ha/year. In general, the average annual growth of forest stands in Quang Nam is at a medium level of the country.

The average reserve of forest stands increases with age from age 1 to age 7. Different from the method of determining reserves using the GHF formula, this reserve determination is based only on the value of tree trunk diameter and current density. Therefore, although the diameter growth of age 7 forests is lower than that of age 6 forests, the density of age 7 forests is much higher than that of age 6 forests, therefore the average reserve of age 7 forests is still higher than that of age 6 forest one (Table 6).

**Table 6:** Potential commercial reserves of forest stands by forest age

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Forest age**  **(planting year)** | **M**  **(m3/ha)** | **ΔM**  **(m3/ha/năm)** | **Mmin**  **(m3/ha)** | **Mmax**  **(m3/ha)** |
| 1 (2022) | 15.093 | 15.093 | 1.464 | 34.36289 |
| 2 (2021) | 38.461 | 19.231 | 18.111 | 67.22649 |
| 3 (2020) | 85.095 | 28.365 | 55.118 | 116.0176 |
| 4 (2019) | 116.680 | 29.170 | 89.155 | 142.6384 |
| 5 (2018) | 135.569 | 27.114 | 126.862 | 144.2755 |
| 6 (2017) | 172.746 | 28.791 | 160.447 | 180.2015 |
| 7 (2016) | 212.126 | 30.304 | 211.409 | 212.8418 |

(Source: Analysis from field survey in 2023)

The average reserve of age 1 forest is about 15 m3/ha and gradually increases until age 7 reaching about 212 m3/ha. The forest stands with the lowest average reserve surveyed is 1.5 m3/ha in age 1 forests while the highest average reserve is 212.8 m3/ha in age 7 forests (Table 6).

The average annual growth in reserves tends to increase gradually from age 1 to age 7. However, for forest stands aged 3 to 6, the average annual growth is almost approximately the same (about 28 m3/ha/year). The overall average growth in reserves is about 25,438 m3/ha/year, of which the lowest is at age 1 reaching 15.1 m3/ha/year and the highest is at age 7 reaching 30.3 m3/ha/ year. In general, the average annual growth of FSC Acacia forest stands in Quang Nam province is at a medium level compared to that in the region or in the country.

**3.2. Biomass and Carbon stocks of forest stands**

3.2.1. Fresh and dry biomass of forest stands

Fresh biomass (FB) and dry biomass (DB) of the forest stands of each tree have a trend of increasing with forest age. However, for age 7 forests, the average fresh biomass and dry biomass of trees are both smaller than those for age 6. While for age 6 forests, fresh biomass reaches 77.872 Kg/tree and dry biomass reaches 37.95 Kg/tree, the age 7 forest only has 74.153 Kg/tree for fresh biomass and 36.038 Kg/tree for dry biomass (Table 7)

**Table 7: Fresh biomass (FB) and dry biomass (DB) by forest age of FSC Acacia forest in Quang Nam province**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Forest age (planting year)** | **Density**  **(tree/ha)** | **Tree FB (Kg/tree)** | **Average FB (Ton/ha)** | **Tree DB (Kg/tree)** | **Average DB (Ton/ha)** |
| 1 (2022) | 4461 | 5.285 | 23.578 | 2.213 | 9.874 |
| 2 (2021) | 3704 | 16.209 | 60.034 | 7.230 | 26.780 |
| 3 (2020) | 3029 | 36.646 | 111.008 | 17.116 | 51.848 |
| 4 (2019) | 2695 | 56.154 | 151.336 | 26.866 | 72.405 |
| 5 (2018) | 2575 | 62.200 | 160.164 | 29.931 | 77.071 |
| 6 (2017) | 2517 | 77.872 | 195.979 | 37.950 | 95.507 |
| 7 (2016) | 3275 | 74.153 | 242.852 | 36.038 | 118.024 |

(Source: Analysis from field survey in 2023)

The smallest fresh biomass is in trees at age 1 with 5.285 Kg/tree and the largest is in trees at age 6 with a total fresh biomass of 77.872 Kg/tree. Similar to fresh biomass, the smallest dry biomass is the 1-year forest with 2.213 Kg/tree while the 6-year-old forest has the highest dry biomass of 37.950 Kg/tree.

For average fresh and dry biomass per area, the age 7 forests reach the greatest value because the existing density of age 7 forests is much higher than that of age 6 forests. Therefore, fresh and dry biomass are lowest at age 1 corresponding to 23.578 tons/ha and 9.874 tons/ha separately. Meanwhile, fresh biomass and dry biomass of 7-year-old forests reached the highest levels at 242.852 tons/ha and 118.024 tons/ha respectively.

**3.2.2. Carbon reserves and CO2 absorption of forest stands**

In addition to the product value of wood, planted forests also have environmental value in the ability to absorb carbon and CO2 in the air, reducing greenhouse gases, thus reducing the impact of climate change.

Carbon reserves and CO2 absorption of forest stands tend to increase gradually with forest age. The lowest ability to absorb C and CO2 is in age 1 forests (4,937 tons of C/ha equivalent to 18,119 tons of CO2/ha) and the highest is in age 7 forests with 59,012 tons of C/ha and 216 tons of CO2/ha. However, if calculating the average annual absorption of C and CO2, the 4-year-old forest has the largest average absorption value of 9,051 tons of C/ha/year, equivalent to 33,216 tons of CO2/ha/year. The overall average C and CO2 absorption capacity of forest stands in Quang Nam province reaches 7,632 tons of C/ha/year, equivalent to about 28 tons of CO2/ha/year (Table 8).

**Table 8:** Carbon reserves and CO2 absorption by forest age in Quang Nam

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Forest age (planting year)** | **Density (tree/ha)** | **Carbon Stock (CS) (ton/ha)** | **ΔCS (Ton/ha/year)** | **CO2 stock (CO2S) (ton/ha)** | **ΔCO2S (Ton/ha/year)** |
| 1 (2022) | 4461 | 4.937 | 4.937 | 18.119 | 18.119 |
| 2 (2021) | 3704 | 13.390 | 6.695 | 49.142 | 24.571 |
| 3 (2020) | 3029 | 25.924 | 8.641 | 95.142 | 31.714 |
| 4 (2019) | 2695 | 36.202 | 9.051 | 132.863 | 33.216 |
| 5 (2018) | 2575 | 38.536 | 7.707 | 141.426 | 28.285 |
| 6 (2017) | 2517 | 47.754 | 7.959 | 175.255 | 29.209 |
| 7 (2016) | 3275 | 59.012 | 8.430 | 216.574 | 30.939 |

(Source: Analysis from field survey in 2023)

**3.3. Scenarios forecasting forest productivity and carbon reserves**

In order to make business plans for FSC-certified Acacia Forest plantations in Quang Nam province economically (commercially viable wood yield) as well as environmentally (C and CO2 reserves absorbed), it is necessary to conduct forecasts of targets according to production and business scenarios, mainly forecasting indicators based on forest age to be extended. To make predictions, it is necessary to forecast important indicators including tree trunk diameter and forest density according to forest age.

Because in age 7 forests, the growth values of diameter (D) as well as density (N) do not comply with the trend and are abnormal, the data of age 7 forests cannot be used to develop a regression equation. Thus, the forecast values will start from age 7 forest to age 15 forest.

**3.3.1.** **Correlation between diameter and age of forest stand**

**Figure 1: Relationship between Y (D) and X (A) experimentally and selected theoretical forms**

Based on the results of the 4 developed equations, it can be seen that the power equation form gives the highest R and R2 values. It means that the relationship between diameter (D) and forest age (A) is very close and follows the form of a power equation with the above parameters (Table 9).

**Table 9:** Regression equations between forest diameter and age

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Equation form** | | **Developed equation** | **R** | **R2** |
| 1 | Linear | Y = a + b.X | D = 2.0414 + 1. 6385.A | 0.97 | 0.95 |
| 2 | Logarithmic | Y = a + b. lnX | D = 2.6152+ 4. 7064.ln(A) | 0.98 | 0.97 |
| **3** | Power | Y = a. Xb | D = 3. 1077.A0.7535 | 0.99 | 0.98 |
| 4 | Exponential | Y = a. ebX | D = 2.9483e0. 2511.A | 0.93 | 0.87 |

Based on the selected theoretical equation form, the average diameter value of forest stands according to age can be predicted for the next period of up to 10 - 15 years.

The equation chosen to predict the average diameter of forest stands according to forest age is:D = 3.1077.A0.7535.

**3.3.2.** **Correlation between density and age of forest stands**

Based on the 4 available equation forms in EXCEL, the equations are determined as follows:

**Figure 2:** Relationship between Y (N) and X (A) experimentally and selected theoretical forms.

The results of 4 equation forms show that the Logarithmic functional equation form gives the largest R and R2 values. It means that the relationship between density (N) and forest age (A) is very close and follows the form of a Logarithmic function equation with the above parameters (Table 10).

**Table 10:** Regression equations between density and forest age

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Equation form** | | **Developed equation** | **R** | **R2** |
| 1 | Linear | Y = a + b.X | N = 4507.8 - 384.08. A | 0.93 | 0.87 |
| 2 | Logarithmic | Y = a + b. lnX | N = 4426.3 -1152.ln(A) | 0.99 | 0.98 |
| 3 | Power | Y = a. Xb | N = 4500.9.A-0.342 | 0.98 | 0.96 |
| 4 | Exponential | Y = a. ebX | N = 4645.3.e-0. 116.A | 0.95 | 0.90 |

Based on the selected theoretical equation form, the forest stand density value by age can be predicted for the next stage to analyze and forecast forest business scenarios.

The equation chosen to predict forest stand density according to forest age is:

N = 4426.3 -1152.ln(A)

**3.3.2.** **Forecasting forest yields and carbon and CO2 stocks with different business cycles**

Based on the regression equations that have been developed for the relationship between diameter (D) and forest age (A) as well as between density (N) and forest age (A), it allows for forecasting the actual and theoretical values such as average forest yield, average Carbon and CO2 reserves absorbed by forest age are as follows:

**Table 11:** Forecast of forest yield and C and CO2 absorbed reserves according to forest ages

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Forest age**  **(year)** | **N**  **(tree/ha)** | **D**  **(Cm)** | **M**  **(m3/ha)** | **ΔM**  **(m3/ha/y)** | **CS**  **(ton/ha)** | **ΔCS**  **(ton/ha/y)** | **CO2S**  **(ton/ha)** | **ΔCO2S**  **(ton/ha/y)** |
| 1 | 4426 | 3.11 | 13.724 | 13.724 | 5.323 | 5.323 | 19.537 | 19.537 |
| 2 | 3628 | 5.24 | 39.758 | 19.879 | 13.431 | 6.715 | 49.290 | 24.645 |
| 3 | 3161 | 7.11 | 72.496 | 24.165 | 22.588 | 7.529 | 82.896 | 27.632 |
| 4 | 2829 | 8.83 | 109.594 | 27.399 | 32.242 | 8.061 | 118.329 | 29.582 |
| 5 | 2572 | 10.45 | 149.604 | 29.921 | 42.097 | 8.419 | 154.497 | 30.899 |
| 6 | 2362 | 11.99 | 191.504 | 31.917 | 51.964 | 8.661 | 190.706 | 31.784 |
| 7 | 2185 | 13.47 | 234.521 | 33.503 | 61.709 | 8.816 | 226.474 | 32.353 |
| 8 | 2031 | 14.89 | 278.038 | 34.755 | 71.238 | 8.905 | 261.442 | 32.680 |
| 9 | 1895 | 16.27 | 321.549 | 35.728 | 80.473 | 8.941 | 295.336 | 32.815 |
| 10 | 1774 | 17.62 | 364.627 | 36.463 | 89.357 | 8.936 | 327.939 | 32.794 |
| 11 | 1664 | 18.93 | 406.906 | 36.991 | 97.840 | 8.895 | 359.074 | 32.643 |
| 12 | 1564 | 20.21 | 448.067 | 37.339 | 105.884 | 8.824 | 388.595 | 32.383 |
| 13 | 1471 | 21.47 | 487.827 | 37.525 | 113.455 | 8.727 | 416.379 | 32.029 |
| 14 | 1386 | 22.70 | 525.937 | 37.567 | 120.523 | 8.609 | 442.321 | 31.594 |
| 15 | 1307 | 23.91 | 562.169 | 37.478 | 127.066 | 8.471 | 466.332 | 31.089 |

Thus, the forecast of diameter and density from 1 to 15 years old of forests in Quang Nam province shows that if the forest owners want to do business in large timber forests (D>13 Cm), the forest must be at least 7 years old, then the average DBH value can be about 13.5Cm, It means that the utilization rate of large timber can be relatively high.

Besides that, if the forest at age 6 reaches about 191 m3/ha, but at age 10 the forest can reach 365 m3/ha. It means that just keep the forest for another 4 years then the forest reserve will nearly double (an additional yield is 173 m3/ha). Therefore, to take advantage of the growth rate of the forest, and keep the forest to 10 years old it will be much more effective than 6 years old.

​ Besides economic factors (forest reserves), as the forest ages increase, its ability to absorb C and CO2 also increases significantly. However, for C and CO2 absorption reserves, the trend is to increase with age, but when considering the average annual growth, it shows that the highest average annual C and CO2 absorption reserves are age 9 forests corresponding to 8,941 tons of C/ha/year, equivalent to 32,615 tons of CO2/ha/year.

So, it can be seen that the FSC Acacia plantation forests, extending the plantation business cycle to 9 or 10 years is the best for both the economy and the environment

4. CONCLUSIONS

The existing density of forest stands is very high, most of them have an average density according to forest age of over 2,500 trees/ha. The lowest density is 1250 trees/ha and the highest density is 6100 trees/ha.

The growth of diameter and height has a trend of gradually decreasing from age 1 to age 7 forest. In particular, the average annual growth in diameter decreases from 2.99 Cm/year at age 1 forest to 1.56 Cm/year at age 7 forest, and with a height from 3.46 m/year at age 1 to 1.48 m/year at age 7 forest.

Fresh biomass reached 5.3 Kg/tree at age 1 forest and the highest was 77.9 Kg/tree at age 6 forest. However, total fresh biomass gradually increased from 23.578 tons/ha at age 1 and reached 242.852 tons/ha at age 7 forest. Similar to fresh biomass, the dry biomass reached 2.213 Kg/tree at age 1 and reached 37.95 Kg/tree at age 6. Total dry biomass gradually increased from 9.874 tons/ha at age 1 forest and reached 118.428 tons/ ha at age 7 forest.

Carbon reserves and absorbed CO2 gradually increase from age 1 to age 7 forest. Carbon reserves absorbed are from 4.937 to 59.012 tons/ha, equivalent to the amount of CO2 absorbed from 18.118 tons/ha to 216.574 tons/ha. On average, forests absorb 7.632 tons of C/ha/year, equivalent to 28 tons of CO2/ha/year.

The relationship between diameter and forest age is according to the regression equation: D = 3.1077A0.7535. Meanwhile, the relationship between density and forest age is N = 4426.3 – 1152.Ln(A).

To have the best business results both economically (forest yield) and environmentally (C and CO2 absorption ability), the FSC-planted forests need to have a cycle of 9 to 10 years.

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REFERENCES

1. Dixon R.K., Brown S., Houghton R.A., Solomon A.M., Trexler M.C. and Wiseniewski J. (1994). Carbon pools and fluxes of global forest ecosystems. Science 263: 185-190
2. Brown S. (1997). Estimating Biomass and Biomass Change of Tropical Forests: a Prime, Food and Agriculture Organization of the United Nations Vol. 134, 55 pages.
3. Brown S. (2002). Measuring carbon in forests: current status and future challenges, Environ. Pollut 116 (2002): 363-372.
4. Chave J., Andalo C., Brown S., Cairns M.A., Chambers J.Q., Eamus  D., Folster H., Fromard F., Higuchi N., Kira T., Lescure J. P., Nelson B. W., Ogawa H., Puig H., Riéra B. and Yamakura T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical  forests. Ecosystem ecology, Oecologia 145: 87 – 99.
5. Zianis D., Muukkonen P., Makipaa R. and Mencuccini M. (2005). Biomass and Stem Volume Equations for Tree Species in Europe. Silva Fennica Monographs 4. 63 pages
6. IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 – Agriculture, Forestry and Other Land Use (AFOLU), IGES Japan
7. Chen, J., Wang, L., Li, L., Magalhães, J., Song, W., Lu, W., Xiong, L., Chang, W. Y., & Sun, Condit R. (2008). Methods for estimating above­ground biomass of forest and replacement vegetation in the tropics. Center for Tropical Forest Science Research Manual, 73 pages
8. Paluš, H, Krahulcová, M., & Parobek, J. (2021). Assessment of forest certification as a tool to support forest ecosystem services. Forests, 12(3). <https://doi.org/10.3390/f12030300>
9. Houghton RA., Lawrence KL., Hackler JL., Brown S. (2008). The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Glob Change Biol 7:731–746.
10. Malovrh, S. P., Becirovic, D., Maric, B., Nedeljkovic, J., Posavec, S., Petrovic, N., Avdibegovic, M., Malovrh, Š. P., Bećirović, D., Marić, B., Nedeljković, J., Posavec, S., Petrović, N., & Avdibegović, M. (2019). Contribution of Forest Stewardship Council certification to sustainable forest management of state forests in selected Southeast European countries. Forests, 10(8). <https://doi.org/10.3390/f10080648>
11. Harwood C. E., E. K. S. Nambiar, P. X. Dinh, L. X. Toan & L. T. Quang (2017):  
    Managing wood production from small grower acacia hybrid plantations on eroded soils in central Vietnam, Australian Forestry, DOI: 10.1080/00049158.2017.1395200)
12. Bao T.Q. and Phuc V.T. (2019). Research on Biomass and CO2 Absorption Capacity of Acacia hybrid Forests in Ba Ria Vung Tau Province. Journal of Forestry Science and Technology No. 2 – 2019.
13. IPCC, 2003. Report on good practice guidance for land use, land-use change and forestry. IPCC National Greenhouse Gas Inventories Programme, Kanagawa Japan
14. Manh Hung B., Ti Bich Phuong N., Van Quy N., Van Hop N., Van Cuong L., Habib Y. (2023): Acacia canopy structure and carbon stock in Ba Vi, Vietnam. J. For. Sci.