Effect of Thinning on Carbon Stocks in *Sonneratia apetala* Buch.-Ham Plantations: a Simulation Study

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Research Article

Keywords: Thinning, Aboveground Biomass, Carbon stocks, Simulation, Mangrove Plantations

Posted Date: November 1st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2204941/v1

Abstract

Background

Forests are very important for sequestering atmospheric carbon, and mangroves are amongst the most efficient carbon-sequestering ecosystems. In Bangladesh, several plantations of *Sonneratia apetala* have been raised, with large-scale plantations along the coastal belt. An individual-based model (KiWi model) was developed in order to analyze demographic processes in mangrove forests according to abiotic environmental factors, individual tree spacing, local tree-to-tree interactions, and intra-specific competition. In this study, we selected several silvicultural approaches (with or without thinning and with or without recruitment) to compare the development of planted forests in terms of forest management. Data obtained from the field monitors the output and parameterization of the model. Thinning normally avails more space and thus resources for growth, which leads to enhanced biomass increment. The objectives of this study were to identify the short-and long-term effects of thinning on carbon stocks in a mangrove plantation. Simulation experiments, tuned to observe the configurations of the study sites, provided a forecast of the stand development to be expected in the future.

Results

In this study, two thinnings were done at 15 and 20 years with a 0.5 m to 4.5 m radius while the annual sapling recruitment rate was kept at zero during thinning. Among the different thinning radii, 3.5 m radius thinning shows maximum aboveground carbon stocks in *Sonneratia apetala*, which is comparable to the 1.8 m stick radius thinning practised in Matang Mangrove, Malaysia for *Rhizophora apiculata*. In the case of Bangladesh coastal plantation, 2.5 m and 3.0 m thinning radius are perfect because 2.5 m and 3.0 m thinning radius contain an adequate number of trees and also produce above-ground carbon as much as 3.5 m thinning radius.

Conclusions

This experiment strongly supports that the KiWi model can mimic real dynamic growth patterns and thinning has an effect on carbon stock Simulation experiments, tuned to observe configurations of the study sites, provided a forecast of the stand development to be expected in the future.

Background

Mangroves cover a spacious area of subtropical and tropical coasts, which sequester atmospheric carbon. Mangroves are allocated only on the tropical and subtropical coasts, and they make a great contribution to carbon stocking as they show strong aboveground biomass production as well as aboveground carbon (Saintilan 1997, Komiyama et al. 2000, Khan et al. 2007). Mangroves are more efficient at stocking carbon and sequestering four times more carbon per unit area compared with terrestrial forests in the tropics (Khan et al. 2007, Donato et al. 2011). Aboveground biomass production and aboveground carbon stocks of *Sonneratia apetala* plantations greatly depend on thinning.

The general intensity of resultant sapling recruitment and natural regeneration would play an important role in yield development, and it is generally influenced by the growth and overall tree size distribution in the whole stand and also influences the management priorities of mangrove plantations (Khan et al. 2013). The thinning schedule has some effects on the aboveground biomass production in the mangrove plantations (Fontalvo-Herazo et al. 2011). In such dense *Sonneratia apetala* plantations, thinning of these plantations largely consists of removing stunted trees and cutting smaller stems from multi-stemmed trees and resulting in slightly reduced natural mortality together with marginal annual increases in both girth and height (Saenger and Siddiqi 1993). However, an individual-based model presents the effect of sapling recruitment patterns on the quality and quantity of yield.

The overall goal of this research is to contribute to ongoing research for mangrove silvicultural management alternatives and to estimate aboveground biomass and carbon stocks. This study aims to test different harvesting cycles of mono-cultural plantations of *Sonneratia apetala*. For this purpose, the KiWi model needs to be adapted to *Sonneratia apetala*. Therefore, two steps were performed in this study (Gong and Ong 1995). The first one is the parameterization of the KiWi model for the mangrove species *Sonneratia apetala* based on available data. In the second step, harvesting cycles with thinning schedules should be suggested for the mangrove plantation (Gong and Ong 1995) and simulation should be done in order to evaluate their potential ecological and economic impacts. However, several studies have already been done on biodiversity, biomass, vegetation type assessment, and carbon stock in mangrove plantations, but the current assessment with the simulation model in the mangrove plantation is also a considerable issue. Through this study, we can quantify the aboveground biomass as well as the carbon stock rate with respect to thinning operations. In the future, this study will help the Bangladesh Forest Department, Mangrove researchers and policymakers to take decisions about the management of the Mangrove forest.

Materials And Methods

Description of study site

The research was carried out at Madarbunia (21°92' N and 90°45' E) situated in Rangabali island of Patuakhali district in Bangladesh, on newly acquired (char) lands. At an earlier age, the maximum commercial mangrove species were planted on the newly accreted lands which were inundated by tides periodically. *Sonneretia appetela* is the most successful planted mangrove species along the shoreline, and *Avicennia officinalis* is the second most successful species of the coastal plantations on the newly accreted lands (Siddiqi 2001). The area is part of the delta of the extended Himalayan drainage ecosystem, which forms the lowest landmass. The combined actions of the rivers Brahmaputra, Meghna, and the Ganges have formed the landscape which is low-lying land, estuaries, and islands along the seacoast (Miah et al. 2014). In the monsoon season, the area is subjected to flooding. Tides are semidiurnal and the mean tide ranges from 2.3 to 4.0 m. Water salinity ranges from 0.3 – 2.7% in the monsoon while it ranges from 1.0 – 3.3% in the dry season (Siddiqi 1990). Soil salinity differs enormously between the dry and monsoon seasons. In December, Soil salinity ranges from 0.3 – 4.2 $dS \cdot m^{-1}$ and reaches its extremity in April-May, when average salinity is as high as 9 dSm-1 (Hasan 1987). The pH of the soil is moderately or slightly alkaline, which ranges from 7.5 – 8.0. The soil of the site is silt-clay-loam, non-calcareous and grey floodplain. The mean organic carbon in the soil is 1.4% and the mean nitrogen content is 0.09%. The climate is humid. Temperatures range from 18 to 32°C. Annual rainfall ranges from 2500 – 3000 mm (Siddiqi 2002).

Sample Plot Layout And Mapping Plot

Field data were collected from 30 sample plots (10m×10m each) of *Sonneratia apetala* stands (14, 17, 22, 26 and 27 years old). The proper identification of tree positions, DBH (diameter at breast height, i.e., 1.3m from the ground), and height of every single tree were recorded at the study site by using different instruments (i.e., diameter tape; measuring tape; Spiegel relaskop; Haga altimeter). Twenty sample trees with a wide range of DBH were chosen for sectional diameter measurements. In addition, for the parameterization of the KiWi model, field investigations were conducted in *Sonneratia apetala* stands of different plantation ages.

Kiwi Model Description, Modelling Stand Growth And Development And Parameterization

The KiWi is an individual-based, spatially explicit model which was originally developed to study mangrove forest dynamics (Berger et al. 2004). The simulation model was developed with the purpose of analyzing neotropical mangrove forest dynamics, which are affected by specific competition, environmental settings, and natural or anthropogenic disturbances (Berger and Hildenbrandt 2000, Berger et al. 2008). Simulation experiments were executed using this model to observe the stand development in the mono-specific mangrove plantation stands (Berger and Hildenbrandt 2000). The KiWi model has also been applied to address theoretical issues of self-thinning trajectories and dynamics of size distributions in even-aged stands (Berger and Hildenbrandt 2003); asymmetric competition (Bauer et al. 2004) and cyclic population dynamics in perennials (Berger et al. 2004).

The KiWi model was promoted in particular to investigate the impact of local tree-to-tree interactions on mangrove forest dynamics (Berger and Hildenbrandt 2000). The model has been successfully used for studying trajectories of secondary mangrove succession (Berger et al. 2006). The advantage of the KiWi model is that the parameters are easy to obtain even with the limited availability of data. This model is spatially explicit and it describes single trees by their stem diameter, stem height, stem position, and the so-called field of the neighbourhood (FON) defining the area within which a tree influences its neighbours and is influenced by them. Tree growth depends on nutrients, neighbour competition (FON overlap), tree age, and environmental settings at stem position. Tree mortality due to growth suppression and growth reduction is seen. New saplings establishment depends on both environmental conditions at a certain location and competition strength at this location exerted by the already established trees (described by the sum of their FONs).

We used field data on plant development and floristic recruitment under natural conditions to parameterize the KiWi model so that it actually mimics the dynamic stand growth in the mono-specific mangrove plantation stands. The model parameter values were obtained according to the pattern-oriented modelling (POM) procedure *(*Grimm et al. 1996, Grimm et al. 2005, Fontalvo-Herazo et al. 2011, Khan et al. 2013) considering the observed density, basal area, and biomass at the known stand age of *Sonneratia apetala.*

According to the (Khoon and Eong 1995), four different types of silvicultural treatments were incorporated into the simulation experiments: (A) with recruitment without thinning, (B) with recruitment with thinning, (C) without recruitment without thinning; and (D) without recruitment with thinning.

Simulations were performed in the mono-specific stands of *Sonneratia apetala* with a rotation age of 60 years. The seedlings are left to grow till around 15 years when the first thinning is carried out using various stick circumferences so that any tree within a 0.5m radius to 4.5m radius of a selected central tree is removed (and the bigger trees sold as poles). In practice, seedling densities are increased considerably by natural recruitment even after manual planting, which results in a harvest of about half of the trees during the first thinning. A second thinning takes place every 20 years, with a 0.5m to 4.5m radius used. This thinning also removes a lot of the trees. In the simulation experiments, the thinning operation was implemented using a virtual ecologist approach: trees having the maximum diameter within a circular area (based on the above-mentioned stick circumference radius) become the remaining trees, and all other trees are removed at 15 and 20 years of stand age, while the annual sapling recruitment rate is kept zero during thinning. The annual rate of sapling recruitment in the simulation runs was determined using natural recruitment data from the field. (Kairo et al. 2002, Bosire et al. 2006, Kairo et al. 2009).

To get the desired result in our work, we first selected some parameters which were used for running simulations in the KiWi model. KiWi parameters used for the simulations of the mangrove *Sonneratia apetala were* obtained according to the procedure of pattern-oriented modelling (POM) (Grimm et al. 1996, Berger et al. 2004, Grimm et al. 2005, Fontalvo-Herazo et al. 2011, Khan et al. 2013) and field data.

Table 1
KiWi Parameters for Simulation in *Sonneratia apetala*:

Description	**Parameters**	**Value**	**References**
FON scaling factor	A	**8.209**	Field Data, (Fontalvo-Herazo et al. 2011)
FON scaling factor	B	**0.5352**	Field Data, (Fontalvo-Herazo et al. 2011)
Minimum value of the FON	F_{min}	**0.1**	(Berger and Hildenbrandt 2000)
Maximum value of the FON	F_{max}	**1**	(Berger and Hildenbrandt 2000)
Average annual growth increment (cm/yr)	ΔD_{ave}	**0.7793**	Field data, (Turner et al. 1995)
Maximum annual growth increment (cm/yr)	ΔD_{max}	**1.50**	Field Data, (Turner et al. 1995)
Growth constant	G	**250**	(Botkin et al. 1972)
Maximum D_{130}* (cm)	D_{max}	**250**	Field Data, POM
Maximum height (cm)	H_{max}	**3500**	Field Data, POM
Constant in height to D_{130}	b_2	**26.9**	(Botkin et al. 1972)
Constant in height to D_{130}	b_3	**0.0538**	(Botkin et al. 1972)
Mortality threshold	ΔD_{crit}	**0.289**	(Fontalvo-Herazo et al. 2011)
Resource sharing capacity	**Φ**	**0.95**	POM (Fontalvo-Herazo et al. 2011)

Note: FON: Field of Neighbourhood (Berger and Hildenbrandt 2000); D_{130}- Tree diameter at 130 cm height from the ground (Brokaw and Thompson 2000).

Aboveground Biomass Estimation

The aboveground biomass of live trees, poles, saplings, and dead ones was estimated by the following general equations:

According to (Komiyama et al. 2005)

$$AGB = 0.247 \times \rho \times \left(D^2\right)^{1.23}$$

1

Here, ρ = wood density ($gmcm^{-3}$) (*Sonneratia apetala* = 0.537) (Zanne et al. 2009)d = Diameter (cm).

According to (Chave et al. 2005)

$$AGB = \rho \times e^{[-1.349+1.98\mathbf{ln}(D)+0.207\mathbf{ln}\left(D^2\right)-0.0281\mathbf{ln}\left(D^3\right)]}$$

2

According to (Chave et al. 2005) especially for Mangrove:

AGB = 0.0509 × ρ × D^2×H (3)

Here, AGB = Above-ground Biomass, ρ= wood density, H = Height (m), and D = Diameter (cm).

Conversion Of Aboveground Biomass To Carbon

Estimated biomass from the allometric relationship was multiplied by the wood carbon content (47%). As almost all carbon measurement projects in the tropical forest assume, all tissues (live biomass, dead wood) consist of 47% carbon on a dry mass basis (Hengeveld et al. 2015). According to IPCC (2006):

Carbon = Biomass estimated by allometric equation × Wood carbon content %

= Biomass estimated by allometric equation × 0.47

Statistical Analysis

The normality of the distribution of carbon stock and rates (aboveground) for the entire data set was tested using R programming. When and if distributions were approximately normally distributed, a one-way ANOVA was performed to explore the significant difference between aboveground carbon stocks of different ages. A descriptive analysis was done to explore the minimum, maximum, and mean values of different parameters.

Results

Analysis Of Field Data & Comparison Between Field Data And Simulated Data

In the fieldwork, we have taken the total height, DBH, collar dia, and sectional dia of the *Sonneratia apetala* tree from the sampling plot for calculating the trunk volume. After calculation, we tested many regression equations for estimating the relationship between calculated trunk volume and D^2H of different trees. From the different regression analyses, choose the best fit according to the best R^2 value. The allometric equations having strong non-linear relationships (R^2 = 0.9945) for estimating the trunk volume (Fig. 2) used in this study were established based on wide ranges of tree diameter and height, which offers better predictions of volume for *Sonneratia apetala*.

The output and parameterization of the model were evaluated based on monitoring data obtained in the field. The observed frequency distributions of diameter (D_{130}) in the *Sonneratia apetala* stands showed no remarkable differences from those in the simulated results at stand ages of 27 years, as revealed by the median values in the box plot (Fig. 3). There was no significant difference in the mean diameter between observed and simulated trees at 27 years old ($P > 0.05$) as tested with a t-test (such as a two-way sample t-test).This suggests that the model can mimic real-time dynamic growth patterns.

The highest harvested above-ground biomass, as well as basal area at 60-years-rotation, was obtained through the silvicultural option "with recruitment with thinning," and the lowest biomass and basal area were obtained through the option "without recruitment without thinning" (Fig. 4). This suggests that in *Sonneratia apetala*, both thinning and recruitment provide a significantly ($P < 0.001$) higher rotational yield as tested with a multiple comparison test (such as Tukey's HSD Post Hoc Test; LSD – Least Significant Difference test) after a one-way-ANOVA test of the above-ground biomass and basal area at 60 years of stand age.

Note: 1 = with recruitment without thinning; 2 = with recruitment with thinning; 3 = without recruitment without thinning; 4 = without recruitment with thinning. Same letters (a, b) indicate no significant difference ($P < 0.001$) as tested with multiple comparison test (such as Tukey's HSD Post Hoc Test, LSD – Least Significant Difference test) after a one-way-ANOVA test the above-ground weight at 60 years of stand age.

Table 2
Comparison between Observed Data and Simulated Data using different formulae at 27 years-

Stand Age	Above-ground biomass (ton/ha) Observed Data		Trees/ha Observed	Above-ground biomass (ton/ha) Simulated Data		Trees/ha Simulated
	AGB 1 (Komiyama et al. 2005)	AGB 2 (Chave et al. 2005)		AGB 1 (Komiyama et al. 2005)	AGB 2 (Chave et al. 2005)	
Without thinning Without Recruitment	892.913	545.909	1040	822.151	504.609	998
With Recruitment With Thinning	892.913	545.909	1040	887.988	542.074	963
With Recruitment Without Thinning	892.913	545.909	1040	827.791	507.975	995
Without Recruitment With Thinning	892.913	545.909	1040	884.998	540.629	969

Spacing Dependent Experiment For (Without Thinning Without Recruitment) (Dup: Abstract ?)

The output and parameterization of the model were evaluated based on monitoring data obtained in the field. At first, we set different spacing (2m×2m to 10m×10m) in the model code, and at that time, thinning and regeneration were totally omitted. Then we simulated 10 times. From the output of the model, we can see that at an earlier age, the number of trees is high but the total aboveground carbon is low. But at the end of the rotation age (60 years), the total number of trees is low but the total aboveground carbon is high. At each age, aboveground carbon reaches a peak and then begins to decline, resulting in the bell-shaped curve depicted in Fig. 5.

When we observe the different spacing (2m×2m, 2.5m×2.5m, 3m×3m, 4m×4m, 5m×5m, 6m×6m, 7m×7m, 8m×8m, 9m×9m, 10m×10m) in Fig. 6, the tree density is highest at the 2m×2m spacing but the aboveground carbon is lowest at the 2m×2m spacing. Then the tree density decreases and aboveground carbon increases in a chronological way up to 6m×6m spacing but aboveground carbon is higher at 7m×7m spacing than 8m×8m spacing. Tree density is lowest at the spacing 10m×10m and the maximum aboveground carbon is at 9m×9m spacing. Although the tree density differs, the aboveground carbon is nearly the same in 8m×8m and 9m×9m spacing. The most interesting thing is that, from the spacing of 6m×6m, the tree density becomes fixed at every spacing, but the aboveground carbon increases at every age.

The initial aboveground carbon is almost the same at every stage, and it increases up to the rotation age. From Fig. 7, the aboveground carbon of (2m×2m, 2.5m×2.5m, 7m×7m, 8m×8m, 9m×9m, 10m×10m) spacing increases continuously, but others show a difference. At 3m×3m spacing, the aboveground carbon decreases at 26 and 27 years, and after that, it increases linearly up to 60 years. Aboveground carbon decreases after 40 years in 4m4m spacing and then increases linearly up to 60 years. In 5m×5m spacing, the aboveground carbon increases for up to 50 years, and after that the aboveground carbon becomes fixed. At 4m×4m spacing, the aboveground carbon increases up to 25 years, then up to 40 years it stand in steady condition and after that, it begins to increase up to 60 years. 9m×9m spacing produces the maximum amount of aboveground carbon after the rotation age, which is shown in Fig. 7.

Effect Of Thinning Operation In Carbon Stocks (Dup: Abstract ?)

The output and parameterization of the model were evaluated based on monitoring data obtained in the field. At first, we set different radius (0.5m to 4.5m) in the model code, and at that time, regeneration was totally off. Then we simulated it 10 times. From the output of the model, we can see that at an earlier age, the number of trees is high but the total aboveground carbon is low. But at the end of the rotation age (60 years), the total number of trees is low but the total aboveground carbon is high. The aboveground carbon is found to be at its maximum when the number of trees is approximately 200/ha. At the age of 14 years, the aboveground carbon is the same in all stages, but at the age of 17 years, the aboveground carbon decreases continuously, which is shown in Fig. 8. At every other age, the aboveground carbon is maximum at a certain stage and then it starts to reduce, which creates a bell-shaped curve.

When we observe the different thinning radius (0.5m, 1.0m, 1.5m, 2.0m, 2.5m, 3.0m, 3.5m, 4.0m, 4.5m) in Fig. 9, the tree density is the highest at the 0.5m radius, but the aboveground carbon is lowest at the 0.5m radius. Then the tree density decreases and aboveground carbon increases chronologically up to a 3.0m thinning radius, but aboveground carbon is greatest at a 3.5 m thinning radius. Tree density is lowest at the 4.5m thinning radius and the maximum aboveground carbon is at the 3.5m thinning radius. Aboveground carbon is lower in the 4.0m and 4.5 m thinning radiuses than in the 3.5 m thinning radius. The most interesting thing is that from the 3.0m thinning radius, the tree density becomes fixed at every thinning radius but the aboveground carbon increases at every age. On the other hand, the 2.5m and 3.0m thinning radius contain an adequate number of trees and also produce above-ground carbon as the 3.5m thinning radius.

The initial aboveground carbon is almost the same at every stage, and it increases up to the rotation age. From Fig. 10, the aboveground carbon of 0.5m, 1.0m, and 1.5m thinning radius increases continuously, but others show differences. In 2.0m to 4.5m radius thinning, the aboveground carbon decreases after the first thinning (17 years), and after that, the aboveground carbon starts increasing up to 60 years. A 3.5m thinning radius produces the maximum amount of aboveground carbon after the rotation age, which is shown in Fig. 10. The 4.0m thinning radius produces the 2nd highest aboveground carbon. A 4.5m radius produces less carbon than a 3.5m, 4.0m, or 3.0m radius. When the thinning radius is set at 0.5, the aboveground carbon production is at its lowest.

Discussion

Analysis of Field Data

In this study, the trunk volume of different trees of *Sonneratia apetala* was best estimated by power curves. The best estimate of trunk volume (R^2 = 0.9945) was obtained using a combination of tree height and diameter at breast height (D^2H) as the independent variables (Kairo et al. 2009). The strength of the reported allometric relationships of *Sonneratia apetala* (R^2 = 0.9945) in particular was probably due to the wide ranges of D_{130} classes (8.65 ~ 46.24 cm) of the datasets used. Hence, the maximum D_{130} in *Sonneratia apetala* was 46.24 cm only, and since the stand was very eldest (27 years old), a strong allometric regression can easily be expected, and extrapolated use of that regression becomes more reliable and applicable. Even within the same species, regression models will vary at different localities depending on site-specific factors such as tree density, location on the ground, whether it is a monoculture or mixed forest, and management practices (Kairo et al. 2009).

Comparison Between Field Data And Simulated Data

In *Sonneratia apetala* stands, the observed frequency distribution of diameter (D_{130}) was well imitated and simulated, revealing the suitability of the model in predicting the development of mono specific mangrove stands. The mean differences in D_{130} distribution in the simulated results were significant and the median of D_{130} distribution in the simulated results was very close to the observed results (Fig. 3). There was no significant difference in the mean diameter between observed and simulated trees at 27 years old ($P > 0.05$). This suggests that the model can mimic real-time dynamic growth patterns.

In *Sonneratia apetala*, the highest harvested above-ground biomass and basal area were obtained when there was the availability of sapling recruitment and periodic thinning was practiced at 15 and 20-year stand ages (Fig. 4), and the lowest biomass and basal area were obtained when there was an absence of sapling recruitment and there were no thinning operations. This reveals that both thinning and natural regeneration have a positive impact on yield in terms of biomass as well as basal area in *Sonneratia apetala.* Thinning normally avails more space and thus resources for growth, which leads to enhanced biomass increment, while continuous recruitment (natural regeneration) guarantees forest restocking.

Spacing Dependent Experiment For (Without Thinning Without Recruitment)

At an earlier age, the number of trees is so high but the total aboveground carbon is low. But at the end of the rotation age (60 years), the total number of trees is low but the total aboveground carbon is high. At every age, the aboveground carbon is maximum at a certain stage and then it starts to reduce, which creates a bell-shaped curve shown in Fig. 5, which supports the ecological logistic growth curve.

When the spacing is low, the aboveground carbon content is low. When the spacing is increasing, the aboveground carbon is also increasing because the tree density decreases. The remaining trees get more space, nutrition, and light to grow. When tree density is higher, the trees don't get the proper space, and nutrition to grow. After a certain spacing, the aboveground carbon production starts decreasing. So we should fix the proper spacing to get maximum biomass.

9m×9m spacing produces the maximum amount of aboveground carbon after the rotation age, which is shown in Fig. 6. 9m×9m spacing can be suggested for proper management to obtain maximum benefit. But the number of trees is so low which does not support the coastal plantation's objectives. On the other hand, 6m×6m spacing contains an adequate number of trees and also produces above-ground carbon as same as 3.5 m thinning radius.

From the ANOVA test, we can say that the *Sonneratia apetala* stands show no remarkable differences from those in the simulated results in different spaces at different stand ages, such as 27 years, 40 years, and 60 years separately. But when we take all the stand ages at different spacings, the *Sonneratia apetala* stands show no remarkable differences from those in the simulated results.

Effect Of Thinning Operation In Carbon Stocks

Although there are many trees at an earlier age, there is little total aboveground carbon. However, the overall number of trees is minimal but the total amount of aboveground carbon is significant towards the end of the rotation age (60 years). The highest harvested above-ground biomass and basal area were obtained in *Sonneratia apetala* when sapling recruitment was available and periodic thinning was practiced at 15 and 20-year stand ages (Fig. 4).

Low aboveground carbon content is associated with low thinning radius. When the thinning radius is increasing, the aboveground carbon is also increasing because the tree density decreases. More space, food, and light are provided for the remaining trees to grow. The trees don't receive enough space and food to flourish when there is a higher tree density. The aboveground carbon production starts to fall down after a certain thinning radius. We found that a 3.5 m thinning radius produces the maximum amount of aboveground carbon at the rotation age (Fig. 9). Among the different thinning radius, 3.5 m radius thinning shows maximum aboveground carbon stocks in *Sonneratia apetala*, which is comparable to the 1.8 m stick radius thinning practiced in Matang Mangrove, Malaysia for *Rhizophora apiculata*. But in a 3.5 m thinning radius, the number of trees is so low which does not support the coastal plantation's objectives. On the other hand, the 2.5 m and 3.0 m thinning radius contain an adequate number of trees and also produce above-ground carbon as the 3.5 m thinning radius.

In our simulation code, we used a 1 m to 9 m thinning square. Half of these are .5 to 4.5 m in radius. In Matang, it is 1.2 m radius at 15 yrs and 1.8 m radius at 20 yrs. In our case, 3.5 m is a little bit higher than Matang's 1.8. This is for species differences, i.e., keora may require more space to grow to its maximum size. But if we think ecologically, a 2.5 m or 3.0 m thinning radius is perfect for coastal plantations.

To maximize benefits and conserve the coastal green belt, a thinning radius of 2.5m or 3.0m can be suggested for proper management. This experiment strongly supports that the KiWi model can mimic real dynamic growth patterns.

Conclusion

Bangladesh is a pioneer country in raising successful plantations of *Sonneratia apetala* along the shoreline and offshore islands. This study is based on a combination of field and simulated data to describe the success, importance, and performance of *S. apetala* in the development of monospecific stands in coastal areas. The performance of different management options or silvicultural treatments suggests that periodic thinning and spacing offer a higher yield than that with no silvicultural treatment. Simulation experiments, tuned to observed configurations of the study sites, provided a forecast of the stand development to be expected in the future. Although the main objective of coastal mangrove plantations by the Bangladesh Forest Department is coastal protection, Keora plantations can be more productive if an initial spacing of .5 m x .5 m is followed and a thinning at the age of 15 with a thinning radius of 2.5m to 3.0m is followed.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and material: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests

Funding: No funding

Authors' contributions: Md. Arifuzzaman Arif: Conceptualization, Data collection, Formal analysis, Software, Visualization, Literature review, Writing - original draft, review and editing. **Md. Nabiul Islam Khan:** Conceptualization, Formal analysis, Software, Visualization, Writing - review & editing. **Rahul Biswas:** Data collection, Visualization, Writing - review & editing. **Atikur Rahman:** Data collection, Writing - original draft, Final review. **Md. Akramul Islam:** Data collection, Final review. **Asma-Ul-Husna Monika:** Data collection, Final review.

Acknowledgements: Not applicable

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Figures

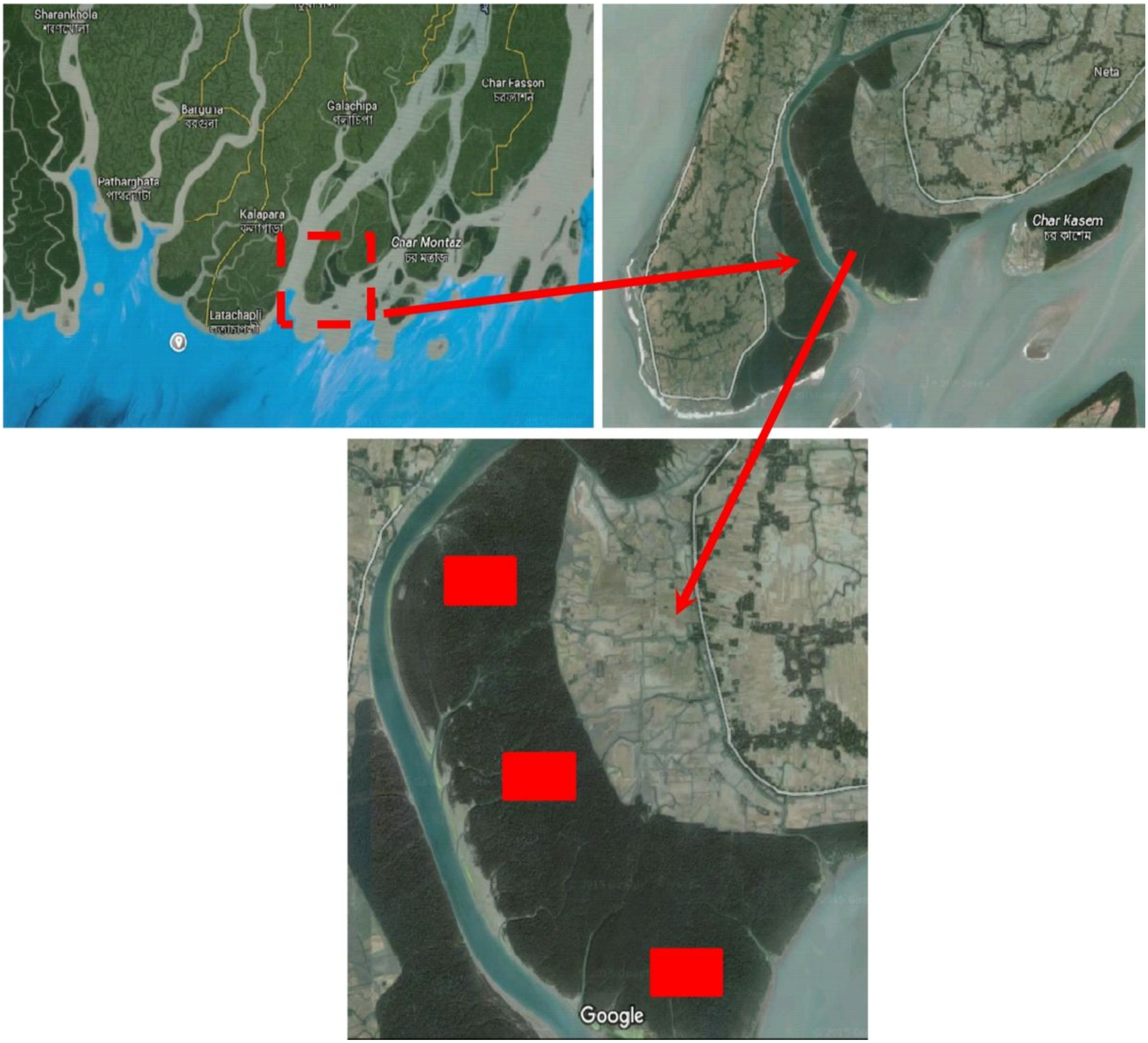

Figure 1

Map of the study site (Madarbunia, Rangabali, Patuakhali) and Location of sample plots (in Red colors) (Source: Google Map and Google Earth).

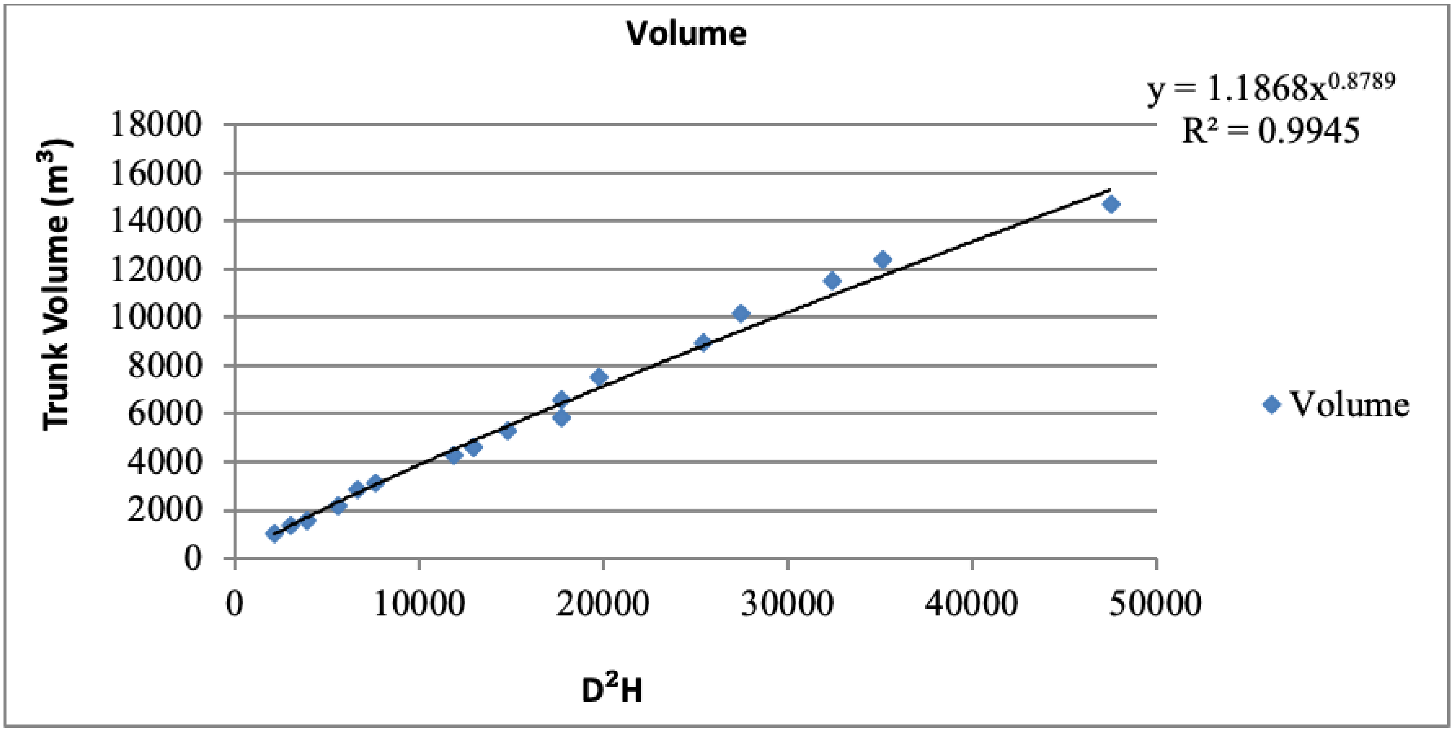

Figure 2

Allometric relationship of trunk volume (m^3) in relation to tree diameter and height in *Sonneratia apetala* using field data ($y = 1.1868x^{0.8789}$, $R^2 = 0.9945$)

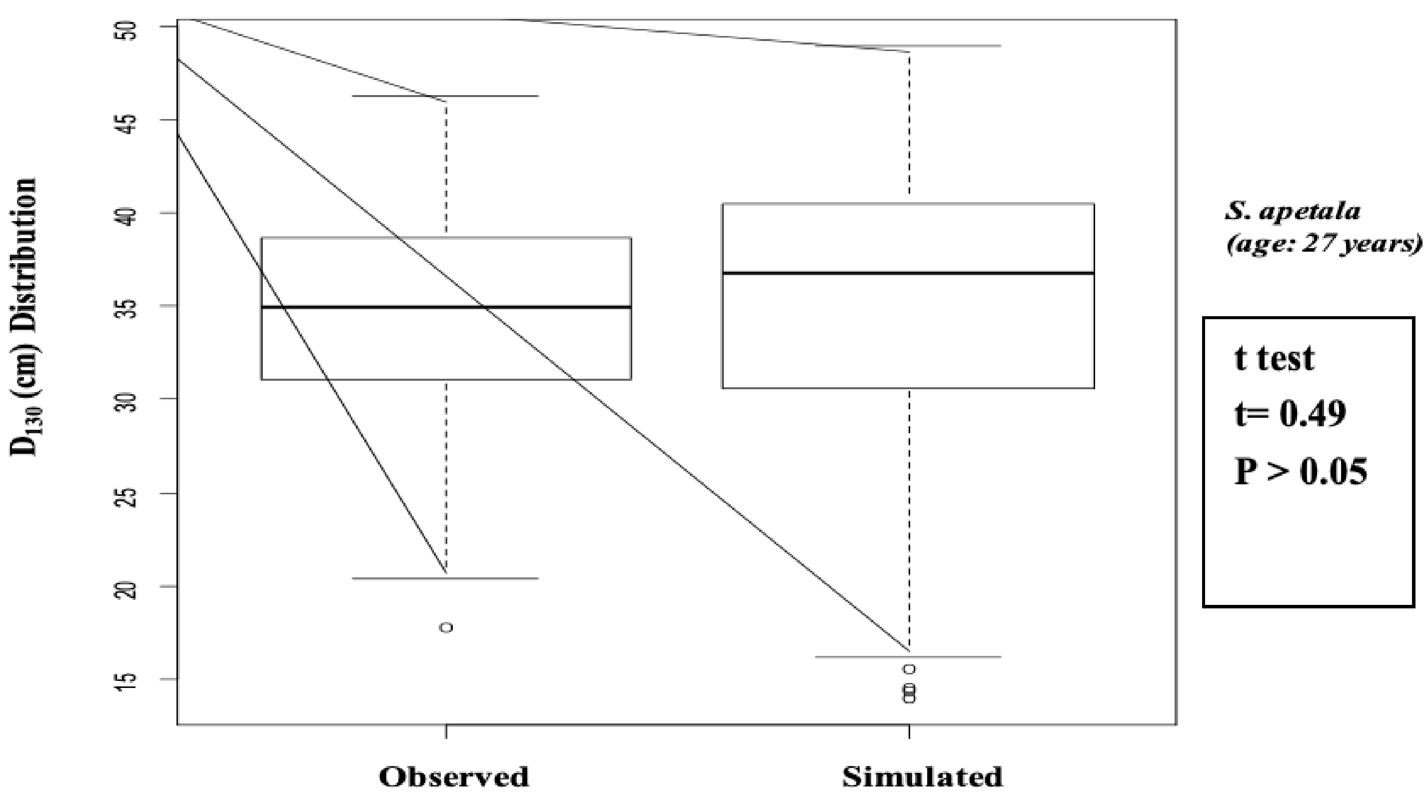

Figure 3

Box plot of observed and simulated distribution of tree diameter (D_{130}) in *Sonneratia apetala* stands

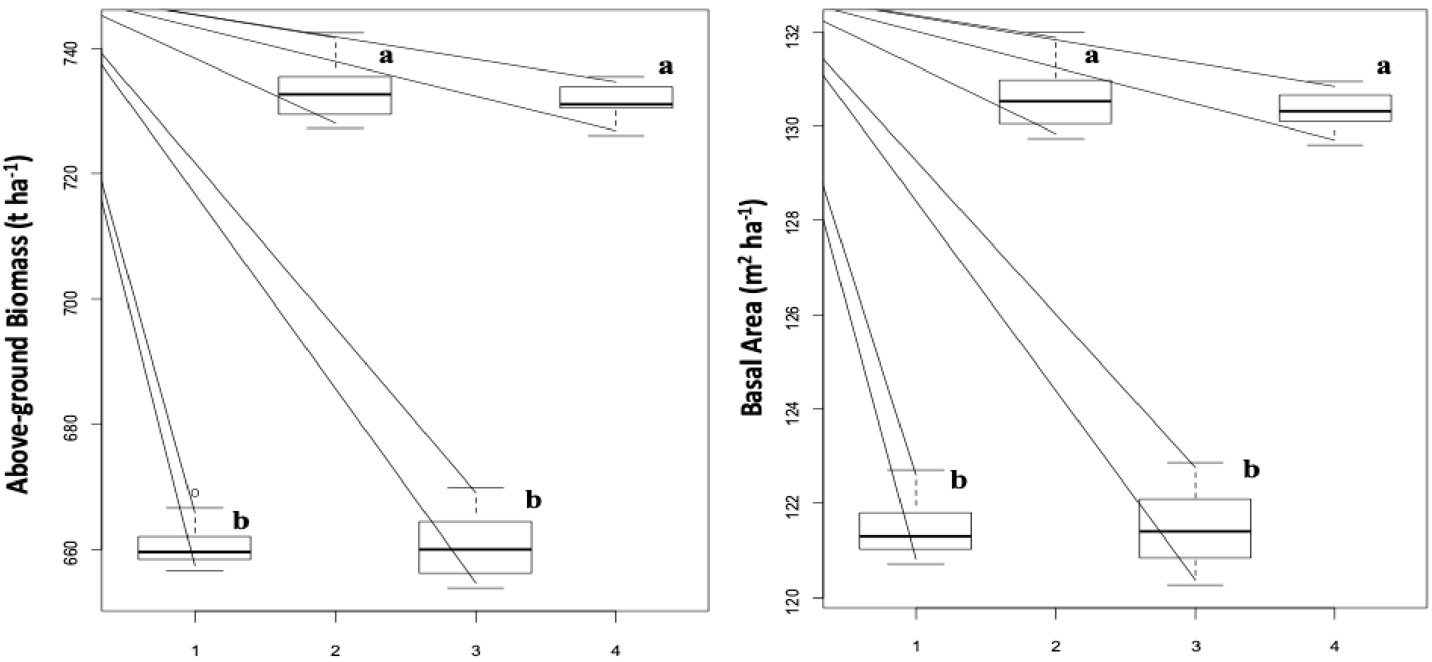

Figure 4

Above-ground biomass and basal area in *Sonneratia apetala* over 60 year’s rotation period.

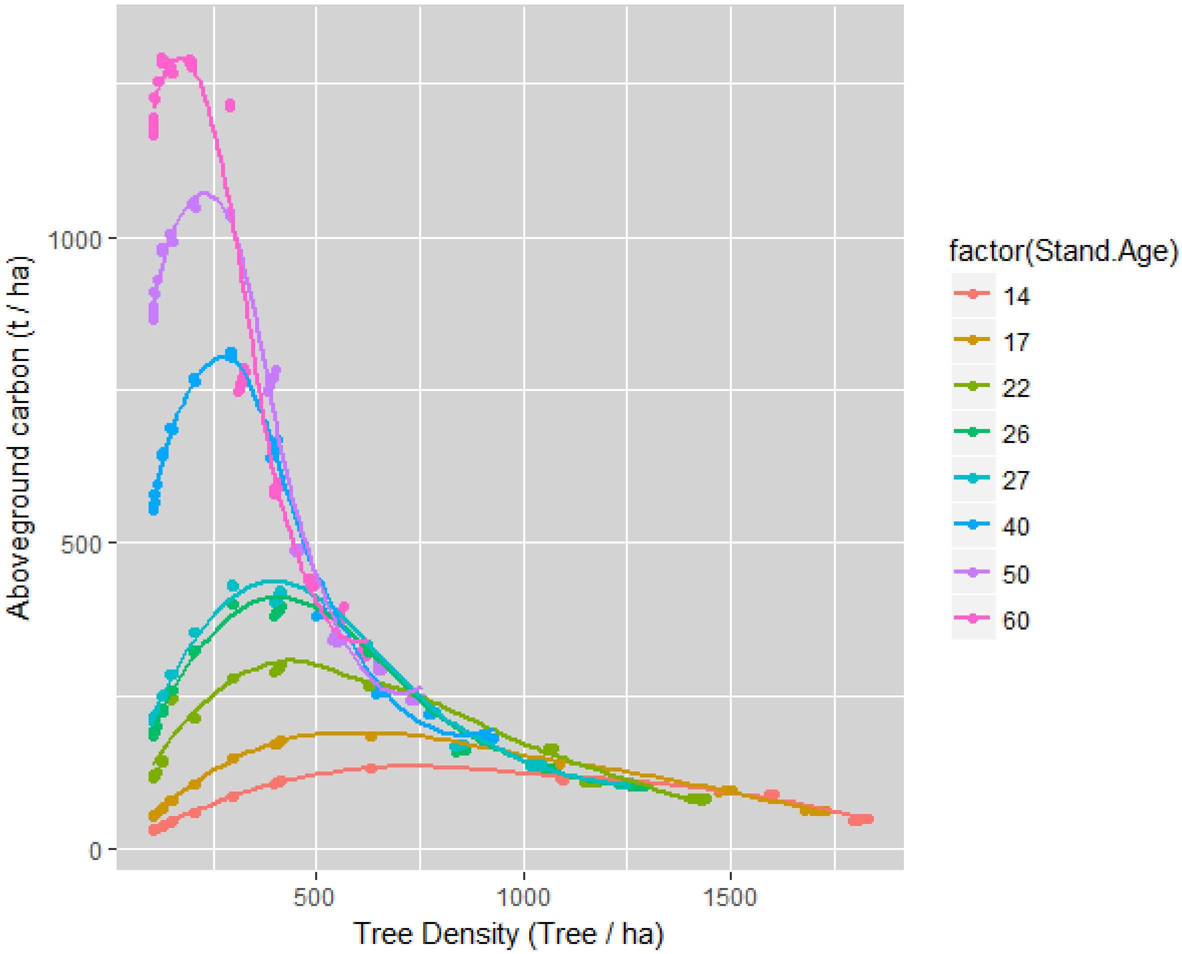

Figure 5

Tree density (Trees/ha) and aboveground carbon at different ages

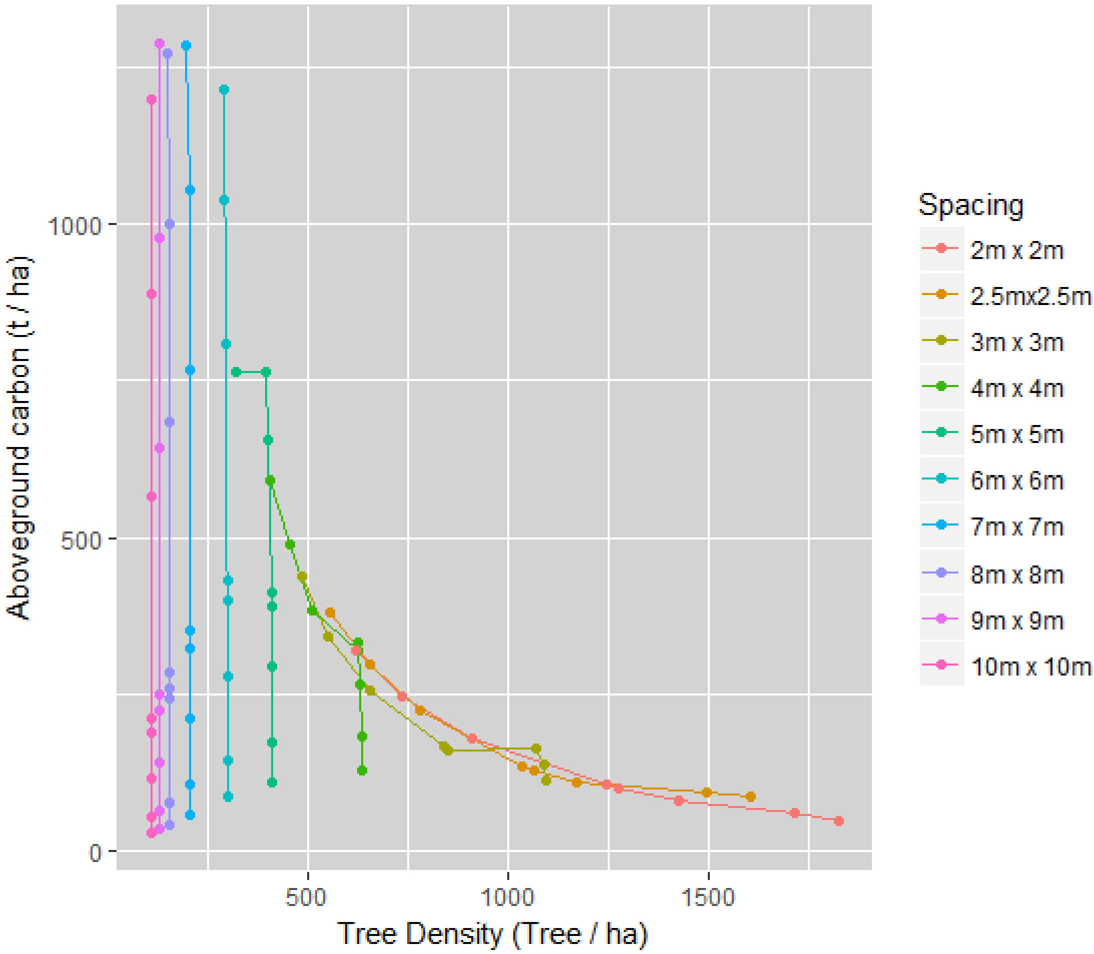

Figure 6

Tree density (Tree/ha) and aboveground carbon at different ages due to spacing variation

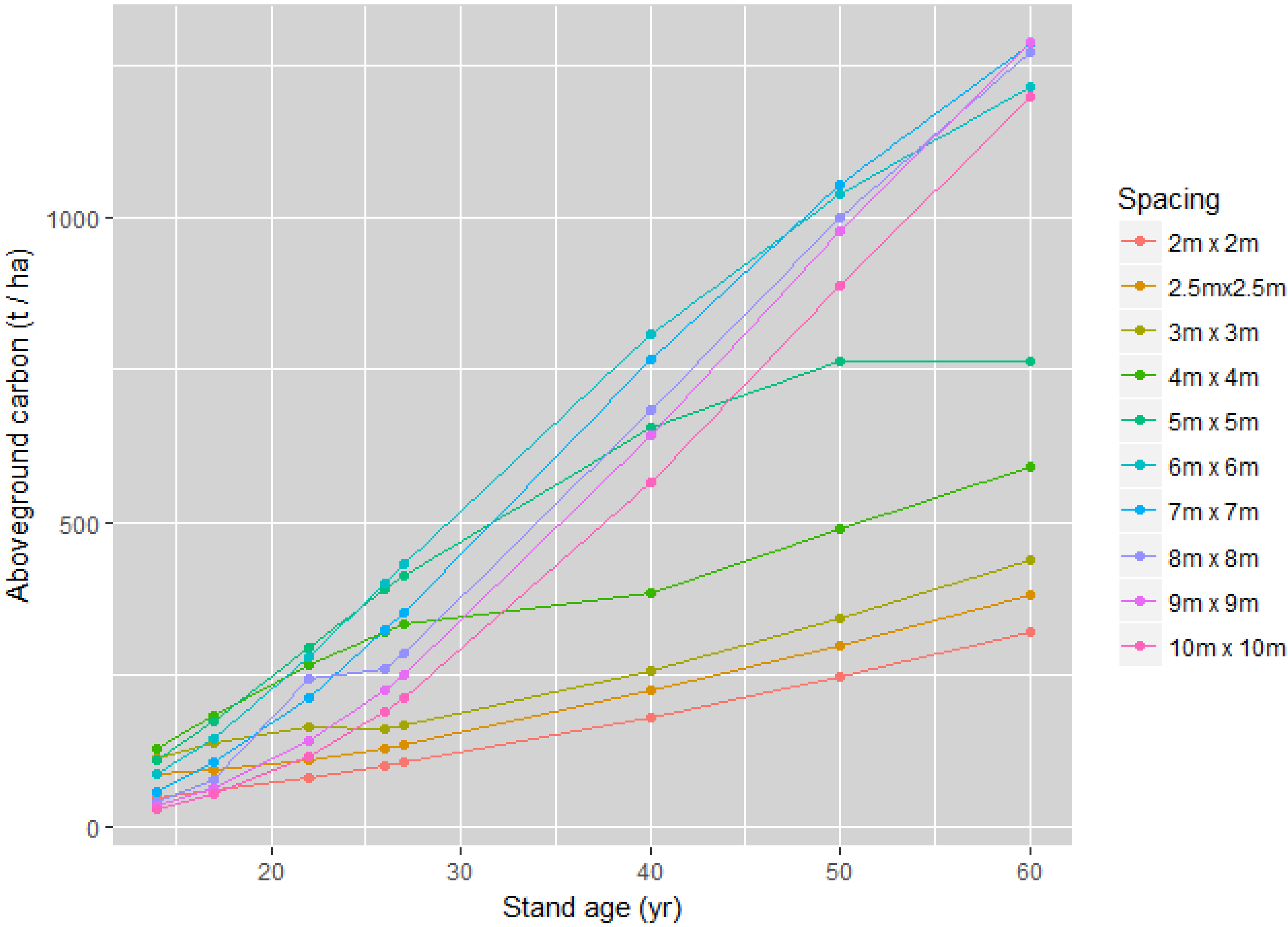

Figure 7

Stand age (yr) and aboveground carbon (t/ha) due to spacing variation

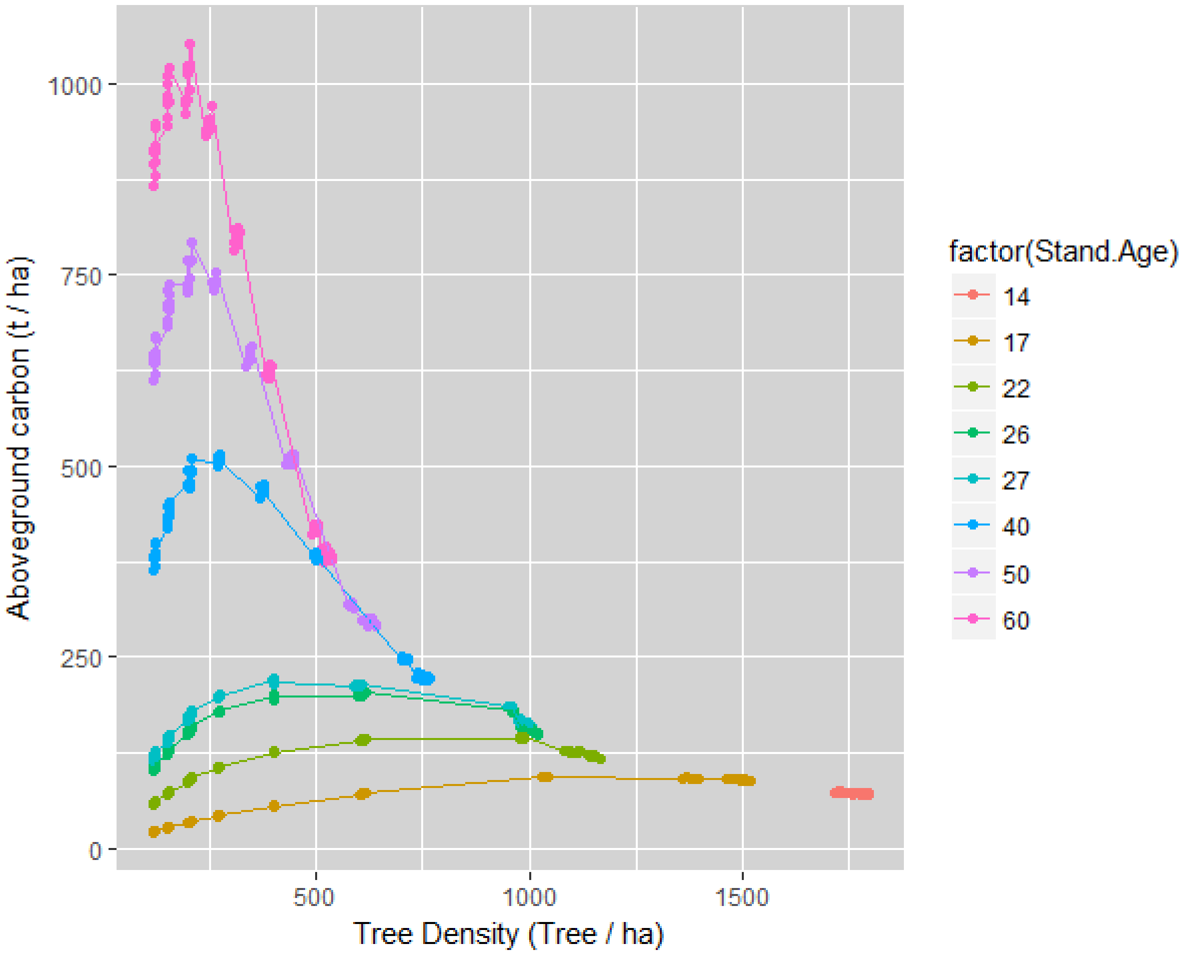

Figure 8

Stand age (yr) and aboveground carbon (t/ha) due to thinning radius variation

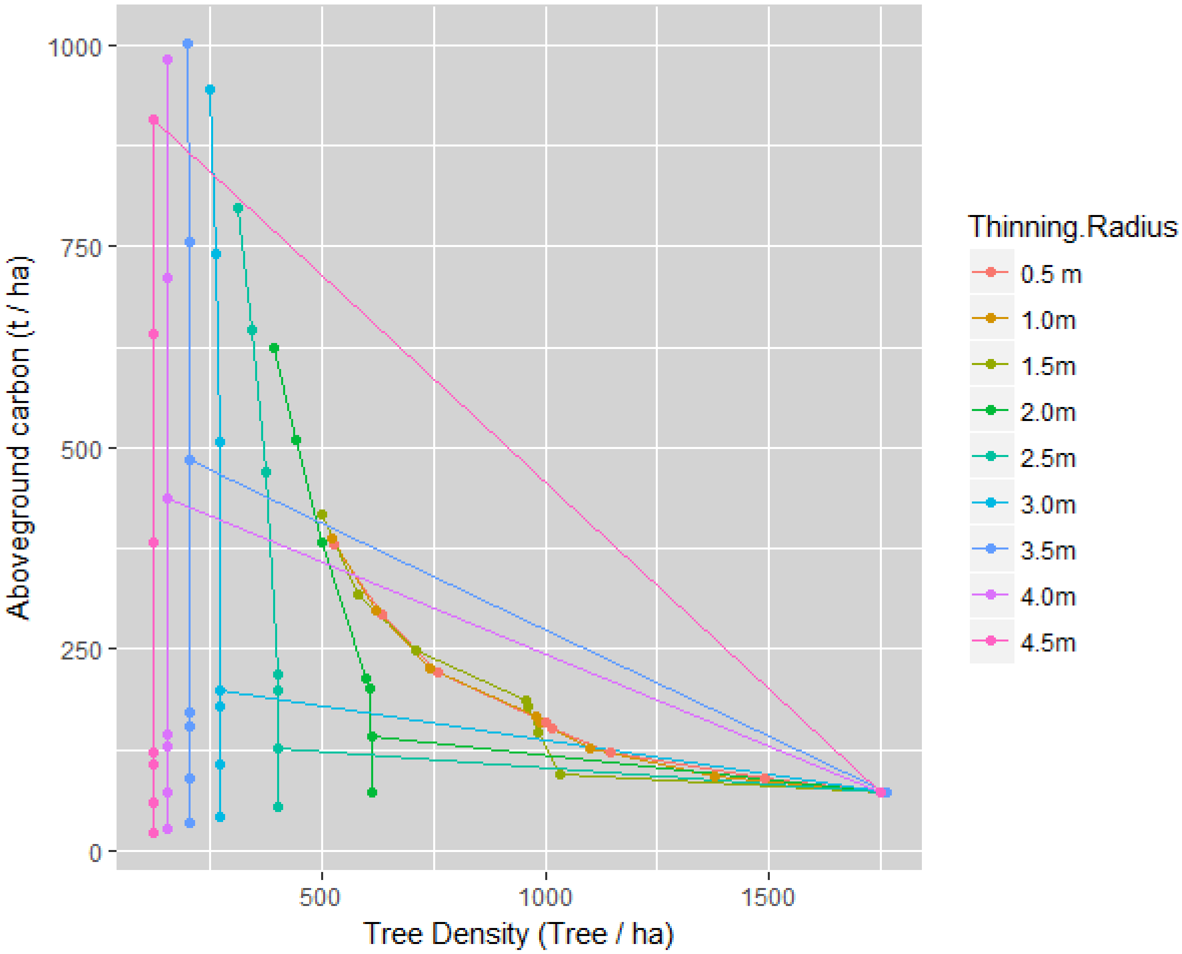

Figure 9

Stand age (yr) and aboveground carbon (t/ha) due to thinning radius variation

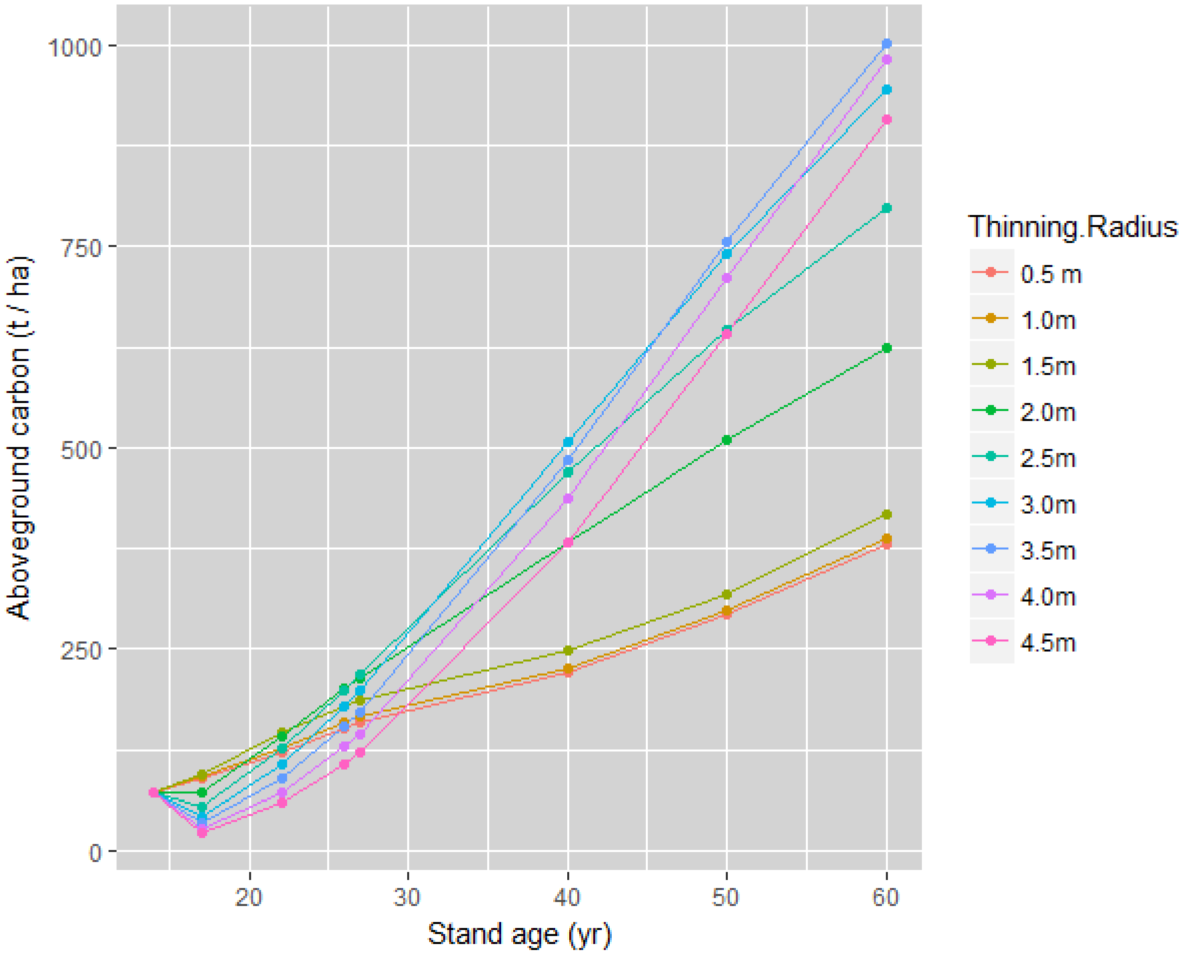

Figure 10

Stand age (yr) and aboveground carbon (t/ha) due to thinning radius variation