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Assessment of Carbon Stock in Forest Biomass and Emission Reduction Potential in Malaysia

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Abstract: Malaysia has a large extent of forest cover that plays a crucial role in storing biomass carbon and enhancing carbon sink (carbon sequestration) and reducing atmospheric greenhouse gas emissions, which helps to reduce the negative impacts of global climate change. This article estimates the economic value of forest carbon stock and carbon value per hectare of forested area based on the price of removing per ton CO_2eq in USD from 1990 to 2050. The economic value of biomass carbon stored in the forests is estimated at nearly USD 51 billion in 2020 and approximately USD 41 billion in 2050, whereas carbon value per hectare forest area is estimated at USD 2885 in 2020 and USD 2388 in 2050. If the BAU scenario of forest loss (converting forests to other land use) continues, the projected estimation of carbon stock and its economic value might fall until 2050 unless further initiatives on proper planning of forest management and ambitious policy implementation are taken. Instead, Malaysia's CO_2 emission growth started to fall after 2010 due to rising forest carbon sink of 282 million tons between 2011 and 2016, indicating a huge potential of Malaysian forests for future climate change mitigation. The estimated and projected value of carbon stock in Malaysian forest biomass, annual growth of forest carbon, forest carbon density and carbon sink would be useful for the better understanding of enhancing carbon sink by avoiding deforestation, sustainable forest management, forest conservation and protection, accurate reporting of national carbon inventories and policy-making decisions. The findings of this study could also be useful in meeting emission reduction targets and policy implementation related to climate change mitigation in Malaysia.

Keywords: forests; carbon sequestration; economic valuation; climate change mitigation; Malaysia

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1. Introduction

Global climate change and its negative effects on natural ecosystems have become a major environmental issue due to the continuous increase in greenhouse gases (GHGs) dominated by carbon dioxide (CO_2) [1]. Forests play a vigorous role in mitigating climate change by absorbing the atmospheric CO_2 and storing it in tree biomass [2,3]. The process of absorbing atmospheric carbon by the trees is called carbon sequestration, which is one of the forest ecosystems services [4]. Global forests hold 296 Gt (1 Gt = 1 billion tons) carbon in aboveground and belowground biomass [5]. However, forests perform a dual role in climate change by sequestering atmospheric carbon through photosynthesis and releasing carbon back to the atmosphere when deforested [6]. Deforestation and forest degradation contribute 13% of the total global CO_2 emissions [7]. However, tropical forests account for 42% of the global forests [8], which contain 60% of the total global forest carbon [9].

Thus, tropical forests have great potential in mitigating climate change by enhancing the carbon sink. Between 1995 and 2050, reforestation, agroforestry, regeneration and avoided deforestation operations in tropical Asia are expected to sequester 7.50, 2.03, 3.8–7.7 and 3.3–5.8 Gt carbon, respectively [10].

However, Malaysia is one of the Southeast Asian countries which is rich in tropical forest biodiversity [11]. Malaysia possesses 55.3% forested area of the total land area, which plays a crucial role in the national carbon balance [12]. Figure 1 presents the land use map of Peninsular Malaysia where the major land use is cropland (49.02%) followed by forest (42.11%), settlement (5.81%), wetland (1.46%), mangrove (0.97%), grassland (0.06%), peat swamp (0.01%) and others (0.05%). The increasing population places pressure on forests to satisfy the increased demand for food production, agriculture, accommodation, transportation, industries and other infrastructures [12,13]. Agriculture, settlements, industrialization, urbanization, mining and clearing forests for oil-palm plantations have resulted in the loss of more than half of Peninsular Malaysia's forest cover [14,15]. Land use change, characterized by rapid urban expansion and the loss of forests because of deforestation and forest degradation, can result in substantial carbon emissions and contribute to climate change [16]. Lack of knowledge and awareness about the actual value of forest services would provoke the conversion of forests into other land use. The economic value of biomass carbon, therefore, arises from the carbon sequestration services rendered by the forests, which result in a reduction in the amount of carbon that could be found in the atmosphere.

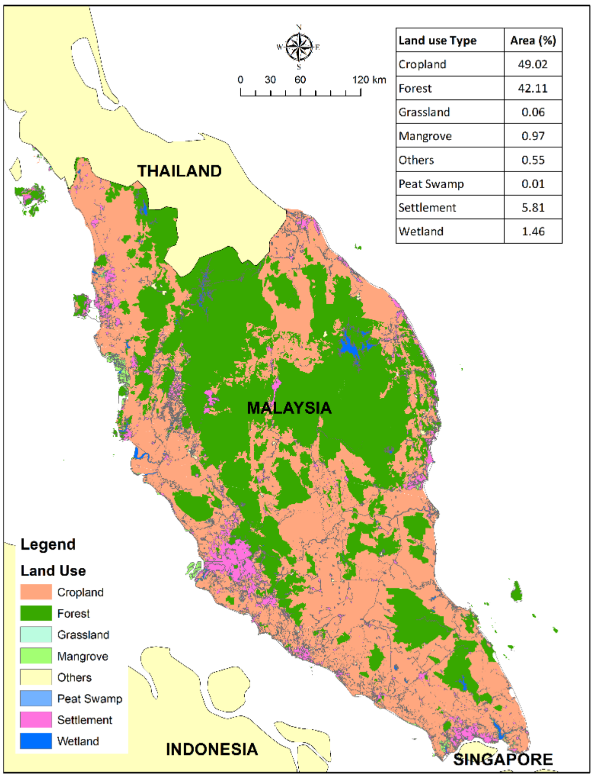


Figure 1. Land use map of Peninsular Malaysia.

Tropical forests are gaining attention due to their low maintenance cost, rapid plant growth and high carbon sequestration rates [17]. Thus, measurements and evaluations of forest carbon are critical for better managing Malaysia's forest resources. Estimating the economic value of forest carbon stock is a comprehensive method for climate change mitigation [18]. The economic valuation of forest carbon sequestration helps policymakers in evaluating competing forestry and environmental projects and increases community willingness to pay for forest conservation [19]. In order to maximize the value of forest ecosystem services, economic valuation of forest carbon is required. Developing countries such as Malaysia can benefit financially from preserving natural carbon storage. It is possible to increase forest conservation while decreasing deforestation and degradation by valuing forests economically. Hence, economic valuation of forest carbon helps reduce GHG emissions while reducing climate change. Therefore, economic valuation of forest carbon plays a significant role in reducing GHG emissions by enhancing the carbon sink while mitigating climate change. However, there is a limited body of research focusing on the economic valuation of forest carbon stock in Malaysia. Thus, this study attempts to estimate the economic value of forest carbon stock in order to assess the climate change mitigation potential in Malaysia.

2. Forested Area and Carbon Sequestration in Malaysia

Forests in Malaysia are categorized by protected forests, permanent reserved forests and state land forests. Table 1 presents the total forested area in Malaysia by different types of forests. The total forested area was almost 18.8 million hectares in 1990. Suddenly, it dropped to 17.96 million hectares in 1995 and started to increase again. The total forested area rose to almost 18.2 million hectares in 2000. The total forested area started to proceed downward again from 2000 and reduced to 17.82 million hectares in terms of forested area in 2005. Deforestation and forest degradation due to excessive logging could be the main causes for the shrinkage of forested area. Malaysia lost approximately 0.86 million hectares of forests between 1990 and 2010, which is 4.23% of the total forested areas. The total forested area in Malaysia shows a rising trend from 2010 due to increasing forestry activities that make it to 18.28 million hectares of forests in 2014.

Table 1. Total forested areas by different forest types in Malaysia [12].

Year	Forest Types							Total Forested Area (Million ha)
	Protected Area (Million ha)	Permanent Reserved Forest (Million ha)					State Land Forest (Million ha)	
		Inland Forest	Peat Swamp	Mangrove	Plantation Forest	Total (Million ha)		
1990	1.436	10.568	1.030	0.470	0.071	12.140	5.206	18.782
1995	1.706	10.533	0.930	0.440	0.121	12.025	4.225	17.956
2000	1.793	10.560	0.780	0.440	0.116	11.896	4.506	18.196
2005	1.937	11.382	0.660	0.440	0.136	12.618	3.260	17.818
2010	2.111	10.903	0.490	0.430	0.248	12.071	3.746	17.927
2014	2.757	10.120	0.510	0.460	0.582	11.672	3.848	18.278

However, Malaysia had 1.44 million hectares of protected forests in 1990 that turned into 2.76 million hectares in 2014, which almost doubled within 24 years. This indicates a growing potential to mitigate climate change through forest protection and conservation. Moreover, permanent reserved forests in Malaysia consist of inland forest, peat swamp forest, mangrove forest and plantation forest. The inland forested area was around 10.57 million hectares in 1990, which increased to 11.38 million hectares in 2005 but started to decrease gradually in the following years. In 2014, the inland forested area was 10.12 million hectares. Within 25 years, almost half of the area of peat swamp forests has reduced, which store and accumulate vast amounts of carbon. There was around one million hectares of peat swamp forests in 1990 that reduced to 0.5 million hectares. However, there was no significant change in mangrove forests, which remains at around 0.45 million hectares within these 25 years. In addition, numerous non-forest land has been planted throughout the years, and the area of plantation forest in Malaysia is increasing every year. In 1990, there were only 0.07 million hectares of plantation forests, but it turned into approximately 0.6 million hectares in 2014. Overall, the total area of permanent reserved forest was balanced around 12 million hectares, which shows a little bit of a downward trend after 2010. The area of state land forests in Malaysia was 5.2 million hectares in 1990, which decreased gradually during the years and turned into nearly 3.85 million hectares in 2014.

Furthermore, Figure 2 presents the projected forested area until 2030 by the Ministry of Natural Resources and Environment Malaysia (MNRE) [12]. Annually, 70,000 hectares of forest loss is projected under BAU (business as usual) scenario. A forest loss of 60,000 hectares per year is expected between 2015 and 2025 in the PLAN (Planning) scenario, which reduces to annually 30,000 hectares of forest loss by 2030. Finally, the AMB (Ambitious) scenario predicts annual forest loss of 50,000 hectares between 2015 and 2025, dropping to zero forest loss by 2030. The total forested area in 2020 for BAU, PLAN and AMB scenarios is projected as 17.858, 17.918 and 17.918 million hectares, which would be 17.158, 17.588 and 17.678 million hectares in 2030. Based on these scenarios, Malaysia would still preserve 51.9%, 53.2% and 53.4% of its total land as forested areas under the BAU, PLAN and AMB scenarios, respectively, by 2030.

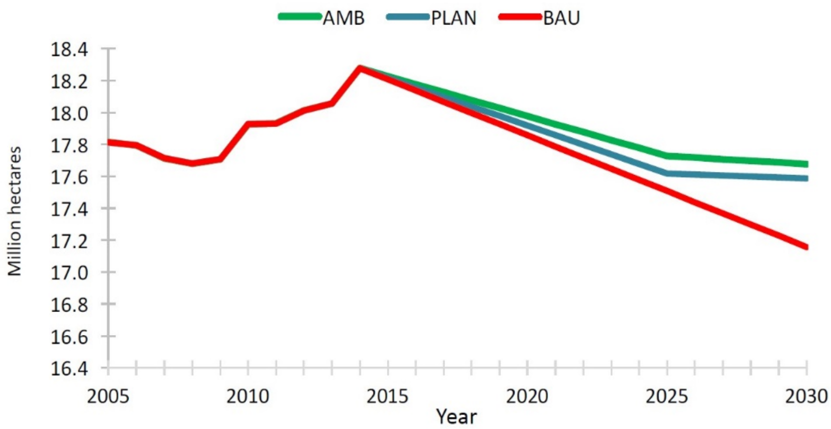


Figure 2. Expected forest cover in Malaysia from 2015 to 2030 under BAU, PLAN and AMB scenarios [12].

Forest biomass refers to the aboveground (tree biomass) and belowground (roots) biomass of trees in the forests [20]. Tree biomass refers to the oven-dry mass of the aerial part and the root of trees, and 50% of the dry mass of trees is carbon [3]. Table 2 presents the aboveground and belowground forest biomass in Malaysia along with the carbon in biomass and litter. The aboveground and belowground forest biomasses in Malaysia were 4782 and 1148 million tons, respectively, in 2015 where the amount of carbon in aboveground and belowground biomasses were 2248 and 539 million tons, respectively. The aboveground and belowground forest biomasses in 1990 were around 4842 and 1162 million tons, respectively, which increased to 6105 and 1465 million tons in 2000. The forest carbon increased from 1990 to 2000 due to the increase in forest biomass. Table 2 provides evidence that both aboveground and belowground carbon stored in the forest biomass were reduced from the 2000 to 2010, although a partial amount of biomass carbon was enhanced in 2015. There is no significant change in terms of the carbon in litter.

Table 2. Forest biomass and carbon stock (million tons) in Malaysian forests [5].

Year	Aboveground Biomass	Carbon in Aboveground Biomass	Belowground Biomass	Carbon in Belowground Biomass	Carbon in Litter
1990	4842	2276	1162	546	47
2000	6105	2869	1465	689	45
2005	5767	2711	1384	651	44
2010	4355	2047	1045	491	46
2015	4782	2248	1148	539	47

Malaysia has a large extent of forest cover, which has an enormous potential for carbon sequestration in tree biomass and forest soil. Figure 3 presents a comparison of forest biomass carbon density in Malaysia with different continents. Figure 3 shows that the average forest biomass carbon density in Malaysia is higher than Europe, North America and South American regions. The rate of carbon sequestration in Malaysia is relatively high due to the rapid growth of plants [21]. Saatchi et al. [22] reported that forests in Malaysia have carbon densities from 164 to 196 tons of carbon per hectare. According to FAO [5], the carbon density in Malaysian forests ranges from 89 to 276 tons of carbon per hectare.

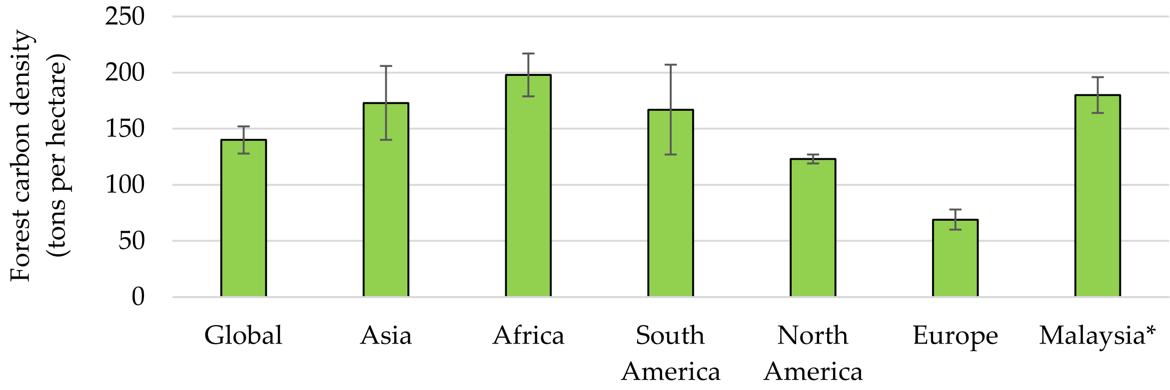


Figure 3. Comparison of forest biomass carbon density in Malaysia with different continents (the error bars represent the range of forest carbon density). Adapted from Yingchun et al. [23] and * Saatchi et al. [22].

3. Methodology

3.1. Data Collection and Sources

Data on forested areas were collected from Ministry of natural resources and environment, Malaysia (MNRE). Data on forest biomass carbon in Malaysia were collected from the Food and Agricultural Organization (FAO). Data regarding CO_2 emissions were collected from the World Development Indicator (WDI) dataset. The research design of the study is depicted in Figure 4.

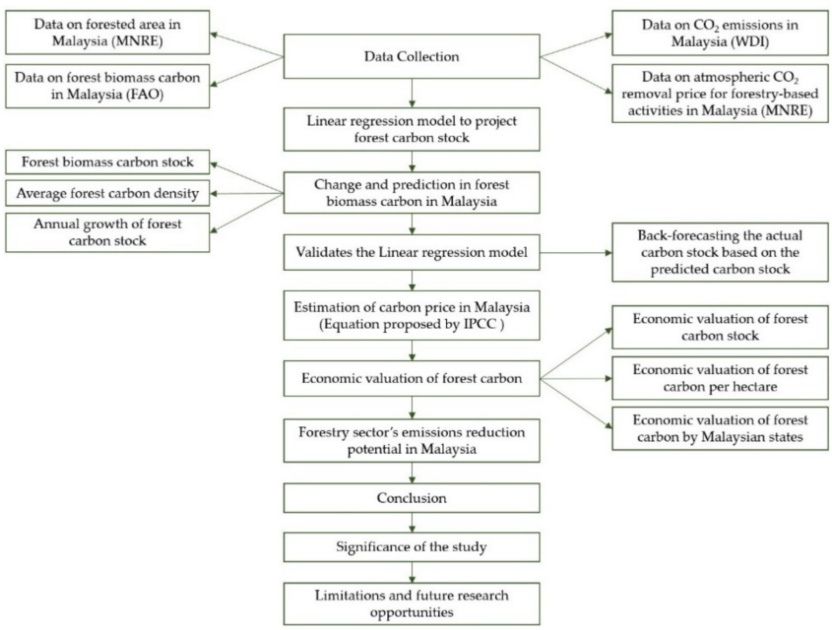


Figure 4. Research design of the study.

3.2. Linear Regression Model to Project Forest Carbon Stock

The total carbon stock (TC) in forest biomass of Malaysia comprised three main carbon pools: aboveground biomass (CAG), belowground live roots (CBGR) and carbon in the litter (CL). The forest carbon stock up to the year 2050 is projected by using a linear regression model based on the data from 1990 to 2015 by using the following equation:

$$Y_t = \beta_0 + \beta_1 X_t$$

where Y_t is the projected carbon stock in the year X_t and the coefficients β_0 and β_1 denote the intercept and the slope of the line, respectively.

This study validates the prediction model by using the same equation for back-forecasting the carbon stock based on the predicted carbon stock to test for prediction accuracy.

3.3. Estimated Carbon Price in Malaysia

The atmospheric CO_2 removal price varies widely and may range from USD 3.00 to USD 40.00 per ton CO_2eq [24]. Atmospheric CO_2 removal prices for forestry-based activities in Malaysia ranges from USD 2.90 to USD 7.30, where a conservative price of USD 5.00 per ton CO_2eq is assumed by Malaysia's report of second national communication to the UNFCCC [24]. The price of per unit carbon stored in forest biomass was estimated by the following equation proposed by IPCC [25]:

$$P_C = \frac{PCO2}{0.273}$$

where P_C is the price of one-ton carbon stored in forest biomass and PCO_2 is the price for removing one ton of CO_2eq.

According to the price ratio between CO_2eq and biomass carbon specified by IPCC [25], 0.273 ton of carbon would be stored in tree biomass with USD 5.00 if trees sequester one ton of atmospheric CO_2. Hereafter, the price for one ton of carbon stored in forest biomass would approximately be USD 18.32 (5.00/0.273 = 18.32).

3.4. Estimated Economic Value of Forest Carbon Stock

The economic value of the total forest biomass carbon stock (V_T) in USD is estimated by the following formula [26]:

$$V_T = T_C \times P_C$$

where T_C is total carbon stock in a certain year.

In order to obtain the economic value of biomass carbon per hectare forest, the economic value of total forest carbon stock is divided by the total forested area (FA). Therefore, the economic value of forest biomass carbon per hectare area (V_{ha}) is estimated by the following equation [26].

$$V_{ha} = \frac{V_T}{FA}$$

3.5. Estimated Forest Carbon Value by Malaysian States

This study estimates the forest carbon value relative to Malaysian states for the year of 2007 until 2019. Data regarding the forested area of the states are collected from the Forestry Department's annual reports. The economic value of forest carbon by Malaysian states is estimated by following equation:

$$Vs = FAs \times V_{ha}$$

where Vs is the total economic value of forest biomass carbon for a particular state, FAs is the total forested area for that particular state and V_{ha} is the average carbon value per hectare.

4. Results and Discussion

4.1. Change and Prediction in Forest Biomass Carbon Stock, Carbon Density and Annual Growth of Carbon Stock in Malaysia

This study estimates forest biomass carbon stock and average forest carbon per hectare in Malaysia from 1990 to 2050. Table 3 presents the change and prediction in forest biomass carbon stock and average forest carbon density in Malaysia. The forest biomass carbon stock in Malaysia is estimated at 2789 million tons in 2020. The forest carbon stock was 2869 million tons in 1990, which increased to 3603 million tons in 2000 with an additional 734 million tons of carbon in Malaysian forests. However, the forest biomass carbon stock reduced drastically to 2584 million tons in 2010 where Malaysia lost around 980 million tons of forest carbon from 2000. It seems that the carbon stored in Malaysian forests is reduced due to excessive deforestation and forest degradation. Nevertheless, Table 3 provides evidence that forest carbon stock started to recover within the year 2011 to 2015 but started to decrease again, which would turn into 2213 million tons in 2050. Furthermore, the average carbon density was 152.75 tons per hectare in 1990, which increased to 198.02 tons per hectare in 2000. The average forest carbon density started to decrease from 2001 and turned into 144.14 tons per hectare in 2010. However, the average carbon density in Malaysian forests is estimated at 157.5 tons per hectare in 2020, which decreases gradually to 130.36 tons per hectare in 2050. According to Ratnasingam et al. [27], the changes and variation in the carbon density observed in the Malaysian forests are triggered by logging activities and forest fires.

Table 3. Change and prediction in forest biomass carbon stock and average forest carbon density in Malaysia.

Year	Forest Carbon Stock (Million Tons)	Forest Carbon Density (Tons Per Hectare)
1990	2869	152.75
1995	3236	180.22
2000	3603	198.02
2005	3406	191.19
2010	2584	144.14
2015	2834	154.78
2020	2789	157.50
2025	2693	153.14
2030	2597	148.71
2035	2501	144.22
2040	2405	139.66
2045	2309	135.04
2050	2213	130.36

The minimum and maximum forest biomass carbon density in Malaysia is estimated at 144 tons and 198 tons carbon per hectare in the year 2010 and 2000, respectively. Saatchi et al. [22] reported that carbon density in Malaysian forests is 164 to 196 tons carbon per hectare. Moreover, Saatchi et al. [22] estimated the carbon density in some of the South Asian countries, for instance, Indonesia (158 tons per hectare), Myanmar (157 tons per hectare) and Papua New Guinea (153 tons per hectare). Average carbon density in three of these South Asian countries support the outcome of the present study in Malaysia (161 tons per hectare) as the forest type among the South Asian countries is almost similar. Saatchi et al. [22] also estimated forest carbon density in some other tropical countries of South America, for example, Peru (160 tons per hectare), Cameroon (151 tons per hectare), Colombia (141 tons per hectare) and Venezuela (139 tons per hectare). The average forest carbon density in these South American countries also supports the outcome of the present study due to the same climatic condition and tropical forest type in South Asian and South American countries.

The present study estimates the average carbon density 157.50 tons per hectare for the year 2020 in the Malaysian forests where the contributions of aboveground biomass, belowground biomass and litter are 124.94 tons per hectare (79.33%), 30.07 tons per hectare (19.09%) and 2.56 tons per hectare (1.63%), respectively. The result indicates that the most forest biomass carbon remains in the aboveground biomass pool, followed by belowground biomass and litter. Omar et al. [28] estimated aboveground and belowground biomass carbon in Malaysian forests consisted of about 79% and 19%, respectively, and dead-wood and litter additionally share about 1%. Matthew et al. [6] also estimated the above-ground carbon (78.93%), belowground carbon (18.93%) and other components (2.14%) in a mixed dipterocarp forest of Malaysia. This ratio of forest carbon in aboveground biomass, belowground biomass and in litter found by Omar et al. [28] and Matthew et al. [6] strongly supports the result of the present study.

Moreover, the changes and predictions in the annual increment rate of forest biomass carbon stock from 1990 to 2050 are presented in Figure 5. The average annual increment of forest carbon stock is estimated at around 2.25% within 1990 to 2000, which radically dropped to −1.15% in 2005 and −6.35% in 2010. However, the annual growth of forest carbon stock became positive again from 2001 with 1.9%, which decreased to 1.1% in 2016. It continues to decrease gradually to −0.67% in 2017, which would become −0.86% in 2050.

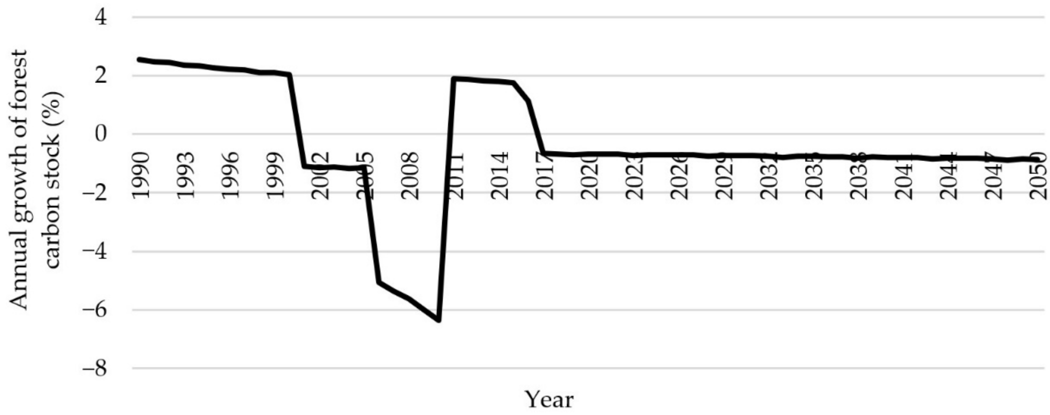


Figure 5. Change and prediction in annual increment rate of forest biomass carbon stock in Malaysia.

4.2. Back-Forecast to Validate the Prediction Model

We validate the prediction model by back-forecasting the actual forest carbon stock based on the predicted future carbon stock in order to test for prediction accuracy. Figure 6 shows a graphical presentation of the comparison between actual data on forest carbon stock for the period 1990–2015 and the back-forecasted carbon stock based on the predicted carbon stock up to 2050. Figure 6 also presents the linear regression equation relative to back-forecast the forest carbon stock. The outcome from back-forecasting the model shows almost similar quantities of forest carbon stock, which indicates that the model used by this study to predict the forest carbon stock is accurate. In addition, this study tested the goodness of fit for the linear regression equation model in order to validate the model with back-forecasting. The R^2 value for back-forecasted carbon stock is 0.9734, which clarifies that nearly 97% of the variation in change of total carbon stock can be explained by the years. Thus, the R^2 value from the back-forecasting model validates the linear regression equation model for predicting the future forest carbon stock.

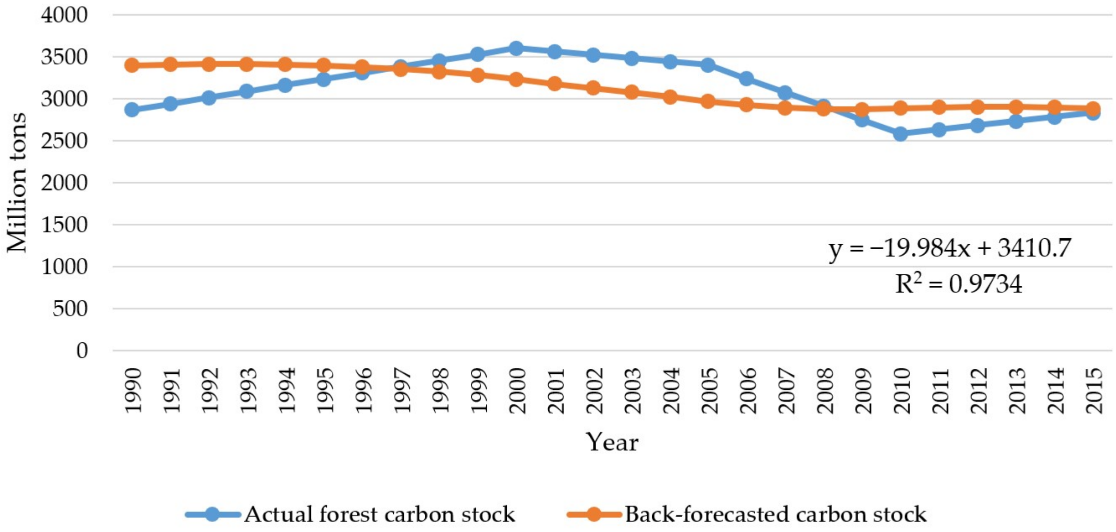


Figure 6. Comparison between the actual data on forest carbon stock and the back-forecasted carbon stock.

4.3. Economic Valuation of Forest Carbon Stock in Malaysia

This research study estimates the economic value of forest biomass carbon in Malaysian forests. Figure 7 presents the change and prediction in the economic value of total forest carbon and forest carbon per hectare in Malaysia from 1990 to 2050. The economic value trend shows an upward trend from 1990 to 2000, where the economic value of forest carbon reached the peak point of the curve at approximately USD 66 billion from USD 52.56 billion with an average annual increment rate of 2.25%. Within 1990 to 2000, the carbon value per hectare forest increased from USD 2798 to USD 3,628, with an average increment of USD 83 per hectare per year. The curve turned to a downward trend from 2000. Hence, the economic value decreased steadily from 2000 to 2005 with a moderate negative rate, and the value reduced drastically from 2005 to 2010 with a rapid negative rate. It is apparent that the economic value started to decrease because of the shrinkage of forest biomass due to excessive deforestation and forest degradation. The economic value of forest carbon reduced from 2000 to 2005 by approximately USD 3.61 billion, which is a reduction in forest carbon value of USD 125 per hectare. From 2005 to 2010, deforestation rate in Malaysia was so high that, within these five years, the forestry sector lost an estimated carbon value of nearly USD 15.06 billion, with an average reduction rate of 4.92% per year. The economic value of forest carbon reduced drastically from 2005 to 2010 by USD 862 per hectare or USD 172 per hectare per year. The total economic value of forest biomass carbon in 2010 is estimated at USD 47.34 billion or USD 2641 per hectare, which started to increase gradually.

The economic value of total forest carbon increased to nearly USD 52 billion (USD 2836 per hectare) in 2015, with an average annual increment of 1.76%. The average annual increment of economic value per hectare within 2010 and 2015 was around USD 39. This study estimates the total economic value of existing forest carbon stock in Malaysia as approximately USD 51.1 billion in 2020, with an average economic value USD 2885 per hectare forested area. The estimated economic value of total forest biomass carbon in 2050 is approximately USD 40.54 billion, with an average economic value USD 2388 per hectare. Due to the increasing rate of population in Malaysia, forests are being converted to other land uses for meeting higher demands of food, accommodation, transportation, industries and other infrastructures [12]. If the BAU scenario of forest loss (converting forests to other land use) continues, the projected estimation of carbon stock and its economic value might fall until 2050 unless further initiatives on proper planning of forest management and ambitious policy implementation are taken into consideration.

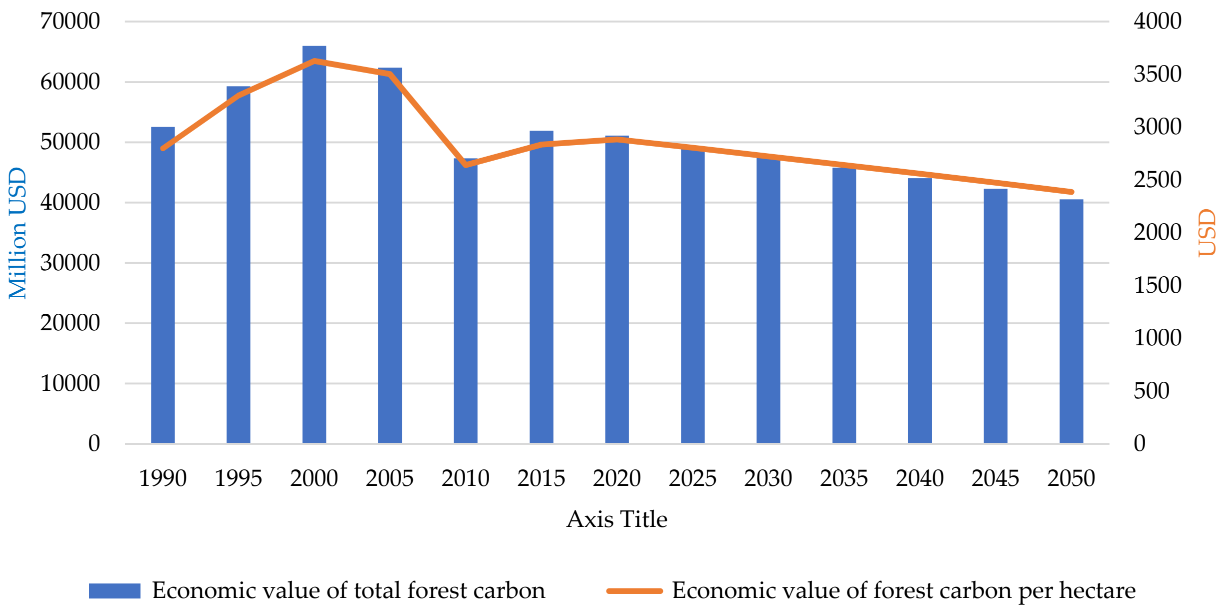
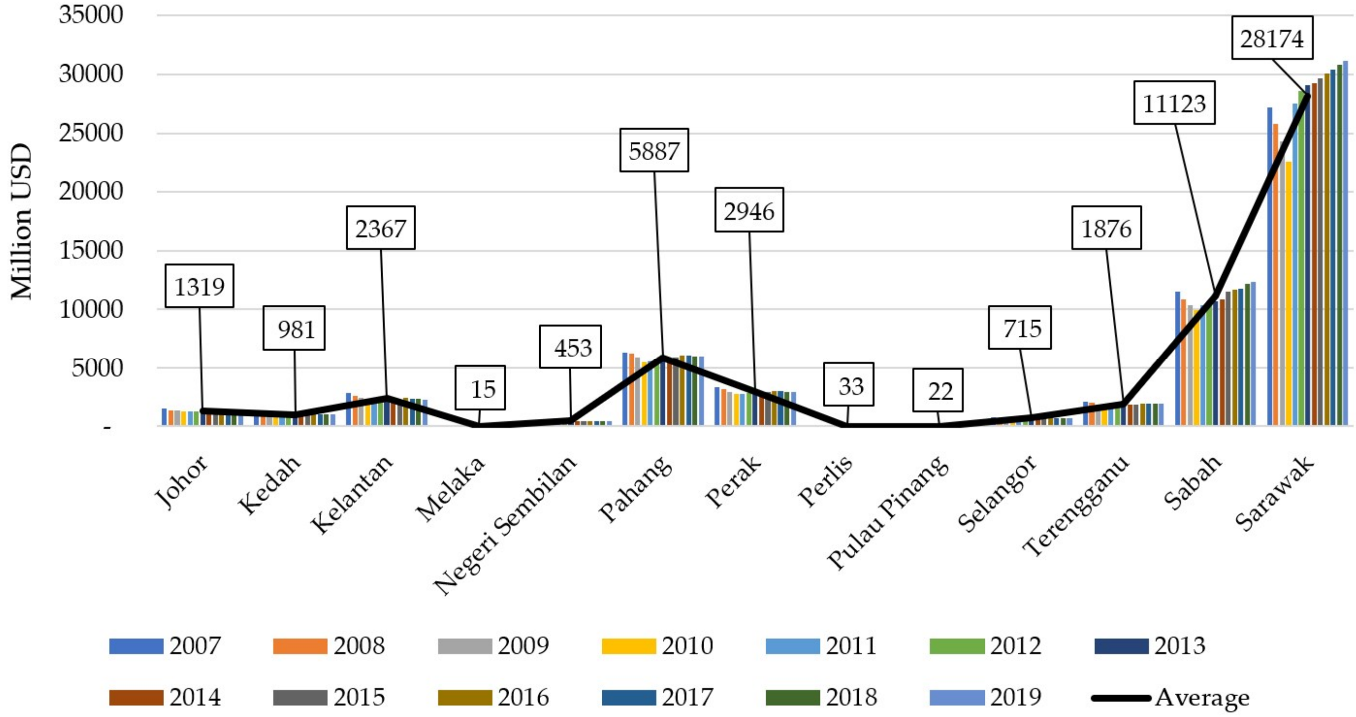


Figure 7. Change and prediction in the economic value of forest biomass carbon in Malaysia.

Moreover, Figure 8 presents the economic value of forest biomass carbon stock from 2007 to 2019 in the Malaysian states and their average percentage of contribution to the total forest carbon stock in Malaysia. Figure 8 shows that Sarawak holds nearly half (50.18%) of the total economic value of forest carbon stock as it is the largest state in Malaysia with a huge amount of forest land. Sarawak has nearly 7.91 hectares of forested area (MNRE, 2018), which holds biomass carbon valued approximately at USD 31 billion. This study found Sabah as the second uppermost state with an economic value of forest carbon at nearly USD 12 billion (19.81%), followed by Pahang (10.61%), Perak (5.33%), Kelantan (4.30%), Terengganu (3.37%), Johor (2.39%), Kedah (1.77%), Selangor (1.29%) and Negeri Sembilan (0.82%). The average percentage of contribution by Perlis (0.06%), Pulau Penang (0.04%) and Melaka (0.03%) in the total forest carbon stock is negligible as they are small states with less forested area compared to the other states. Figure 8 indicates that only three states (Sarawak, Sabah and Pahang) hold almost 80% of the total economic value of forest carbon in Malaysia.

This study aims to evaluate the forest biomass carbon in Malaysia with the purpose of evaluating the enormous economic value that could help to comprehend the necessity of reducing deforestation and forest degradation. The value of ecosystem services, such as carbon sequestration, reflects whether the community is willing to trade-off for conserving the natural resources. In addition, the importance of the ecosystem towards society is realized through these indications. On a global scale, this comprises carbon stock and reduces emissions by reducing the rate of deforestation. The present study estimates that the economic value of forest carbon per hectare in Malaysia for 2020 is around USD 2885, while Matthew et al. [6] estimated the economic value at USD 2161 per hectare in a mixed dipterocarp forest of Malaysia. Hazandy et al. [29] estimated the economic value of carbon at USD 2284 per hectare in a Malaysian forest. The economic values of biomass carbon per hectare forest estimated by Matthew et al. [6] and Hazandy et al. [29] are less in terms of amount than compared to the outcome from the present study.



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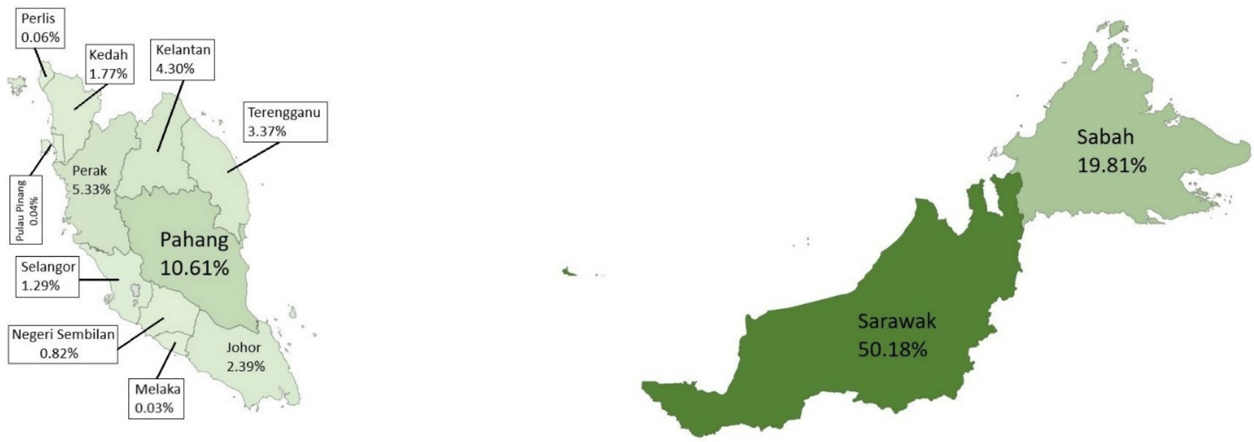

(**b**)

Figure 8. Contribution to the total forest carbon stock among the states in Malaysia. (**a**) Economic value of forest biomass carbon stock from 2007 to 2019 among the Malaysian states; (**b**) Average percentage of contribution to the total forest biomass carbon stock among the Malaysian states.

The economic value of forest biomass carbon per hectare estimated by the present study is supported by Saner et al. [30] and Ismariah and Fadli [21]. Saner et al. [30] estimated the economic value at USD 3477 to USD 6531 for the biomass carbon per hectare area of the Malaysian Borneo forest. In addition, Ismariah and Fadli [21] estimated that the economic value of forest carbon stock fluctuated from USD 500 to USD 6000 per hectare in Peninsular Malaysia. Moreover, Kumari [31] evaluated the carbon stored in the North Selangor peat swamp forest in Peninsular Malaysia under sustainable and unsustainable scenarios. Kumari [31] reported that the Net Present Value (NPV) of carbon under unsustainable options ranges from USD 2832 to USD 3204 per hectare, while under the sustainable scenario it was estimated at USD 3220 to USD 3471 per hectare.

Reducing emissions through forest carbon sequestration has been considered as a cost-effective method for climate change mitigation in many countries and regions [1]. Forest carbon sequestration is more cost-effective than improving energy efficiency, fuel switching, switching to renewable energy production and other approaches for capturing and storing CO_2 emissions [32]. Raihan et al. [20] reported that effective implementation of the potential and cost-effective options mitigates climate change through maximum carbon sequestration with minimum cost. Forest protection, afforestation, reforestation, forest conservation, sustainable forest management, agroforestry, urban forestry, short rotation tropical tree plantations, enhanced natural regeneration, use of wood-based bioenergy and REDD+ (Reducing Emissions from Deforestation and Degradation plus) initiatives are the most effective forest carbon activities that can help mitigate climate change [17]. The forest carbon sequestration capacity in Malaysia and its economic valuation suggest that improved forest management and enhanced forest carbon sink could be a vigorous and cost-effective strategies for reducing atmospheric CO_2 as well as GHG emission.

4.4. Forestry Sector's Emissions Reduction Potential in Malaysia

The forest carbon sink (annual increment of forest carbon stock) is an effective measure for mitigating climate change. Figure 9 presents the forest carbon sink and annual CO_2 emission growth in Malaysia. The average rate of forest carbon sink was higher than annual CO_2 emission in Malaysia between 1990 and 2002. The average forest carbon sink in Malaysia was nearly 66.1 million tons per year between 1991 and 2000. In addition, the average increment of CO_2 emission within this period was approximately 2.25 million tons per year. Figure 9 shows that carbon sinks in Malaysian forests decreased between 2001 and 2010. Malaysia lost 31.6 million tons of carbon per year between 2001 and 2005 due to heavy deforestation and forest degradation, which resulted in severe forest carbon loss of nearly 131.6 million tons per year between 2006 and 2010. Consequently, average CO_2 emission increased 2.41 million tons annually in between 2001 and 2010.

According to MNRE [12], the rate of deforestation in Malaysia has stabilized and there was no net loss of forests after 2009. The annual CO_2 emission growth started to fall after 2010 due to the increase in forest carbon sink as a result of increasing forested area by reducing deforestation and forest degradation. Average forest carbon sink increased approximately 47 million tons per year between 2011 and 2016 due to afforestation, reforestation, natural regeneration, forest protection and conservation. Ismariah and Fadli [21] reported that the rate of carbon sequestration in Malaysia is relatively high due to the rapid growth of plants. This study estimates that the average annual increment of CO_2 emission in Malaysia is 5.22 million tons between 2021 and 2030, annually 4.27 million tons between 2031 and 2040, which resulted in 3.33 million tons per year between 2021 and 2030. Malaysian forests absorb a gigantic amount of CO_2 emitted from all the sectors which indicates a huge growing potential for future climate change mitigation through the forestry sector of Malaysia.

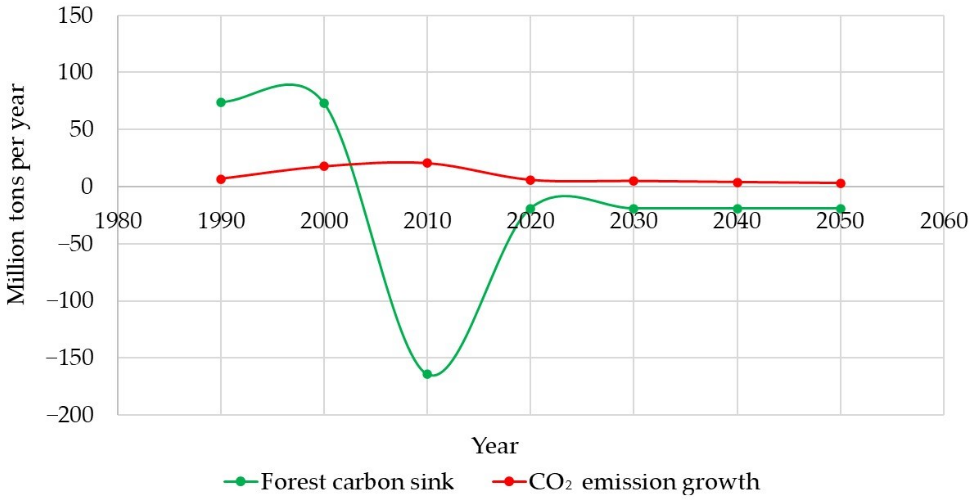

Figure 9. Change and prediction in CO_2 emission reduction through forest carbon sink in Malaysia.

Nevertheless, this study estimates that without further quality improvements, the carbon sink will decline steadily at 15.4 million tons per year between 2016 and 2020 and annually at 17.3 million tons between 2021 and 2030, which will result in 18.25 million tons yearly carbon loss between 2031 and 2050. According to IPCC [7], land-based mitigation action with a combination of different forestry activities is required to limit global warming 1.5 °C. However, climate change mitigation and adaptation actions are being established in Malaysia through the implementation of policies, plans and programs that have mitigation co-benefits and, at the same time, meet the development needs of the country. For example, one of the main targets in the Eleventh Malaysia Plan (2016–2020) is 'Pursuing Green Growth for Sustainability and Resilience'. Apart from the greater efforts in mitigation, awareness and necessity are growing among the government agencies and the private sectors in Malaysia for accurate measuring of the mitigation actions and their effects.

Moreover, Malaysia is constantly maintaining more than 50% of its land area as forests, which consist of protected areas, permanent reserved forests and state land forests [12]. Malaysia has launched Peninsular Malaysia Forestry Policy 2020 on the International Day of Forests 2021. It is a comprehensive policy that considers the interests towards achieving sustainable development along with sustainable management of forests. Based on the Forestry Policy 2020, special focus will be given to the greening Malaysia agenda in order to enhance forest conservation through tree planting, rehabilitation and restoration of degraded forested areas, in collaboration with state governments under the 12th Malaysia Plan (2021–2015). Malaysian forestry policy also encourages private investment in forest development through the establishment of private forest plantation areas. Thus, the actual implementation of National Forestry Policy 2020 indicates a huge potential for the forestry sector to make Malaysia an emission free country by increasing the national carbon sink.

5. Conclusions

The increase in GHGs emissions, which caused climate change is dominated by CO_2 emitted from burning of fossil fuel and deforestation. Forests absorb the atmospheric CO_2 and store it in trees as biomass carbon; hence, it is critical to estimate economic valuation of carbon stock in forest biomass and emission reduction potential for mitigating climate change. The economic value of biomass carbon stored in the forests is estimated at nearly USD 51 billion in 2020 and approximately USD 41 billion in 2050. In addition, the carbon value per hectare forest area is estimated at USD 2885 in 2020, which would be USD 2388 in 2050. Due to the increasing rate of population in Malaysia, forests are being converted to other land uses for meeting higher demands of food, accommodation, transportation, industries and other infrastructures. If the BAU scenario of forest loss (converting forests to other land use) continues, the projected estimation of carbon stock and its economic value might fall until 2050 unless further initiatives on proper planning of forest management and ambitious policy implementation are taken into consideration. Nevertheless, Malaysia's CO_2 emission growth started to fall after 2010 due to the rising forest carbon sink of 282 million tons between 2011 and 2016. The outcomes of this study indicate that there is an enormous potential for the forestry sector in Malaysia to mitigate climate change due to the high economic value and rapid growth of the carbon stock. The study's outcomes on the economic value of carbon stock in forest biomass would be helpful in understanding the necessity of avoiding deforestation and conserving more forested areas due to the economic benefits from carbon sequestration that ultimately helps to achieve the country's emission reduction targets and assist in mitigating global climate change.

5.1. Significance of the Study

This research significantly contributes to the area of estimating economic value of forest biomass carbon stock. This study is the first attempt at estimating and predicting the economic value of forest biomass carbon by considering the whole Malaysia with a period of 60 years (1990–2050). This research provides insight on the economic value of forest carbon in Malaysia, which could create awareness for reducing emission from deforestation and increase forest conservation by improving the status of natural carbon sinks while maintaining national green growth and sustainable management of the forests. In addition to the economic value of carbon stock in Malaysian forest biomass, this article also estimates and projects the total forest biomass carbon stock, forest carbon density, annual growth of forest carbon and carbon sink in Malaysia until 2050. The trend of future prediction for forest carbon and its economic value could be useful in meeting emission reduction targets and policy implementation related to climate change mitigation in Malaysia. Moreover, this analysis estimates the economic value of forest carbon by Malaysian states from 2007 to 2019, which would be beneficial for the state forestry department and policymakers with respect to making appropriate decisions for forest protection and conservation by understanding the present condition of forest carbon in the individual states of Malaysia. The estimated economic value of forest carbon by the present study could be useful for accurate forest resources accounting, evaluating forestry and environmental projects and incorporating public willingness to pay in forest conservation projects. In addition, the findings of the study may help Malaysia to obtain benefits from the global carbon trading system. This study also encourages other countries to estimate the economic value of their forest carbon stock, which could play a key role in enhancing global carbon sink by avoiding deforestation while reducing GHG emissions and thereby mitigating climate change.

5.2. Limitations and Future Research Opportunities

This study estimates the economic value of forest carbon only from aboveground biomass, belowground biomass and litter; the soil carbon pool was not included due to data unavailability. There is still limited data on soil carbon in the natural tropical forest, specifically in Southeast Asian countries as the forest conditions change swiftly from time to time. Further research on economic valuation of forest carbon can include the carbon stored in the forest soil and dead wood. Moreover, future studies should be carried out in order to assess the economic losses due to deforestation and forest degradation in order to highlight the importance of forest conservation in Malaysia. In addition, future research should focus on the comprehensive valuation of biodiversity and other forest ecosystem services in order to improve the competitiveness of preserving forests over converting land to other uses.

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