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A Review of Emission Reduction Potential and Cost Savings through Forest Carbon Sequestration

Asif Raihan, Rawshan Ara Begum[1]*, Mohd Nizam Mohd Said and Sharifah Mastura Syed Abdullah

Institute of Climate Change (IPI), Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor D.E., Malaysia
[1]Center for Water Cycle, Marine Environment and Disaster Management (CWMD), Kumamoto University, Japan
✉ rawshan@kumamoto-u.ac.jp; asifraihan666@gmail.com

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Abstract: Rising atmospheric concentration of greenhouse gases has been increasing with its negative effects on climatic system. Forests absorb and store a huge amount of atmospheric carbon dioxide (one of the major greenhouse gases) as tree biomass. Because of such capacity of forests which is called carbon sequestration, it has received much attention due to the concerns of global climate change. The research question is whether forest carbon sequestration could potentially reduce emissions in a cost effective way or not. Therefore, this article reviews and summarises emission reduction potential and cost savings through forest carbon sequestration. However, tropical forests have the highest aboveground carbon density and carbon sequestration potential compared to the subtropical, temperate and boreal forests. Instead, carbon sequestration potential found to be higher in Africa followed by North America, Asia, South America, Europe and Australia. The cost for one tonne of forest carbon sink enhancement ranges between 0 to US$ 443 in 2011 prices. Forest carbon sink enhancement cost in tropical region is found cheaper than any other region in the world. Carbon forestry options i.e. forest management, afforestation and reforestation can decrease the equilibrium carbon price up to 80% and reduce the emission reduction costs up to 40% whereas afforestation found to be the most low-cost carbon sequestration option. Hence, forest carbon sequestration plays an important role in reducing emissions which offers an opportunity for cost-effective climate change mitigation.

Key words: Carbon sequestration, carbon price, mitigation, emission reduction.

Introduction

Over the past few decades, rising atmospheric concentration of greenhouse gases (GHGs) caused disruptive climate change. Strategies to mitigate this climate change focus on reducing emissions of GHGs, the most prevalent of which is carbon dioxide (CO_2). Deforestation and burning of fossil fuels are the major anthropogenic sources of carbon dioxide emission that increase the negative effects on climatic system (Generosa, 2007). Carbon emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010 (IPCC, 2014). Annual GHG emissions grew on average by 1.0 gigatonne carbon dioxide equivalent ($GtCO_2$-eq) (2.2%) per year from 2000 to 2010 compared to 0.4 $GtCO_2$-eq (1.3%) per year from 1970 to 2000. Thus, limiting climate change will require substantial and sustained reduction of CO_2. Forestry has been proposed as a means to reduce net GHG emissions, by either reducing deforestation or enhancing sinks.

However, the world's forests play a critical role in the global carbon cycle by fixing, storing, and emitting

*Corresponding Author

vast quantities of carbon. Van der Werf et al. (2009) approximate that 12-15% of global CO_2 emissions come from the clearing of forests. Reducing forest carbon emissions and increasing forest carbon stocks are potentially important elements of a global climate change mitigation strategy (Murray, 2013). Activities like forest conservation, afforestation, reforestation, sustainable forest management, agroforestry and so on enhance tree growth help to remove carbon (C) from the atmosphere and store it in biomass, and thus should be eligible activities for creating carbon offset credits (Mishra et al., 2011).

Concern about rising carbon emission and atmospheric concentrations of GHGs has inspired the search for tactics of sequestering carbon in plant biomass. Due to cost effectiveness, high potential rates of carbon uptake, and associated environmental and social benefits, much attention has been focused on promoting tropical forestry for offsetting carbon emissions (IPCC, 1992). Carbon sequestration through forestry has the potential to play a significant role in reducing carbon emission, atmospheric accumulation of GHG's as well as the negative impacts of climate change (Moura-Costa, 1996). The estimation of cost and amount of carbon sequestration is essential as there is a substantial economic role to mitigate climate change through forestry sector with a lower cost compared to the other mitigation sectors such as energy supply, transport, buildings, industry, agriculture etc. Thus, this article attempts to provide an insight of the emission reduction potential and cost savings of forest carbon sequestration.

Emission Reduction Potential through Forest Carbon Sequestration

The removal of carbon from the atmosphere is the process of carbon sequestration. This can be accomplished by storing atmospheric carbon into the ground, water, or into vegetation. Figure 1 shows that forests draw carbon from the atmosphere in the process of photosynthesis, and the carbon may remain stored for long periods in trees and other forest vegetation (in above and belowground biomass and in forest soils) and in forest products in use or in landfills. Because of such capacity to store carbon in forests, carbon sequestration has received much attention due to the concerns of global climate change. Maximum 1,145,348 $MtCO_2$-eq can be sequestered globally by the forests (IPCC, 2006) that indicates a huge carbon sinks potential which would be ultimately obliging climate change mitigation.

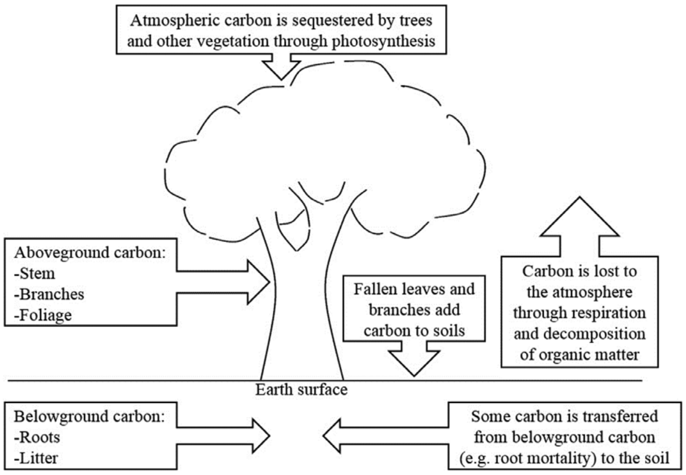

Figure 1: Process of forest carbon sequestration. (US Environmental Protection Agency, 2010)

Forest carbon sequestration potential is the amount of carbon dioxide that sequester in forests. Table 1 shows the average aboveground carbon density and carbon sequestration potential by different type of forests (IPCC, 2006). The world's forests have the potential to sequester 356.7 Pg (one petagram = one billion metric tonnes) carbon with average carbon density 140 ± 12 Mg C per hectare. Tropical forests show the highest average aboveground carbon density followed by subtropical, temperate and boreal forests. Carbon sequestration potential reduces from tropical to boreal, temperate and subtropical forests in respect to 142.5, 55.9, 53.7 and 34.3 Pg C.

Based on the carbon storage of each continent in the world, the carbon sequestration potential is highest in Africa followed by North America, Asia, South America, Europe and Australia in respect to 95.6, 78.5, 71.4, 55.5, 38.2 and 17.4 Pg C (IPCC, 2006). According to FRA (2015), global forests contain 250 GtC in above and belowground biomass where tropical forests may contain about 300-400 tonnes CO_2-eq per hectare in biomass (Kindermann et al., 2008). However, Malaysia is one of the tropical countries with 67.09% forest land of total land area (FRA, 2015). Of this 22.71% is classified as primary forest, the most biodiverse and carbon-dense form of forest. The amount of above and belowground biomass carbon in the forestry sector of Malaysia is 2,248 and 539 million metric tonnes respectively (FRA, 2015). Malaysian forests have carbon density ranging from 164 to 196 Mg C per hectare in aboveground vegetation (Saatchi et al., 2011). This wide range of values shows high variation of carbon density and huge carbon sequestration potential in Malaysian forests.

Table 1: Aboveground biomass carbon density and carbon sequestration potential in different types of forests

Ecological zone	*Area (10^9 ha)*	*Average carbon density Mean ± SD (Mg C ha^{-1})*	*Carbon sequestration potential (Pg C)*
World	4.19	140 ± 12	356.7
Tropical forests*	1.91	186 ± 20	142.5
Boreal forests**	1.22	65 ± 2	55.9
Temperate forests***	0.63	136 ± 13	53.7
Subtropical forests	0.41	160 ± 18	34.3
Polar	0.03	49 ± 18	1.3

*Forest areas approximately bounded by the tropics of Cancer and Capricorn; **Forests in the northern hemisphere, roughly between latitude 50º to 70º N, also known as Taiga or snow forest; ***Forests located between tropics and polar regions Adapted from IPCC, 2006

Cost Savings of Forest Carbon Sequestration

There are different ways of estimating the costs of forest carbon sequestration. For example, carbon sequestration costs are estimated in the context of cost-benefit analysis, where the net benefits of afforestation programmes are compared with the net benefits of current land-use practices. The estimation of the costs of carbon sequestration is a necessary input for determining its potential in relation to other climate change mitigation measures. The cost of carbon sequestration varies within and between forests in tropical, temperate and boreal zones. Marginal cost of creating carbon offset is the cost for one tonne of forest carbon sink enhancement. Table 2 shows the marginal cost range of global sink enhancement found in different studies. Sedjo et al. (1995) presented the marginal cost ranges from 1.5 to 133 US$ per tonne CO_2-eq. Richards and Stokes (2004) found the cost that varies between 13 and 188 US$ per tonne CO_2-eq. Van Kooten et al. (2009) estimated the marginal cost ranges from near-zero to 60 US$ per tonne CO_2-eq. Abenezer and Ing-Marie (2014) reported that the marginal cost of carbon sequestration range between 0 and 443 US$ as measured in 2011 prices.

Furthermore, Table 3 shows the potential marginal costs of creating carbon offset credits via afforestation, forest management and forest conservation (van Kooten and Sohngen, 2007). The estimation shows that marginal costs of creating carbon offset through afforestation is cheaper than other forestry options in Europe, boreal and tropical regions. Overall, marginal cost of creating carbon offset is highest in Europe and lowest in tropical regions. Tree growth rate as well as the carbon sequestration rate in the tropical regions is higher than any other regional forest. This is the main reason for the cheapest carbon sequestration cost in tropics. The other factors which affect the carbon sequestration cost are the diversity of planting cost, opportunity cost of land, availability of labour and labour cost in different regions.

However, Table 4 presents the net cost of emission reduction for some of the EU countries with and without forest carbon sequestration, and emissions when EU targets are met in a cost-efficient manner (Vass et al., 2013). France, Germany, Italy and Spain have the highest net cost in both scenarios. These are also the countries with the highest GDP and therefore have a larger national abatement burden as well as fewer

Table 2: Relevant studies on global sink activities and marginal sink enhancement cost, in 2011 prices

Studies	*Carbon sink activity*	*Marginal cost range (US$/ton CO_2-eq)*
Sedjo et al. (1995)	Forest plantation and reforestation	1.5 - 133
Richards and Stokes (2004)	Forest plantation, forest management and agroforestry	13 - 188
Van Kooten et al. (2009)	Forest plantation, forest conservation, management, agroforestry and bioenergy	0 - 60
Abenezer and Ing-Marie (2014)	Forest plantation, forest conservation, management, agroforestry and bioenergy	0 - 443

Adapted from Abenezer and Ing-Marie, 2014

Table 3: Marginal costs of creating carbon offset (US$ per tonne CO_2) through various forestry activities in different regions

Forestry activities	*Marginal costs of carbon offset*			
	Global	*Europe*	*Boreal*	*Tropics*
Afforestation	$22-33	$158-185	$5-128	$0-7
Forest management	$60-118	$198-274	$46-210	$34-63
Forest conservation	$47-195	n.a.	n.a.	$26-136

Adapted from van Kooten and Sohngen, 2007

Table 4: Net costs and net projected emissions in the cost-efficient solutions with and without forest carbon sequestration in some of the EU countries

EU countries	*Net cost of emission reduction without sequestration (Million Euro)*	*Net cost of emission reduction with sequestration (Million Euro)*	*Emissions 2020 without sequestration (Thousand tons CO_2)*	*Emissions 2020 with sequestration (Thousand tons CO_2)*
Austria	989	128	64172	51572
Estonia	42	-3	11668	8300
Finland	399	211	43840	13949
France	2813	1098	330060	264670
Germany	7224	2752	626800	609300
Greece	367	364	82790	80185
Hungary	580	170	49121	47232
Ireland	622	609	39403	38451
Italy	6346	4054	417980	329000
Latvia	366	-30	7224	-13260
Lithuania	-82	-66	10589	3305
Netherlands	1505	1460	155840	155280
Poland	991	562	230650	191440
Portugal	318	127	59808	55784
Slovakia	413	98	31931	30620
Slovenia	227	41	13000	9547
Spain	3503	1350	303970	288050
Sweden	2290	9	45360	25362

Source: Vass et al., 2013

emission allowances. The EU countries that experience the highest cost saving by including forest carbon sequestration are Austria, Estonia, Latvia, Slovenia and Sweden. Table 5 also shows cost-efficient emissions in 2020 with and without sequestration. Altogether, the total emission level is reduced by 11.4% when including forest carbon sequestration.

Nevertheless, it is crucial that forests play a dual role by acting as both sink and source of carbon emission. Reducing carbon emission by both decreasing deforestation and storing carbon as biomass are possible only through forest carbon sequestration. Thinking about reducing carbon emission without forest carbon sequestration is so expensive that it's almost impossible for most of the countries over the world. Compared to other mitigation options, carbon emission can be reduced by increasing carbon sink through forest carbon sequestration within short time duration with the lowest cost.

Moreover, Table 5 presents the calculated cost savings from introducing carbon sequestration into various GHG emission reduction programme. It shows that carbon forestry options can decrease the equilibrium carbon price up to 80% when all options are included

Table 5: Costs savings from introducing carbon sequestration into GHG reduction programme

Region and target	*Carbon sequestration options*	*Cost savings & decrease of carbon price*
Global	All carbon forestry options	80% reduction of carbon price
Global, 550 ppmv target in 2100	Forest management, afforestation, and reduced deforestation	40% total cost savings; 50% reduction of carbon price
Global, 5.2% emission reduction in 2020	Reduced deforestation	40% total cost savings; 35% reduction of carbon price
Global, 535 ppm target in 2100	Reduced deforestation	25% total cost savings
EU 27, 20% and 30% emission reduction by 2020	Forest management, afforestation	25-29% reduction of total cost and carbon price
EU 27, 20% reduction by 2020	Forest management and afforestation	40% reduction of total cost

Adapted from Abenezer and Ing-Marie, 2014

and reduce the total emission reduction costs up to 40%. The major carbon forestry options are improved forest management, afforestation, reforestation, reduced deforestation and agroforestry. The equilibrium carbon price can decrease by approximately 80% only when all carbon forestry options are included (Jung, 2005). Tavoni et al. (2007) found that introduction of carbon sink reduces the equilibrium carbon price by approximately 50% and the total emission reduction costs by 40% for achieving 550 ppmv target in 2100. Moreover, Anger and Sathaye (2008) calculated associated cost savings at the global scale for achieving the Kyoto target of 5.2% emission reduction in 2020 where total cost savings by 40%, and carbon price decrease by 35%.

Bosetti et al. (2011) reported that the inclusion of deforestation avoidance could reduce total abatement costs for achieving 535 ppm target in 2100 by approximately 25%. Michetti and Rosa (2011) calculated the total abatement costs for EU27 are reduced by 26% and 29% for obtaining the 20% and 30% reduction target, respectively. Cost saving for reaching the EU 2020 climate policy from introduction of afforestation and forest management could reduce overall abatement cost of achieving the EU 2020 climate policy by 40% (Gren and Elofsson, 2014).

However, Malaysia's Second National Communication (NC2) assumed the atmospheric carbon reduction cost RM 16 (US$ 3.98) per tonne CO_2-eq (MNRE, 2011). Thus, carbon sequestration cost in Malaysia can be cheaper than Europe or North American countries. According to the Ministry of Natural Resources and Environment (MNRE, 2018), Malaysia had 18.28 million ha of forest land in 2014. Instead, the above and belowground forest biomass were 4,782 and 1,148 million metric tonnes whereas the amounts of carbon in above and belowground biomass were 2,248 and 539 million metric tonnes in 2015 (FRA, 2015). The average carbon density in Malaysia's forests ranges between 164 to 196 tonne carbon per hectare (Saatchi et al., 2011). Cairns et al. (1997) demonstrated that the carbon density of Malaysia's mature lowland forest was approximately 216 Mg C (megagrams of carbon) per hectare while Ismariah and Ahmad Fadli (2007) estimated carbon density for logged over forest ranging from 104 to 111 Mg C per hectare.

The average carbon density varies by different studies which depends on the type of forests, maturity and biomass contents. Nevertheless, the cost of protecting climate can be increased by 70% in absence of carbon capture, storage and utilization (Ibrahim et al., 2016). Carbon capture and storage can be a great potential mitigation option in Malaysia (Begum et al., 2017). Forestry sectors in Malaysia could play a key role in enhancing cost-effective carbon sequestration and sinks while reducing global GHG emissions and thereby mitigate climate change.

Discussion and Conclusion

Due to the increase of carbon emission, current impacts and future risks of climate change become more apparent. Hereafter, climate change mitigation through carbon sequestration in tree biomass and soils is gaining attraction day by day. Forests act both as sources and sinks of GHG, through which they have significant influence on the climate on earth. Approximately 17.4% of annual global carbon dioxide emissions are caused by deforestation and forest degradation and it will be impossible to solve the climate change problem without addressing these emissions. Forests and other terrestrial systems annually absorb approximately 2.6 GtC (9.53

$GtCO_2$-eq), while deforestation and degradation of forests emit approximately 1.6 GtC (5.87 $GtCO_2$-eq), for net absorption of 1 GtC (3.67 $GtCO_2$-eq) (IPCC, 2007). Thus, reducing emissions from deforestation by forest carbon sequestration could be one of the most cost-effective tools for reducing GHG emissions as well as climate change mitigation.

Moreover, forests are at the heart of the transition to low-carbon economies. Forests and forest products have a key role to play in mitigation and adaptation, not only because of their double role as sink and source of emissions, but also through the potential for wider use of wood products to displace more fossil fuel intense products. Forests have potential for climate change mitigation in both developed and developing countries, through a range of activities. Mitigation potential and costs of forest carbon sequestration differ greatly by activity, region, system boundaries and time horizon. According to IPCC (2000), biological sinks have the potential to mitigate about 100-367 Gt CO_2, within the year 2000 to 2050, amounting to 10-20% of fossil fuel CO_2 emissions over the same period. The global potential for afforestation and reforestation activities between 1995 and 2050 would sequester between 1.1-1.6 GtC per year, of which 70% would be in tropical forests (Schlamadinger et al., 2000). Sohngen (2009) suggested that an additional 6.8 billion tonnes CO_2-eq per year may be sequestered in forests by 2030 for $30 per tonnes CO_2-eq. Around 42% of this would arise from avoided deforestation, with the rest roughly equally split between afforestation and forest management options.

This article demonstrates the variation among the potential and costs of carbon capture and storage in forest ecosystems at the global and regional level. After adjusting for the variation among the studies, it becomes apparent that forest carbon sequestration can play a cost-effective role in the global GHG emissions reduction programme by strengthening the climate change mitigation potential. Literatures on the cost and potential of forest carbon sequestration suggest that it would be possible to increase this carbon efficiently to reduce the future damages of climate change. It appears that at a cost range of 0 to 443 US$ per tonne of carbon, it is possible to reduce emission by sequestering 6-7 billion tonnes carbon per year globally. However, afforestation is found to be the most low-cost carbon sequestration option.

In sum, this review on emission reduction potential and cost savings through forest carbon sequestration suggests that there remains much work to be done in the area on economics of forest carbon sequestration. In particular, economic analysis of each mitigation options in the forestry sector could be helpful to reduce emissions more cost-effectively by choosing and implementing vastly of the most low-cost carbon forestry option. This article could be useful for the further studies of empirical economic analysis of climate change mitigation potential through various forestry options in Malaysia.

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