

## Soil Carbon Sequestration Potential of Terrestrial Ecosystems: Trends And Soil Priming Effects

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### Abstract

Carbon sequestration in the terrestrial ecosystems by forest and agricultural management activities is being considered the best sustainable method to diminish the increasing concentration of atmospheric carbon dioxide (CO<sub>2</sub>). This paper presents soil carbon sequestration potential of terrestrial ecosystem and the concept of soil priming effect. According to forest survey of India, the carbon stock of Indian forests increased at the rate of 0.3% as compared to the previous assessment, i.e., from 2017 to 2019. Indian forests soils are a reservoir of 7124.6 million tonnes of carbon and they still have high potential to store more carbon. As per soil carbon 4 mille concepts, India must intensify the process of afforestation, land restoration, and agricultural management practices to increase the soil carbon storage, i.e., up to 0.4%. However, organic manure amendments or a fresh supply of carbon substrates via rhizodeposits into the rainfed or irrigated lands changes the microbial communities and may decompose the already stored soil carbon, i.e., positive priming effect. Thus, accurate measurement of soil organic carbon (SOC) content in various types of ecosystems like forest, agricultural land, desert, agroforest, and plantation is still crucial to ascertain how much they can help to reduce the increasing concentration of atmospheric CO<sub>2</sub>.



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### Introduction

The concentration levels of carbon dioxide (CO<sub>2</sub>) in the atmosphere plays a precarious role in


maintaining the global surface temperature.<sup>1,2</sup>

The level of atmospheric CO<sub>2</sub> concentration is increased at alarming rate after the industrial

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revolution across the world. As compared to the pre-industrial level (280 ppm), the current CO<sub>2</sub> concentration is about ~414 ppm.<sup>3</sup> A lot of studies have reported that the increase in concentrations of atmospheric CO<sub>2</sub> is due to anthropogenic activities especially fossil fuel burning, deforestation, and agricultural management practices.<sup>4-7</sup> The global surface temperature has increased by around 1.1°C in 2017 since 1850, i.e. above the preindustrial level, and it's expected to increase at 0.2°C per decade.<sup>8</sup> The escalation in the earth's surface temperature affects the terrestrial ecosystem processes, ecosystem services and disturbs the terrestrial ecosystem carbon fluxes.<sup>9</sup> It's essential to ascertain suitable scientific techniques or natural processes for alleviating atmospheric concentrations of CO<sub>2</sub> in the terrestrial ecosystem. The United Nations climate entity is United Nations Framework Convention on Climate Change (UNFCCC) and several countries (both developed and developing) are its members and they have agreed to tackle the problem of global climate change by reducing the CO<sub>2</sub> emissions from industrial activities. The Kyoto Protocol, consented by industrialized and unindustrialized countries in the year 1997, specified that the well-developed industrialized nations required to cut their CO<sub>2</sub> emissions from industrial and other activities with reference to the 1990 level.<sup>10</sup> Kyoto protocol, article 3.3 and 3.4, mentions that the industrialised nations (mostly developed) are required to cut some significant amount of carbon emissions by reforestation and afforestation programs and invest clean energy projects in the developing countries to curb CO<sub>2</sub> emissions through clean development mechanism activities.<sup>10,11</sup> The Copenhagen and Durban climate accords are not successful especially to decide on a officially binding agreement to reduce the major greenhouse gases emissions by member countries. However, they agreed to focus on reduction of emissions from deforestation and forest degradation (REDD+).<sup>12</sup> Major features of REDD+ are to reduce CO<sub>2</sub> emissions from forests that suffer loss of vegetation cover and forest degradation activities and to increase sequestration potential of forests across the globe resulting in effective carbon sink.<sup>12</sup> According to Paris climate accords (2015), all the member states of UNFCCC agreed to make policies needed for sustainable future. Also, the agreement made a framework for controlling global warming well

below 1.5°C by the end of this century.<sup>8</sup> Carbon sequestration in terrestrial ecosystems, by plantation activities, is considered as the best approach to absorb significant amount of atmospheric carbon and also to reduce land degradation. There is a scarcity of data on the impacts of afforestation and plantation activities on carbon sink and sequestration potential across the world.<sup>13,14</sup> Besides an earlier study<sup>15</sup> showed the importance of agricultural management practices especially no tillage, organic manure amendments and nitrogen fertilization on organic carbon storage in soils. There have been several studies reported that the fresh carbon substrates (via photosynthates) accelerate the already stored carbon i.e. called priming effect. An attempt has been made in this review to presents soil carbon sequestration potential of terrestrial ecosystem and the significance of soil priming effect.

#### **Global and Indian Forest Cover**

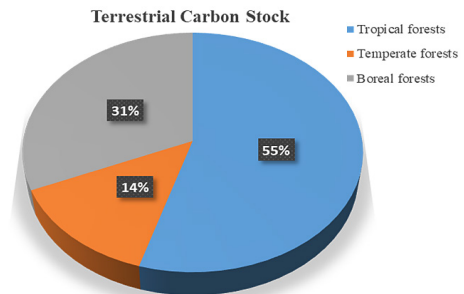
On a global scale, forests comprise of about 4.06 billion hectares i.e. 30.8% of the complete land area.<sup>16</sup> More than 50% of the global forests are situated in United States of America (USA), Canada, the Russian Federation, Brazil etc.<sup>17</sup> The total forest cover of India is 24.56% of the geographical area which also includes the tree outside forest cover (2.89%) of the country.<sup>18</sup> According to an earlier study, out of 328.7 million hectares of the total geographical area of India, 161.8, 57, 68.35, 11.05, and 7.95 million hectares are of arable land, irrigated land, forest land, permanent pasture, and permanent croplands respectively.<sup>19</sup> Hence, increasing agricultural activities through deforestation in temperate, tropical, arid and semiarid regions have a more profound effect on terrestrial ecosystem carbon flux. Hence an earlier study<sup>7</sup> estimated the net carbon flux due to land use and land cover change for the period 1850-2015 was 145±16 Pg C and more from the tropical regions (102±5.8 Pg C) of the world. Indian forests (the Western Ghats and Himalayan forests) are considered as one of the major biodiversity hotspots of the world. Therefore, Indian forest ecosystems plays a crucial role in regulating carbon cycle at regional and global level.

#### **Carbon Storage in the Terrestrial Forest Ecosystems**

In the earth's terrestrial ecosystems, forest ecosystems occupy a significant part and play

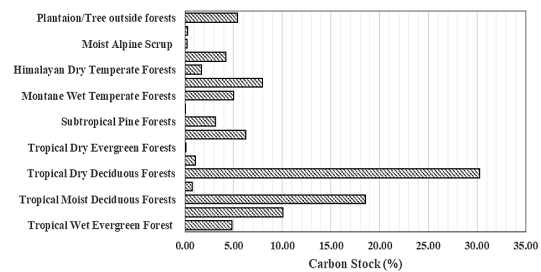
a central role in the terrestrial carbon cycle.<sup>14</sup> Forest ecosystems, around the world, stored higher amounts of organic carbon in above and below-ground parts with longer residence times especially in the soil via the carbon sequestration process.<sup>20</sup> Globally, forest ecosystems absorb a lot of atmospheric CO<sub>2</sub> through the process of photosynthesis. The forest ecosystem releases an almost equal amount of CO<sub>2</sub> into the atmosphere via the respiration process.<sup>20</sup> However, a significant amount of carbon is stored in forests vegetation biomass, dead twigs, leaves, detritus matters, and soil.<sup>20</sup> Therefore, forest ecosystems are considered an important carbon sink of terrestrial ecosystems. World forest ecosystems occupy about 4.06 billion hectares and act as a reservoir of carbon.<sup>17,21</sup> Research studies<sup>22,23</sup> reported that tropical, temperate and boreal forests sequestered about 55-63%, 26-31% and 11-14% of the total carbon stock of the world's forests respectively (Figure 1). Tropical forests occupy about 1.76 million hectares and are considered as nature's green engines of our planet earth.<sup>24</sup> The soils of tropical forests stored three folds more carbon as compared to the above ground vegetation biomass. Thus tropical forests store 471±93 PgC (Pg = petagram) and they can store up to 120-194 Mg ha<sup>-1</sup> of carbon.<sup>14,24</sup> Tropical forests are very dynamic in terms of plant growth, mineralization, and litter decomposition because of their unique climatic conditions.<sup>25,26</sup> It has been reported that deforestation and forest degradation in tropics to release about 0.5 to 3.5 Pg C yr<sup>-1</sup>.<sup>27-29</sup> Also it has been reported that tropical trees accomplish 60% of the world photosynthesis and release almost similar amount via litter decomposition by microbes.<sup>27</sup> An earlier study<sup>30</sup> reported that the age of soil carbon, in tropical forests and grasslands, increases (7 to 1250 years) with an depth increases. For example, 45% of topsoil carbon (0-30cm) comes under the age of 50 years. Therefore, small changes in the carbon stocks in the tropical forests may alter the earth's carbon cycling. Furthermore, tropical forests are more fragile, due to the climatic conditions, and they respond so rapidly, if they are under environmental stress conditions, to the global carbon cycle.<sup>28</sup> Global forests and soils together stored about 1240 PgC.<sup>21</sup> Soils are considered as a potential reservoir of carbon in the terrestrial ecosystem of our planet earth. Global soils are considered as a major sink or source of CO<sub>2</sub> with

the subject to conventional and/or different types of agricultural management activities.<sup>14</sup>



**Fig. 1: Terrestrial carbon stock of major forests in the world (Pan et al., 2011<sup>23</sup>)**

In the year 2009, the total carbon stocks of Indian forests, trees and soils was estimated to be about 6621 million tonnes.<sup>18</sup> The recent FSI report (2019) states that Indian forests stored about 7124.6 million tonnes carbon. Among different forest types in India, tropical dry deciduous forests stored the maximum amount of carbon (2158 million tonnes carbon) followed by other types of forests.<sup>18</sup> Tropical dry deciduous forests occupies about 40% of total forest cover in India.<sup>18</sup> Moreover tropical dry deciduous forest soils can act as a major sink for carbon for longer time periods<sup>31,32</sup> (Figure 2).



**Fig. 2: Carbon stock (%) in different types of Indian forests (FSI, 2019).**

According to FAO,<sup>29</sup> decreasing forest areas due to anthropogenic activities in the recent decade come down because of policies and actions taken by many of the developed and developing countries. Especially, afforestation or plantation activities may play a greater role in ecosystem restoration and increasing forest cover. According to the 4 per mille concept, every nation should increase their total soil carbon storage capacity by 0.4% per year to compensate the global emission of greenhouse gases.<sup>33</sup> The forest and tree cover of the country

had increased about 0.65% (5,188 sq km) during the FSI assessment period from 2017 to 2019.<sup>18,34</sup> Besides, Indian forests stored about 7124.6 million tons of carbon in five different components viz., biomass lying above and below the ground, debris, vegetation litter and soil.<sup>18</sup> Among them, soil stored 56.19% (4003.6 million tons) of carbon.<sup>18</sup> Also they found an increase in carbon stock (21.3 million tons) from 2017 to 2019. Thus accurate measurement of carbon stock in five different components, temporality, in different forest ecosystem is also very important.

**Soil Organic Carbon (SOC) Pools**

The CENTURY-C and ROTH-C carbon models are effectively applied to understand the changes of SOC pools in agricultural and forest soils.<sup>35,36</sup> The ROTH-C and CENTURY-C model has different organic carbon pools based on their turnover time. For example, the CENTURY-C model has three different pools viz., active, slow and passive.<sup>35</sup> Whereas the ROTH-C model has five different pools

viz., Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM) and Inert Organic Matter (IOM).<sup>37</sup> Above mentioned pools are not directly quantifiable, instead they are conceptual pools. Thus several researchers have tried to fractionate different soil organic matter pools based on particle size (sand, silt and clay fractions) and chemical (labile or mineral associated/recalcitrant).<sup>38</sup> Understanding the changes of soil organic carbon pools in terrestrial ecosystem becomes imperative to develop new sustainable or management practices to store more carbon in the soils. Table 1 shows the SOC content in different particles and chemical fractions. A combination of physical and chemical fractionation method is most effective in separation of organic carbon fractions with different turnover rates from soils.<sup>39</sup> However, still there is no discrete method or technique available to separate the organic carbon fractions with different turnover rates in all types of soils.

**Table 1: Fractions of soil organic carbon content in different land use and cover types**

No	Name of fractions	SOC	Reference	
1.	Particle size fractions Tropical forest in Costa Rica, Gallery Secondary forest	SOC (%)	40	
		<20µm		:34.7%
		20-53 µm		:23.2%
		53-105 µm		:23.8%
	15-year-old Secondary forest	105-200 µm		:18.3%
		<20µm		:29.2%
		20-53 µm		:26.0%
		53-105 µm		:24.4%
	25-year-old Secondary forest	105-200 µm		:20.4%
		<20µm		:30.5%
20-53 µm		:25.7%		
53-105 µm		:23.8%		
Abandoned plantation (>60 years old)	105-200 µm	:19.9%		
	<20µm	:34%		
	20-53 µm	:27.1%		
	53-105 µm	:21.6%		
2.	Different vegetation covers in north eastern china	105-200 µm	:17.2%	
		0-20cm	41	
		TSOC		
		2.1-66.6 g kg <sup>-1</sup>		
		20-40cm		
0.8-46.1 g kg <sup>-1</sup>				
	0-20cm			

	Heavy fractions	1.8-65 g kg <sup>-1</sup> 20-40cm	
	Resistant fractions	0.7-45.8 g kg <sup>-1</sup> 0-20cm	
		0.7-54.4g kg <sup>-1</sup> 20-40cm	
		0.3-37.3 g kg <sup>-1</sup>	
3.	Chemical fractionation	Mardi watershed, Nepal	42
	Fulvic acid	Forest :01.36 kg Cm <sup>-2</sup> Grass land :01.59 kg Cm <sup>-2</sup> Agricultural land :0.80 kg Cm <sup>-2</sup>	
	Humic acid	Forest :01.82 kg Cm <sup>-2</sup> Grass land :01.45 kg Cm <sup>-2</sup> Agricultural land :0.57 kg Cm <sup>-2</sup>	
	Hummin	Forest :02.25 kg Cm <sup>-2</sup> Grass land :01.72 kg Cm <sup>-2</sup> Agricultural land :01.44 kg Cm <sup>-2</sup>	
	Total SOC	Forest :06.13 kg Cm <sup>-2</sup> Grass land :05.03 kg Cm <sup>-2</sup> Agricultural land :02.84 kg Cm <sup>-2</sup>	
4.	Physical fractionation	0-15 cm	43
	Particulate organic matter >53 - 250 μm (POM/TOC)	Sandy loam Monocropping :39.8% Agroforestry :26.5% Sandy clay loam Mono-cropping: 17.9% Agroforestry : 25.2%	
5.	Physical fractionation	Agramunt site ( 0-40 cm)	44
	POM	No tillage :17.9Mg ha <sup>-1</sup> Reduced tillage :13.8Mg ha <sup>-1</sup> Sub-soil tillage : 14.0Mg ha <sup>-1</sup> Conventional tillage : 15.4Mg ha <sup>-1</sup>	
		Selvanera site No tillage :11.5Mg ha <sup>-1</sup> Reduced tillage :12.5Mg ha <sup>-1</sup> Sub-soil tillage : 14.9Mg ha <sup>-1</sup> Conventional tillage : 17.0Mg ha <sup>-1</sup>	
		Penaflo in continuous barley cropping system No tillage :08.2Mg ha <sup>-1</sup> Reduced tillage :06.0Mg ha <sup>-1</sup> Conventional tillage :05.7Mg ha <sup>-1</sup>	
	Mineral associated carbon (<53 μm)	Agramunt site No tillage :28.8Mg ha <sup>-1</sup> Reduced tillage :32.4Mg ha <sup>-1</sup> Sub-soil tillage :30.0Mg ha <sup>-1</sup> Conventional tillage :31.2Mg ha <sup>-1</sup>	
		Selvanera site No tillage :44.5Mg ha <sup>-1</sup> Reduced tillage :48.6Mg ha <sup>-1</sup> Sub-soil tillage :48.4Mg ha <sup>-1</sup> Conventional tillage :46.2Mg ha <sup>-1</sup>	

		Penaflor in continuous barley cropping system	
		No tillage	:42.2Mg ha <sup>-1</sup>
		Reduced tillage	:42.1Mg ha <sup>-1</sup>
		Conventional tillage	:41.8Mg ha <sup>-1</sup>
6	Density fractionation	0-20 cm	45
	Light fraction	Conventional tillage	:42.2 g kg <sup>-1</sup>
		No tillage	:44.1g kg <sup>-1</sup>
		Forest (oak forest)	:86.9 g kg <sup>-1</sup>
	Heavy fraction	Conventional tillage	:7.9 g kg <sup>-1</sup>
		No tillage	:9.8 g kg <sup>-1</sup>
		Forest (oak forest)	:20.4 g kg <sup>-1</sup>
7	Particle size fractionation	Arable land top-soil	:1750 mgC kg <sup>-1</sup>
	Coarse-silt (63-20µm)	Arable land sub-soil	:530 mgC kg <sup>-1</sup>
		Grassland top-soil	:1700 mgC kg <sup>-1</sup>
		Grassland sub-soil	:430 mgC kg <sup>-1</sup>
		Woodland top-soil	:8900 mgC kg <sup>-1</sup>
		Woodland sub-soil	:8470 mgC kg <sup>-1</sup>
	Medium-silt (20-6.3 µm)	Arable land top-soil	:6400 mgC kg <sup>-1</sup>
		Arable land sub-soil	:1060 mgC kg <sup>-1</sup>
		Grassland top-soil	:9770 mgC kg <sup>-1</sup>
		Grassland sub-soil	:730 mgC kg <sup>-1</sup>
		Woodland top-soil	:28870 mgC kg <sup>-1</sup>
		Woodland sub-soil	:19270 mgC kg <sup>-1</sup>
	Fine-silt (6.3-2 µm)	Arable land top-soil	:4850 mgC kg <sup>-1</sup>
		Arable land sub-soil	:1800 mgC kg <sup>-1</sup>
		Grassland sub-soil	:1610 mgC kg <sup>-1</sup>
		Woodland top-soil	:14970 mgC kg <sup>-1</sup>
		Woodland sub-soil	:10440 mgC kg <sup>-1</sup>

**Priming Effect (PE)**

The change in the rate of decomposition of already stored organic carbon (loss of carbon) when you supply the fresh carbon substrates into the soils is termed as priming effect.<sup>47-49</sup> It is categorized as real priming effect (loss of carbon) and apparent priming effect (extra CO<sub>2</sub> production by microbial populations).<sup>50</sup> Globally, several studies have reported that freshly added carbon substrate accelerates the priming effect (loss of native carbon) through rejuvenation of microbial populations and their biomass turnover.<sup>47-50</sup> Besides, the freshly added carbon substrates (rhizodeposits or fine roots) control the alterations in the growth of microbial populations and in turn affect the real priming effect or no effect on already stored carbon in the soils.<sup>51-55</sup> These alterations in the decomposition of stored carbon depend on the nutrient composition and /or budget of the particular soil.<sup>51,56</sup> An earlier study<sup>48</sup> hypothesized that r-strategists types of

microbes dominate till the easily utilizable substrates (like glucose) are exhausted in the soil system. After that, the gradual change from r-strategists to the k-strategists group of microbes dominate to decompose the resistant carbon in the soils. Thus there is a competition between the fast-growing microbes i.e. r-strategists (utilize the easily decomposable substrate like glucose etc.) and k-strategists for utilization of the substrates in the soil.<sup>56</sup>

The easily utilizable substrates are exhausted in the soil then the r-strategists become dormant and the k-strategists dominate in the system to decompose the insoluble organic compounds available in the soil organic matter.<sup>50</sup> The real priming effect would not occur even after the addition of easily utilizable substrates into the soil, because r-strategists may dominate in the system but they are unable to utilize the native soil organic matter. Thus an earlier study<sup>50</sup>



suggested that such priming effect may be “apparent” which is due to accelerated microbial biomass rather than by decomposition of already stored and /or build in soil organic matter. The acceleration of organic matter decomposition is totally dependent upon the living (microbes) and dead organic components. The microbial biomass acts as one of the important soil organic matter pools besides carbon and nitrogen in the terrestrial soil ecosystem.<sup>57</sup> A small change in the quantity and/or turnover rate of various soil organic pools, especially labile and recalcitrant, may have a greater impact on the total carbon budget of regional to global scale level.

### Conclusion

Understanding the carbon sequestration potential of natural forests, abandoned lands, grasslands, agricultural lands, and plantations is very crucial to store the atmospheric carbon in the terrestrial ecosystem. The selection of native plant species for the plantation activities, in any region, is essential in order to maintain the sustainable ecosystem process. It is a challenge to assess the soil-carbon sink and carbon sequestration potential strategy of afforestation activities of any region in the world. A multidisciplinary approach (climatologists, ecologists, geologists, etc.) is required to understand the mechanisms of

soil-carbon sink relationship and sequestration potential of any terrestrial ecosystem. An accurate estimation of carbon stock and monitoring the factors that affect the storage of carbon in forests and plantation soils are more important while assessing the total carbon stock of any ecosystem. It is essential to understand the changes of already stored organic matter pools in different types of forest ecosystems and plantations. Thus, more research analysis is warranted to comprehend the positive or negative priming effect of already stored carbon in terrestrial ecosystems.

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### Conflict of Interest

The authors do not have any conflict of interest.

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