Soil organic carbon and carbon sequestration. Present situation and research needs in Thailand.

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Abstract

The soil is a warehouse for carbon, because CO_2 taken from the atmosphere by photosynthesis is stored in living biomass, then in the dead residues and ultimately in the soil. In Thailand, soil organic matter has been depleted for a long time because of intense cultivation. We tested some changes in the management of the uplands, *i.e.* surface mulching and return of crop residues to try to stop soil carbon erosion and stabilize soil carbon content. Stopping erosion by surface mulching was an effective way to keep soil C, as C content in the eroded sediment was 2-3 times higher than in the undisturbed soil. Tillage practices were adapted to maintain crop residue on the soil surface (minimum tillage, surface mulching, tillage by chisel and disc plough). Returning15-30% of the crop residues (500-1000 kg.ha^{-1}) lead to a stabilization of soil C content. In addition, the management of wetlands has also a largely unknown potential for C sequestration.

All Thailand has been surveyed and mapped at the scale of 1/50 000 by the Land Development Department over the last decades. This unique effort in Southeast Asia has provided the basic data about soil organic and inorganic carbon for most soil series. At the depth of 25 cm soil organic carbon (SOC) was 4-8 kg.m^{-2} in the central, northern and southern regions and 2-4 kg.m^{-2} in the other regions, except in the mountains still under forest where SOC ranged from 8 to 9 kg.m^{-2}. It was also found that the SOC content of the clay fraction at the depth of 25, 50 and 100 cm was 5.0, 7.4 and 11.6 kg.m^{-2}, respectively, probably because the clay content tended to increase with depth. The montmorillonite had a SOC of 4.3, 6.8 and 11.4 kg.m^{-2} at the depth 25, 50 and 100 cm, respectively, followed by the kaolinitic, mixed, siliceous and calcareous minerals.

Soils with SOC ranging from 4 to 8 kg.m^{-2} over a depth of 100 cm covered an area of 260 000 km^2 and soils with SOC ranging from 12 to 16 kg.m^{-2} over a depth of 100 cm covered an area of 95 000 km^2.

A gap in research has been recognized about the impact of soil erosion, tillage methods, residue management and nutrients management on SOC and C sequestration. Research needs to be strengthen on the effect of soil conservation measures and organic matter management on SOC and C sequestration, especially for marginal land where little information is still available, like eroded land, low fertility soils and wetland areas.

Key words: Thailand, Carbon storage, Carbon sequestration, Conservation tillage, No tillage

Matière organique du sol et séquestration du carbone Situation actuelle et besoins de recherche en Thaïlande.

Résumé

Le sol est un puits pour le carbone, car le CO_2 de l'atmosphère fixé par photosynthèse est stocké dans les organismes vivants, puis dans les résidus morts et finalement dans le sol. En Thaïlande le taux de matière organique du sol a été réduit depuis longtemps à des valeurs très basses par suite d'une mise en valeur intense. Nous avons testé de deux changements de gestion des sols exondés (apport de mulch de surface et restitution des résidus végétaux) pour tenter de stopper l'érosion du carbone et de stabiliser la teneur en carbone du sol. Arrêter l'érosion par apport de mulch de surface est un moyen efficace pour maintenir le carbone dans le sol, étant donné que la teneur en carbone de la terre érodée est 2 à 3 fois plus élevée que celle du sol en place. Les pratiques de travail du sol ont été adaptées pour maintenir les résidus de culture à la surface du sol (minimum tillage, mulch de surface, travail du sol au chisel et à la charrue à disque). La restitution de 15 à 30% des résidus de récolte (500 à 1000 kg.ha^{-1}) permet de maintenir la teneur en carbone du sol. De plus, l'amélioration de la gestion des sols engorgés présente un potentiel encore largement inconnu pour la séquestration du carbone.

La Thaïlande a été entièrement caractérisée et cartographiée à 1/50 000 par le Département du Développement Rural (Land Development Department) au cours des dernières décades. Cet effort unique en Asie du Sud-est a permis d'obtenir les données de bases en ce qui concerne le carbone organique et minéral des sols dans la plupart des séries de sols. A 25 cm de profondeur la teneur en carbone organique du sol (SOC) est de 4 à 8 kg.m^{-2} dans la région centrale, la région du nord et la région du sud. Elle est de 2 à 4 kg.m^{-2} dans les autres régions, mais elle peut atteindre 8 à 9 kg.m^{-2} sur les versants sous forêt. La SOC de la fraction argile du sol (< 2µm) est de 5.0 kg.m^{-2} à 25 cm de profondeur, de 7.4 kg.m^{-2} à 50 cm et de 11.6 kg.m^{-2} à 100 cm, probablement parce que la teneur en argile tend à augmenter avec la profondeur. La montmorillonite a une SOC de 4.3 kg.m^{-2} à 25 cm, de 6.8 kg.m^{-2} à 50 cm et de 11.4 kg.m^{-2} à 100 cm. Les teneurs décroissent pour la kaolinite, les sols contenant plusieurs types d'argile, les silicates et les minéraux calcaires.

Les sols avec une SOC comprise entre 4 et 8 kg.m^{-2} sur une profondeur de 100 cm couvrent une superficie de 260 000 km^2 et les sols avec une SOC comprise entre 12 et 16 kg.m^{-2} sur une profondeur de 100 cm couvrent une superficie de 95 000 km^2 sur les 550 000 km^2 du pays.

Il est reconnu qu'il existe un besoin de recherche au sujet de l'impact de l'érosion, des techniques de travail du sol, de la gestion des résidus de récolte et de celle des engrais sur la SOC et la séquestration du carbone. La recherche doit en particulier être renforcée sur l'effet des mesures de conservation et de gestion de la matière organique sur la SOC et la séquestration du carbone dans les sols marginaux (sols érodés, sols pauvres chimiquement et sols engorgés), pour lesquels les données sont encore peu nombreuses.

Mots clé : Thaïlande, stockage du carbone, séquestration du carbone, travail du sol amélioré, no tillage.

Soil organic carbon and carbon sequestration: The present situation and research needs in Thailand

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Introduction

The Kingdom of Thailand, covering 51.31 million hectares is located at the centre of the Indo-China Peninsula between 5'40" to 20'30" N and 97'70" to 105'45" E. Its climate is influenced by the annual monsoon. Most of Thailand's climate can be classified as tropical savannah with the exception of the southeast and southern peninsula, where the tropical monsoon predominates, and the northern mountain areas where higher altitudes produce a climate classed as humid subtropical. Thailand's agriculture is characterized by a considerable increase in production and diversification, based on increasing utilization of land area, labour and machinery, without intensive farm management. However, about 70% of the total area has infertile soil and low plant nutrient contents and 30.78% of the total area has low soil organic matter (SOM) content. Furthermore, upland soils are skeletal, coarse textured and infertile. Acid sulphate soil is an important constraint in lowland areas. Agricultural yields have been declining due to improper management, such as monoculture or continuous use of land without appropriate soil management. Moreover, the gravity of deforestation, drought and flooding has become a major issue, affecting soil fertility and crop production. Recent farmers' practices in some cultivated areas, particularly orchards, fruit trees and vegetable gardens, often use too many chemical fertilizers, pesticides, fungicides and other chemicals to increase crop yields. In general, the SOM content in agricultural areas is lower than 0.5%. In this regard, SOM recycling and organic fertilizer utilization play a prominent role in soil conservation and improvement of the soil organic carbon (SOC) content (FAO, 1999). SOC is a parameter to measure soil fertility, which is the capacity of the soil to perform functions that sustain biological productivity and maintain environmental quality. Tropical soils have an important role in global carbon dynamics because they cover nearly 25% of the world's land surface and contain about one-third of the OC sequestrated in the surface soil (Lal *et al.*, 1998). Technical data and knowledge about properties and processes in relation to carbon dynamics are very limited. Therefore, an estimation of SOC and carbon sequestration in Thailand needs to be carried out and a national research plan should be devised to create a technical database on carbon sequestration, especially in agricultural areas.

Status of organic matter in the soil

The research data of the Soil Survey and Classification Division, Land Development Department (LDD) show that the deteriorating area, which is characterized by infertile soil and reduced plant nutrients, covers approximately 35.98 million hectares (about 70.06% of the total area). Contrariwise, highly fertile and productive soils, with both chemical and physical properties that are conducive for plant growth, cover only 0.07 million hectares (about 0.13% of the total area).

The gravity of the low level of SOM, covering approximately cover 15.80 million hectares (30.78%) is shown in Table 1. The deterioration of soil fertility and productivity in cultivated areas is one of the main reasons for stagnating and declining agricultural production. Other soil problems are attributable to climate (Thailand being under monsoonal influence), steep slopes and shallow soil surfaces; some soils are derived from infertile parent material, and have been cultivated for a long time without appropriate soil improvement technologies. The amount of plant nutrients and organic matter is declining annually, which directly affects the level of agricultural production and farmers' incomes.

The northeast and eastern Thailand are well known for their sandy soils, which have very low SOM content. They require extensive management including the incorporation of recycled organic matter into the soil. In the Central Plains, clayey soils have been exploited by lowland rice cultivation for a long time; as a consequence soil fertility has been reduced and soil compaction has increased. The incorporation of recycled organic matter should solve several problems. The sandy loam of northern Thailand has slightly lower SOM content; this varies according to the slope steepness and deforestation generated by shifting cultivation (these are important factors for the reduction of accumulated organic matter in the surface soil). In southern Thailand, some areas with undulating topography have very low SOM because of the shallow soil surface and the high rate of leaching and erosion caused by heavy precipitation; sandy soils are predominant in this region (Anandana *et al.* 1989).

Table 1: Distribution of SOM content in Thailand

Types of area	Area (hectares)
1. Organic matter < 1.5%	15,797,540
2. Organic matter 1.5-3.5%	17,542,614
3. Organic matter 3.5-5.0%	1,604,651
4. Organic matter > 5.0%	503,702
5. Organic soil (OM. > 20%)	80,829
6. Miscellaneous land types	15,385,312
7. Water body	396,862
Total	**51,311,510**

Source: Anandana, B. 1989

Thus it can be seen that the soil in Thailand has very low levels of SOM, which has a negative effect on improving soil fertility and raising productivity. Organic matter is material that is well decomposed by microbial activities, until it becomes dark brown in colour and a stable substance. SOM is an important factor governing plant growth because it controls the chemical and physical properties of the soil. It makes soil aggregation more stable, improves water absorption and aeration, reduces soil erosion and maintains soil microbial activities for plant growth. Moreover, SOM increases soil fertility and productivity, and biodegradation gradually releases nutrients into the soil.

Natural vegetation

In general, tropical forests play a vital role in nutrient storage and cycling on land. Nutrients are distributed not only through the trees but also in the soils. Nutrient cycling has a key role in the functioning of tropical forest ecosystems and enriches soils, especially surface soils. Any disturbance of forest cover can cause a significant loss of nutrients from the land. The forest types of Thailand are influenced by local climatic conditions, with the development of evergreen and deciduous forest (Vijarnsorn and Eswaran, 2002).

1. The evergreen forest forms about 60% of the total forest area. It can be subdivided into four types: the tropical evergreen, the coniferous, the swamp, and the beach forests.

The tropical evergreen forests occur along the wet belt of the country, where high annual amounts of rainfall of 1,500 mm and up prevail; they are affected by the monsoon. This forest ecotype is further divided into three categories: tropical rain forests, dry or semi-evergreen forests and hill evergreen of lower Montana forests. The tropical rain forests prevail in south eastern and peninsular regions where contact with the monsoon is direct; the precipitation is very high, 2,500 mm or more annually. The principal trees in the lower zone, up to 600 m altitude, are mostly dipterocarps, while in the upper zone, 600–900 m altitude, oaks and chestnuts are common.

The coniferous forest occurs in small pockets in the northwestern highlands and the Khorat Plateau (about 200-1,300 m elevation), where poor acid soil is found. The annual rainfall is about 1,000–1,500 mm. The dominant species are *Pinus merkusii* and *Pinus kesiya*. The swamp forest occupies areas that are more of less subjected to occasional inundation, and is scattered in the wet region of the country where the annual precipitation is high (in excess of 2,000 mm). This forest type can be further classified physiographically into two kinds: the mangrove swamp forest and the freshwater swamp. The beach forest occurs in areas along the seaboard, where sand dunes, rocky seashores, and elevated seashores prevail. The dominant species are *Casuarina equisetifolia* and *Terminalia catappa*.

2. The deciduous forest occupies the dry belt of the country, where precipitation is low (under 1,000 mm annually), the climate is more seasonal; the soil is sandy and lateritic. The vegetation of these zones is classified as deciduous formation. The tree species of this type shed their leaves during the dry season and tend to develop growth of annual rings. Deciduous forests can be subdivided into three main categories: The mixed deciduous, the dry dipterocarps, and the savannah forests.

The mixed deciduous forests occur between elevations of 50–600 m. The soil in this forest type is usually loamy, either calcareous of granitic. The principal tree species are *Tectona grandis, Lagerstroemia, Terminalia, Afzelia, Xylia, Pterocarpus,* and *Dalbergia* spp., most of which are high value commercial species.

The dry deciduous dipterocarp forest occupies areas on the undulating peneplain and ridges, where the soil is sandy and lateritic, and subject to extreme leaching, erosion, and annual burning. The dominant tree species are *Shorea obtusa*, *Shorea siamensis*. *Dipterocarpus tubercltus*, and *Dipterocarpus obtusifolius*.

The savannah forest originates from burning, then forms a deciduous type. It is found more frequently in the northeastern region, where the precipitation is relatively low (from 50–500 mm annually). The savannah is, in essence, a grassland where trees of medium height grow sparsely, forming a very open stand interspersed with thorny shrubs and *Bambusa arundinaceous*.

Land use

Land use of Thailand in 1998 is summarized in Table 2. The total area of agricultural land is 54.53% of the country; 32.90% is forestland and the remaining 12.58% consists of swamps, idle land, urban centres, highways and other miscellaneous areas. Cultivated lands are widespread in Thailand. The lower flood plains, with prolonged, deep flooding, support direct-seeded floating rice. In vast areas of irrigated paddy fields, especially in the Central Plains, direct sowing of germinated seed is practiced commonly. Higher flood plains and lower terraces support transplanted rice with the help of low dikes to retain rain water. Higher terraces, plateaus and foothills throughout the country support upland tilled crops, grazing, and varieties of shrubs and trees for food and fibre. Cultivated crops such as rubber, coconut, oil palm, and fruit trees are found in the south and southeast; cassava is common in the southeast and northeast, beans and cotton in the Central Plains; and shifting cultivation occurs in the mountainous areas of the north and west. Intensive cultivation of vegetable gardens and orchards (such as coconut and banana) is practiced on natural levees and other high ground such as ridges, in nearly all villages, towns, and cities. It is interesting to note that orchard farming on raised-beds in lowland areas with adequate irrigation is applicable elsewhere in the Central Plains, the north, and along the southeast coast (Vijarnsorn and Eswaran, 2002).

Table 2: Types and distribution of land use in Thailand in 1988

Land use type	Area	
	Hectares	%
Urban area	**74.623**	**1.454**
Agricultural land	**2,797.742**	**54.525**
Paddy rice	1,279.054	24.927
Field crops	810.146	15.789
Tree crops	415.002	8.088
Fruit trees	127.362	2.482
Horticultural crops	1.161	0.023
Rotation crops	141.534	2.758
Improved pasture	0.866	0.017
Aquaculture	**22.618**	**0.441**
Forestland	**1688.122**	**32.899**
Evergreen forest	853.940	16.642
Swamp forest	3.873	0.076
Mangroves	16.531	0.322
Mixed deciduous forest	805.652	15.701
Forest replanting area	8.127	0.158
Water body	**56.130**	**1.094**
Miscellaneous	**514.534**	**10.028**
Native grassland	478.352	9.323
Marsh	27.832	0.542
Mine tailings and pits	5.997	0.117
Salt farms and beaches	2.353	0.046
Total	**5131.150**	**100.0**

Source: Vijarnsorn and Eswaran, 2002

Estimation of soil organic carbon content in some soil series

An estimation of SOC content in agricultural areas of each part of Thailand is shown in Table 3. Almost all of the soil texture in the northern region is clay loam and the content of SOC ranges between 0.94 and 1.55% in the A horizon, whereas SOC in the B horizon decreases approximately two times to between 0.39 and 0.77%. In the north, the topography is elevated with sloping land, which is very susceptible to water erosion. This is the most important factor for the low content of OC in the surface soil in this region. In the northeast, the soil texture is sandy loam and the SOC content is very low, ranging between 0.26 and 0.80%, because the soil in this area is sandy and developed from parent material that has low SOM content. Moreover, the content of SOC in the B horizon is very low. Management of organic matter and the application of organic fertilizer to these soils are vital to sequestrate carbon into soil (Virdin, 2001). In the Central Plains the texture is clay and clay loam, since this area is lowland and receives soil sediment in runoff from the north. The SOC content is higher than the northeast and ranges from 1.10 to 3.22% in the A horizon; there is quite high SOC content in the B horizon. In the east the texture is clay loam and the topography consists of uplands and highlands; in general farmers use this area for upland crops and fruit trees. The content of SOC is quite high, ranging from 2.23

to 3.80%; the SOC in the B horizon has decreased nearly two times. It is clear that OC has a relatively high accumulation rate in the surface soil. The topography of the south comprises lowlands, uplands, and highlands and the soil texture varies from clay loam to sandy loam. In general the content of SOC in the A horizon is quite high, ranging from 1.06 to 4.60%, whereas the SOC content in the B horizon has decreased approximately 5 to 10 times compared to the A horizon.

Table 3: Estimation of soil organic carbon in the main soil series in each part of Thailand

Part	Soil series	Type	Texture	OC content (%)	
				A horizon	B horizon
North	Chiang Rai	Lowland	Silty clay loam	1.26	0.39
	Ban Chong	Lowland	Clay	1.54	1.77
	Mae Rim	Upland	Sandy loam	0.94	0.16
	Hang Dong	Upland	Silty clay loam	1.55	0.39
Northeast	Roi-et	Lowland	Sandy loam	0.33	0.045
	Renu	Lowland	Sandy loam	0.26	0.12
	Korat	Upland	Sandy loam	0.53	0.15
	Yasothon	Upland	Sandy loam	0.80	0.33
Central	Sena	Lowland	Clay	1.10	1.00
	Kamphaeng Saen	Upland	Clay loam	3.22	1.42
	Nakhon Pathom	Upland	Clay loam	1.41	0.66
East	Mahaphot	Lowland	Silty clay	3.50	1.33
	Khlong Chak	Upland	Clay loam	3.80	0.72
	Khlong Teng	Upland	Clay loam	2.23	1.26
South	Bang Nara	Lowland	Clay loam	1.06	0.15
	Kho Hong	Lowland	Sandy loam	1.33	0.22
	Ruso	Upland	Silty loam	4.60	1.86

Estimation of SOC in different forest types

An estimation of SOC content in different forest types has been made (Table 4). The results indicate that the accumulation of SOC in the 0–25 cm depth was around 10.27 kg/m^2 in the surface soil. It is somewhat higher in evergreen forests than other types of forest is shown in Table 4. The content of SOC accumulation increases nearly two times in the 0–100 cm soil depth, because this type of forest has a high density of vegetation that covers the soil surface throughout the year. Litter and residue accumulate on the surface and also in the soil. SOC accumulates in the 0–25 cm layer at around 6.99 kg/m^2/cm in mixed deciduous forest and the content of SOC accumulated in the 0–100 cm layer increases to 14.17 kg/m^2/cm. In dry deciduous dipterocarp forest, the content of SOC in the 0–25 cm soil depth is quite low, around 3.66 kg/m^2/cm being lower than pine forests, which is around 9.20 kg/m^2/cm (Moncharoen and Vearasilp, 2001).

The results of the estimation indicate that accumulation of SOC in mixed deciduous forest is clearly higher than other forest types. Organic matter from litter and vegetation residue is accumulated in the soil surface and such residues are decomposed by soil microbial activities; some of the OC is sequestrated into the soil surface (Takahashi *et al.*, 2002). The OC content in these forest types is higher than in agricultural areas, and is a measure of the importance of carbon stocks in tropical regions. If forests are properly conservedusing appropriate management and reforestation techniques, SOC will accumulate in the surface soil; this is an important process of carbon sequestration. On the other hand conservation and appropriate management are essential for controlling the level of SOC in agricultural areas. Tillage and other agricultural activities usually accelerate the process of decomposition of organic matter in the surface soil, especially in tropical regions where the microbial activities in the soil are higher than in temperate regions.

Table 4: Estimated organic carbon content in different types of forest in Thailand

Forest types	Area		Organic carbon ($kg/m^2/cm$)		
	Hectares	%	0–25	0–50	0–100
Dry deciduous dipterocarp	434.07	8.46	3.66	4.94	6.56
Evergreen	740.89	14.44	10.27	15.78	20.82
Mixed deciduous	243.08	4.74	6.99	10.25	14.17
Rubber	23.01	0.45	4.26	6.38	8.18
Pine	9.51	0.19	9.20	12.21	14.33
Deforestation area	71.37	1.39	5.70	8.75	11.99

Estimation of soil organic carbon loss in each area

The status of soil erosion in each part of Thailand has been estimated, and indicates that the south and north have very high soil loss at 4.0 and 3.2 t/ha/yr, respectively. However, the rate of soil loss declines to 1.28–1.32 t/ha/yr in the Central Plains and the eastern part of the country. The lowest rate of soil loss is found in the northeast at around 0.32 t/ha/yr (Srikhajon, 1997). Although the soil texture of this area is sandy, the rate of soil loss is lower than other areas. The estimation of the potential SOC loss from the country is calculated from the rate of soil loss and the average content of SOC in the surface soil as shown in Table 5. The results indicate that the rate of SOC loss by erosion is quite high in the south, at around 93.20 kg/ha/yr, while the rate of loss in the north and the east is around 42.24 and 40.70 kg/ha/yr, respectively. In the northeast, the rate of SOC loss is lowest at around 1.54 kg/ha/yr, because of the low content of SOC in the soil surface.

Table 5: Estimation of soil organic carbon loss by soil erosion in each part of Thailand

Region	Soil loss (t/ha/yr)	Total area (mha)	Problem area (mha)	SOC (%)	SOC loss (kg/ha/yr)
North	3.2	17.12	3.83	1.32	42.24
Northeast	0.32	1.69	0.56	0.48	1.54
Central	1.32	1.87	0.14	1.91	25.21
East	1.28	3.75	0.53	3.18	40.70
West	0.8	4.61	0.68	1.91	15.28
South	4.0	7.07	0.73	2.33	93.20

Regarding SOC management, especially for carbon sequestration, it is necessary to increase organic matter in the surface soil of the agricultural area, especially in the northeast, because carbon stocks in this region are very low. Increasing organic matter in the surface soil can be done by using crop residues and agroindustrial waste for mulch and incorporating them into the soil; this also includes the application of organic fertilizer as compost, green manure and animal manure. Soil and water conservation measures in agricultural areas in the northern and southern part of country are the first priority to consider as well as controlling the amount of SOC loss from that area. In the case of the Central Plains and the east, the integrated management of conservation and soil improvement is crucial, especially the management of surplus organic residues and wastes (Somsopon and Srikhajon, 1988).

The amount of suspended OC in runoff has been assessed as shown in Table 6 and the results indicate that the amount of sediment in runoff in the Central Plains, the eastern and the northern region is about 11.5 t/yr. In the northeast and south, suspended sediment is around 4.23 and 3.06 t/yr. The results of the assessment indicate that the amount of SOC loss through runoff in the south of Thailand is about 0.62 t/yr, and is about 0.44 t/yr in the north. This is substantial OC loss from these areas, which needs to be addressed by suitable soil conservation measures. Organic carbon loss in the northeast, Central Plains and east of the country ranges from 0.14–0.15 t/yr, which it is lower than in the south and north by around 3–5 times. Therefore, implementing suitable conservation practices and improving the OC content in the surface soil is very important; technical data from field experiments is required to clarify the status of SOC.

Table 6: Estimation of soil organic carbon loss by runoff in each part of Thailand

Region	Watershed area (mha)	Annual runoff (mcm/yr)	Suspended sediment (t/yr)	OC in sediment (t/yr)
North	1.16	48,2	10.4	0.44
Northeast	0.74	29,8	4.2	0.14
Central/East	0.77	45,1	13.3	0.15
South	0.53	75,6	3.1	0.62

Potential carbon sequestration in agricultural areas

Application and utilization of crop residues for carbon sequestration in the soil is feasible in Thailand, which has a surplus of agricultural residues and agro industrial wastes, such as rice straw from paddy fields and bagasse from sugarcane factories etc. Both residues account for more than 39.98 mt/yr, and almost all of the crop residues have OC content of around 45–55% as shown in Table 7. Utilization of crop residues (such as mulching) will increase carbon sequestration; application of crop residue at 12.5 t/ha will accumulate approximately 5.88–7.29t/ha of organic carbon into the surface soil. Therefore, continuous application of crop residues is a suitable practice for carbon sequestration. However, it should be noted that incorporation of crop residues or other organic material into soil will accelerate the decomposition rate of microbial activities and some organic carbon will emit from the soil surface in the form of CO_2, especially in residues that have a C/N ratio higher than 20:1.

Table 7: Potential carbon sequestration by incorporation of crop residue into the soil

Kinds	Amount (mt/yr)	Application rate (t/ha)	OC content (%)	OC sequestrated (t/ha)
Rice straw	25.45	12.5	47.97	5.99
Maize husks	7.83	12.5	48.98	6.12
Sorghum	0.92	12.5	47.64	5.88
Beans	0.74	12.5	48.69	6.09
Bagasse	13.53	12.5	53.54	6.67
Sawdust	1.44	12.5	58.50	7.29

The application of green manure as a soil improvement measure is a policy of the government sector; this is to encourage farmers to know and understand the benefit of organic fertilizer application, when fresh green biomass is incorporated into the soil. Green manure should be incorporated at the flowering stage due to the high accumulation of nutrients in the stems. Generally, utilization of green manure is suggested in two stages; planting in the early stage of the rainy season before the main crop, and in the late rainy season after the main crop. The limitations are suitable timing for planting, suitable species of green manure crops for different areas and good quality seed. *Sesbania rostrata*, *S. aculeata* and *S. speciosa* are suggested for lowland areas. *Cajanus cajan, Canavalia ensiformis* and *Crotalaria juncea* are appropriate for uplands. Such green manure crops provide biomass of between 11.00–20.67 t/ha. In this condition the green manure crop will provide 5.36–9.72 t/ha as potential carbon sequestration as shown in Table 8. A high performance green manure crop has fast growth, high biomass, soft stems, drought tolerance and pest resistance qualities.

Table 8: Potential carbon sequestration by incorporating a green manure crop into the soil

Kinds	Types	Biomass (t/ha)	OC content (%)	OC sequestrated (t/ha)
Crotalaria juncea	Upland	20.67	47.04	9.72
Canavalia	Upland	11.53	49.51	5.71
Vigna ssp.	Upland	14.92	46.47	6.93
Sesbania rostrata	Lowland	11.00	48.70	5.36
Vetiver grass	Upland	4.41	53.90	2.38
Ruzi grass	Upland	14.01	51.62	7.23

The estimated generation of animal manure is about 22.54 mt/yr, and around 50% of this is used for soil improvement as organic fertilizer. The rest of the animal manure is not used appropriately and sometimesimpacts adversely on the environment. Suitable management of animal manure will convert it to organic fertilizer for direct application to the soil; the application rate is 25 t/ha and it can sequestrate around 5.22–6.39 t/ha as shown in Table 9.

Table 9: Potential carbon sequestration by incorporating animal manure into the soil

Kinds	Amount (mt/yr)	Application rate (t/ha)	OC content (%)	OC sequestrated (t/ha)
Cattle manure	15.81	25	20.89	5.22
Pig manure	3.61	25	25.56	6.39
Poultry manure	3.12	25	24.55	6.14

Management of crop residues is very important because 45 to 55% is OC. Such crop residues can be used directly as organic material for soil improvement but can also be used as raw material for compost production (Lal *et al.*, 1998). The government sector encourages farmers to make compost by themselves and to use such compost to improve their land. In this case the production scale is not high but sufficient for application in that area. Nowadays the private sector is interested in industrial scale compost production and the use of surplus solid waste from agro industry (Metz *et al*, 2000). The recommended rate of compost application is 25 t/ha and it can sequestrate carbon at around 3.99–5.60 t/ha as shown in Table 10.

Table 10: Potential carbon sequestration by incorporating compost into the soil

Type	Amount (t/yr)	Application rate (t/ha)	OC content (%)	OC sequestrated (t/ha)

Bagasse	100,000	25	15.98	3.99
Eucalyptus chips	50,000	25	22.72	5.68
Rice husk and straw	30,000	25	17.12	4.28

Research needs for carbon sequestration

To realize soil management and conservation for the mitigation of greenhouse gas and carbon sequestration in the soil, a committee of climate change has been established in the LDD. A database of soil properties and quality has been created and information has been collected; a framework for research activities has been drawn up for researchers in the LDD to create proposals. The objectives of the research framework are mitigation of greenhouse gas emission and sequestration of OC in soil through suitable technologies on soil management and conservation, especially in agricultural areas. The research mandate of the Land Development Department is classified into short- and long-term perspectives as follows:

Short term

1) SOC and organic matter dynamics in major agricultural soils.
2) Strengthening the database on soil properties and quality, emphasis on soil erosion and SOC in agricultural areas.
3) The effect of organic material and crop residues on carbon sequestration efficiency.
4) Analysis and interpretation of the change in soil fertility and OC in different land uses and under vegetative cover.

Long term

1) The impact of soil erosion on carbon sequestration in the soil.
2) The effect of soil management and conservation on SOC dynamics.
3) The impact of soil management on problem soils (saline soil, acid soil and organic soil) for the enhancement of carbon sequestration.
4) The effect of organic fertilizers on soil fertility restoration and carbon sequestration in agricultural areas.

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