# Organic Carbon Storage and Management Strategies of the Rural Soils on the Basis of Soil Information System in Taiwan

Shih-Hao Jien[1], Zeng-Yei Hseu[2]*, Horng-Yuh Guo[3], Chen-Chi Tsai[4], and Zueng-Sang Chen[5]

[1] Department of Soil and Water Conservation, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan.
[2] Department of Environmental Science and Engineering, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan.
[3] Division of Agricultural Chemistry, Taiwan Agricultural Research Institute, Council of Agriculture, Taichung 41301, Taiwan.
[4] Department of Forestry and Natural Resources, National I-Lan University, I-Lan 26065, Taiwan.
[5] Department of Agricultural Chemistry, National Taiwan University, Taipei 10617, Taiwan.
*Corresponding author (E-mail: zyhseu@mail.npust.edu.tw)

**Abstract:** With the increasing concern over global climate change, it has become vital to quantify global and local soil organic carbon (SOC) storage. A total of 620 soil series have been established for the rural soils in Taiwan, which may provide a clear scenario of a national scale SOC stock from the soil information system (SIS). This study for Taiwanese rural soils aimed to (1) calculate the current SOC stocks in the major Soil Orders, (2) estimate total SOC pools in different depths of Taiwanese rural soils, (3) compare SOC storage with different land uses particularly on the change from paddy to upland cropping, and (4) propose the sustainable soil management for sequestrating SOC associated with improved SIS. The Taiwanese rural soils are dominated by Entisols, Inceptisols, Alfisols, and Ultisols, which total area is around 16830 $km^2$. The average SOC stocks with 0-30 cm, 0-50 cm, and 0-100 cm depths were about 5.97, 8.06, and 11.0 $kg/m^2$, respectively. However, the major SOC stocks were concentrated in 0-30 cm, which was more than 43-63% of the total stocks in 100 cm depth. Regarding the SOC pools, Taiwanese rural soils contained 81, 113, and 162 Tg in 0-30 cm, 0-50 cm, and 0-100 cm depths. Fluvial and marine terraces are ones of important agricultural lands in Taiwan. The soil age on fluvial terrace was generally high compared to marine terrace. However, correlation between SOC stock and soil age was linearly and significantly positive for fluvial terraces which coverd Entisols, Inceptisols, and Ultisols, but the correlation was not significant for marine terraces with Entisols, Mollisols, and Vertisols. Indeedly, Ultisols played important roles for agricultural production and SOC storage in Taiwan. With respect to the Ultisols, the SOC stock with paddy rice was higher than that with upland uses like pineapple or sugarcane cropping. Although the SOC pools in Taiwanese rural lands is much lower than the other temperate countries of ASPAC regions, the strategies by prolonging waterlogged duration of paddy soils and by efficiently reusing crop residues for all rural soils proposed good ways to sequester SOC.
**Key Words:** Carbon sequestration, Rural soils, Soil ages, Soil Information System (SIS), Soil organic carbon (SOC)

## 1. Introduction

Soil organic carbon (SOC) comprises a large part of C pool on the earth (about 1500 Pg) (Schlesinger and Andrews, 2000), and plays an important role in global C cycling and source of atmospheric $CO_2$ and other trace gases (e.g. $N_2O$ and $CH_4$) which contribute to greenhouse effect. In past decades, many scientists have focused on studying the global C cycle and C stocks change which impacted by global climatic change (Lal et al. 1999, 2004, Kondratyev et al. 2003; Schulp et al., 2008; Jelinski and Kucharik, 2009).

Much estimation was performed to calculate the global C storage in soils (Eswaran et al. 1993; Sundquist et al., 1993). For tropical areas, about 500 Pg of C in soils of the tropics, and about 40% of the C in soils of the tropics in forest soils (Eswaran et al. 1993). Batjes (1996) calculated that total soil carbon pools for the entire land area of the world, excluding carbon held in the litter layer and charcoal, amounts to 2157~2293 Pg of C in the upper 100 cm; SOC is estimated to be 684~724 Pg of C in the upper 30 cm, 1462~1548 Pg of C in the upper 100 cm, and 2376~2456 Pg of C in the upper 200 cm. In Taiwan, the calculation of stored C contents in soils is scarce before 1990s. Chen and Hseu (1997) reported that the estimated total SOC pool was about 347 Tg which included 123 Tg for cultivated soil and 224 Tg for forest soil, stored in upper 100 cm of soils in Taiwan. These values were calculated from a database of 172 soil pedons of cultivated and forest soils in Taiwan.

According to the Kyoto protocol, national householders need to pay attention to the impacts of land use changes on C storage in soils and vegetations. Alteration of C storage in soils have also been certainly indicated by several studies perform in Europe and USA (Li and Zhao, 2001; Schulp et al., 2008; Jelinski and Kucharik, 2009). In general, SOC storage under cropland is lower than that under pasture or forests. Moreover, forest SOC storage tends to be higher than pasture SOC storage. Alteration of forest to cropland or conversion of pasture to cropland will lead to decrease the SOC storage, while conversions usually lead to increase the SOC stocks (Guo and Gifford, 2002; Lettens et al., 2005; Falloon et al., 2006). Losses of SOC from the conversion of prairie to agriculture have resulted in 24 to 89% loss in North American (Knops and Tilman, 2000; Kucharik et al., 2001). In addition, tillage systems (e.g. annually tilled or biennially tilled) or land use in rural soils (e.g. rice-growing, dry farmland and fallow) will alter C sequestration and greenhouse gases emission as compared with those of native soils.

From the viewpoint of temporal in SOC storage change, land conversion, human disturbances and tillage practices will cause the significant changes of SOC in short-term. Paustian et al. (1998) indicated that SOC increases linearly with increased additions of crop residues and root organic matter, however, suggesting that irrigated farming will increase soil C with time (Lal et al., 1998). It is typical that SOC generally declines at the beginning, approaches a steady state in 25 to 50 yr, and shows an evident increase in about 50 yr after conversion of native soil to agricultural land (Janzen et al., 1998; Lal et al., 1998; Swift, 2001). This pattern suggests that time is also an important factor for C sequestration in irrigated cropland.

For estimating the SOC storages with different land uses, soil information systems (SIS) could be an excellent tool to help researcher to gain the area of different land uses in unique area. Furthermore, SIS and soil management system could help government to establish a clear scenario of low productivity soils and degradation soils in Taiwan croplands, and suggest national overview of the relative extent of physical resources limitation to agriculture and other forms of land use and highlighting area which called for the treatment or management of specific land resources constraints. The regional or national action plans therefore can be better focused on specific problems. In addition, it indicated the limitation of the data and the amelioration methods, and hence the priority needs for improved information and research (Guo et al., 2002; Guo et al., 2008).

Advanced understanding of impacts of changing land use and management on SOC storage is relevant to agricultural setting. Regional estimating of C contents and storage can help narrow variations of the global C estimates. Therefore, this study aims (1) to estimate SOC storage and pool in rural soils in Taiwan, (2) to explore the temporal change of SOC storage by the legacy data of rural soils, and (3) to evaluate the impacts of land use on C storage in the rural soils.

## 2. Materials and methods

### 2.1 Soil data source

Based on general soil maps, 140 pedons in the croplands of Taiwan were collected to estimate SOC pools of rural soils of Taiwan (Wang et al., 1988; Chen, 1992; Tsai et al., 2006; Tsai et al., 2009). Soil pedons can be grouped into either 10 Soil Orders or 21 Great Groups in cultivated soils based on Keys to Soil Taxonomy (Soil Survey Staff, 2006) (Table 1). The representative soil pedons were selected from different land uses (mainly in rice-growing, fallow and upland cultivation) and different climate regions (ranging from udic to ustic soil moisture regimes and from hyperthermic, thermic, mesic, or cryic soil temperature regimes) in each country of Taiwan (Chen et al., 2001; 2002; 2003; 2004; 2005 and 2006).

### 2.2 Bulk density and soil organic carbon analysis

The total organic carbon in the soils was measured using the Walkley-Black wet oxidation method (Nelson and Sommer, 1982). The bulk density ($D_b$) was determined using the core method (Blake and Hartge, 1986). Bulk density data are crucial in converting the organic carbon content from a by-weight basis to a by-volume basis (e.g., kg/m$^2$ to 100 cm depth of soil). In Taiwan, there is no actual measured bulk density in Histosols of cultivated soils. The mean bulk density of 0.20 Mg/m$^3$ in global studies

(ranging from 0.15 to 0.25 Mg/m$^3$) was used for Histosols of cultivated soils in this study (Buringh, 1984; Sombroek et al., 1993). For soil pedons lacking the $D_b$ data, we use the pedotransfer function, which reported by Chen and Hseu (1997), to determine the lacking $D_b$ value of pedons firstly, and then the estimated $D_b$ values were used for SOC storage calculation.

## 2.3 Calculating the SOC pool of individual soil pedons

For an individual soil pedon with k layers, the total SOC content by volume-basis can be expressed as follows:

$$T_d = \sum_{i=1}^{k} \rho i\, Pi\, Di\, (1 - Si)$$

where Td denotes the total amount of organic carbon (Mg/m$^2$) per unit area over depth d, ρi represents the Bd (Mg/m$^3$) of layer i, Pi is the proportion of OC (g C/g soil) in layer i, Di denotes the thickness of this layer (m), and Si represents the volume of the fraction of fragments > 2 mm (in diameter), particularly for calculating the soil carbon of forest soils.

## 3. Results and discussion

### 3.1 SOC contents and pools in Soil Order of Taiwanese rural soils

Inceptisol is the dominant Soil Order in the rural soils, which is 51% in area of total rural soils in Taiwan; Alfisol is the minor with 22% in area of total rural soils (Table 1). Other Soil Orders are lower than 10% rural soils in Taiwan. In these rural soils, the mean bulk density ($D_b$) ranged from 0.20 Mg/m$^3$ in Histosols to 1.81 Mg/m$^3$ in Vertisols (Table 2). According to area and $D_b$ of the soils, the calculation of SOC storage was performed for every Soil Order (Table 3, n = 140) to get total SOC pools by multiplying area of each Soil Order in rural soils in Taiwan (Table 4).

Table 1. The area of Soil Orders in rural soils of Taiwan (Chen and Hseu, 1997)

| Soil Order | Area (km$^2$) | Percentage of total rural soils (%) |
|---|---|---|
| Inceptisols | 8,590 | 51 |
| Alfisols | 3,668 | 22 |
| Ultisols | 1,624 | 9.6 |
| Entisols | 1,142 | 6.8 |
| Andisols | 195 | 1.2 |
| Mollisols | 191 | 1.1 |
| Oxisols | 50 | 0.3 |
| Histosols | 6 | 0.04 |
| Vertisols | 1 | <0.01 |
| Miscellaneous lands | 1,363 | 8.1 |
| Total | 16,830 | 100 |

Table 2. The bulk density (Mg/m$^3$) for three soil depth intervals of this study by Soil Order (n = 140)

| Soil Orders | 0-30 cm | | | 30-50 cm | | | 50-100 cm | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | CV | n | Mean | CV | n | Mean | CV | n |
| | Cultivated soils (n=140) | | | | | | | | |
| Inceptisols | 1.52 | 19 | 40 | 1.63 | 17 | 40 | 1.62 | 22 | 40 |
| Alfisols | 1.44 | 8 | 11 | 1.57 | 7 | 11 | 1.63 | 6 | 10 |
| Ultisols | 1.16 | 30 | 29 | 1.49 | 9 | 29 | 1.52 | 8 | 29 |
| Entisols | 1.40 | 11 | 39 | 1.55 | 10 | 38 | 1.54 | 9 | 38 |
| Andisols | 0.48 | - | 1 | 0.69 | - | 1 | 0.69 | - | 1 |
| Mollisols | 1.47 | 38 | 9 | 1.47 | 24 | 8 | 1.48 | 20 | 8 |
| Oxisols | 1.49 | 0 | 3 | 1.51 | 5 | 3 | 1.46 | 4 | 3 |
| Histosols | 0.20 | - | 1 | 0.20 | - | 1 | 0.20 | - | 1 |
| Vertisols | 1.81 | 21 | 7 | 1.82 | 17 | 7 | 1.80 | 13 | 6 |

Table 3. The rural SOC stocks with different depths in Soil Orders of Taiwan (n=140)

| Soil Order | 0-30 cm | | | 0-50 cm | | | 0-100 cm | | | Ratio[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | CV | n | Mean | CV | n | Mean | CV | n | A | B |
| | kg/m$^2$ | % | | kg/m$^2$ | % | | kg/m$^2$ | % | | % | % |
| Vertisols | 10.0 | 45 | 4 | 13.4 | 37 | 4 | 17.0 | 31 | 4 | 59 | 79 |
| Mollisols | 7.27 | 31 | 10 | 9.49 | 36 | 10 | 11.7 | 54 | 10 | 62 | 81 |
| Inceptisols | 5.58 | 56 | 128 | 7.88 | 58 | 128 | 11.5 | 82 | 128 | 48 | 68 |
| Entisols | 5.44 | 55 | 146 | 6.96 | 60 | 146 | 8.66 | 65 | 146 | 63 | 80 |
| Ultisols | 4.86 | 79 | 66 | 6.95 | 80 | 66 | 9.68 | 73 | 66 | 50 | 72 |
| Alfisols | 4.75 | 55 | 18 | 6.43 | 52 | 18 | 9.49 | 51 | 18 | 50 | 68 |
| Oxisols | 3.82 | 67 | 15 | 5.26 | 74 | 16 | 8.86 | 73 | 16 | 43 | 59 |
| **Average** | **5.97** | | | **8.06** | | | **11.0** | | | **54** | **72** |

[a]A stand for the ratio of the soil organic carbon stock of 0-30 cm divided by in the 0-100 cm zone; B stand for the ratio of the soil organic carbon stock of 0-50 cm divided by in the 0-100 cm zone.

Table 4. The estimated total SOC pools (Tg) in different depths of Taiwanese rural soils

| Soil Order | 0-30 cm | 0-50 cm | 0-100 cm |
|---|---|---|---|
| Inceptisols | 47.9 | 67.7 | 98.8 |
| Alfisols | 17.4 | 23.6 | 34.8 |
| Entisols | 6.21 | 7.95 | 9.89 |
| Ultisols | 7.89 | 11.3 | 15.7 |
| Mollisols | 1.39 | 1.81 | 2.23 |
| Oxisols | 0.19 | 0.26 | 0.44 |
| Vertisols | 0.01 | 0.01 | 0.02 |
| Total | 81.0 | 113 | 162 |

Chen and Hseu (1997) compared the SOC contents (g/kg) between the Soil Orders (n = 100), and the order was as fallows: Histosols (185 g/kg) > Andisols (127 g/kg) > Mollosols (18.4 g/kg) > Vertisols (15.6 g/kg) > Ultisols (14.0 g/kg) > Inceptisols (8.70 g/kg) > Entisols (7.80 g/kg) = Alfisols (7.80 g/kg) > Oxisols (6.30 g/kg). In this study, we compared the vertical distribution of SOC in common the Soil Orders (n = 40) (Figure 1), the highest SOC contents were found in the depth of 50 cm from soil surface of Mollisols (10 to 29 g/kg). The order of SOC contents in the depth of 50 cm

was as follows: Mollisols > Entisols > Ultisols > Inceptisols. This result differs from the result by Chen and Hseu (1997), the disagreement could be attributed to the variance of sampled soils. However, the SOC contents ranged from 10 to 30 g/kg in common Soil Orders of rural soils were confirmed.
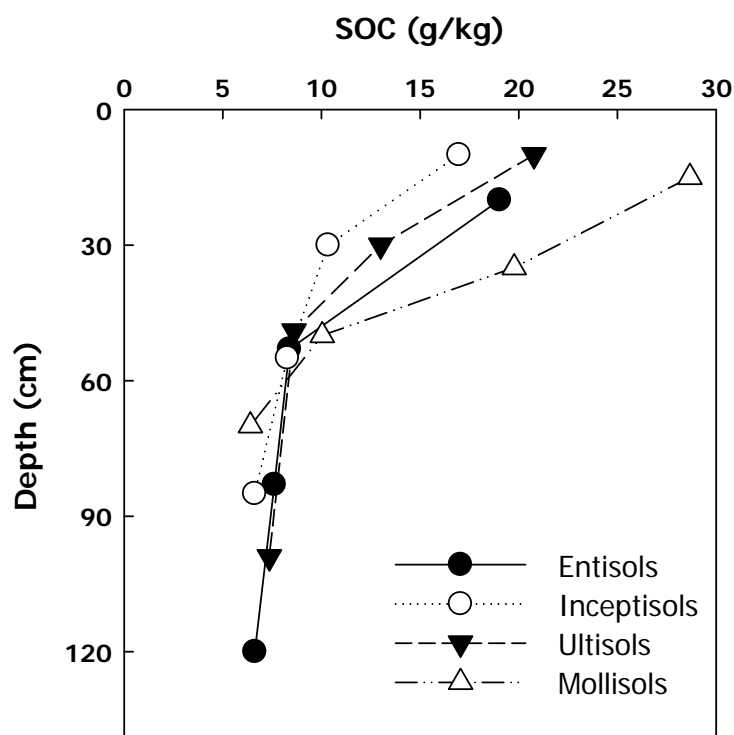


Figure 1. Vertical distribution of SOC content in selected rural soils of Taiwan: (a) Entisols (n=12), (b) Inceptisols(n=12), (c) Ultisols (n=10), and (d) Mollisols(n=6).

From the estimation of SOC storages in pedons of rural soils (Table 3), the highest SOC storage were found in Vertisols, and followed by Mollisols, Inceptisols, Entisols, Ultisols, Alfisols, and Oxisols regardless of soil depths calculated. The Differences between SOC content (g/kg) and storage ($kg/m^2$) in this study could be attributed to natural structures and non-soil components in soils. Carbon storage ($kg/m^2$) is therefore considered as more realistically to reflect the amount of C stored in natural soils (Li and Zhao, 2001). This study indicated that SOC storage ranged from 8.86 to 17.0 $kg/m^2$ to the depth of 100 cm in the rural soils. Similar estimation of SOC storage consisted with the results of Li and Zhao (2001) which indicated that about 15 $kg/m^2$ SOC was found in the cropped soils to 100 cm depth in China. Additionally, 40%-65% of SOC was concentrated in the depth of 30 cm, and about 60%-80% of SOC was found in the depth of 50 cm.

By multiplying area of each Soil Order of rural soils in Taiwan, Table 4 presents estimated total SOC pools in the rural soils. The estimation indicated that 81 Tg, 113 Tg, and 162 Tg of SOC were stored within the depth of 30 cm, 50 cm and 100 cm, respectively, in the rural soils in Taiwan. About 50% of SOC of the 0-100 cm was held in upper 30 cm, and 70% was held in 50 cm depth from soil surface. Many studies estimated the amounts of organic C in the tropical soils. Kimble et al. (1990) estimated a value of 496 Pg C in the upper 100 cm soil, which is comparable to the estimate of 506 Pg C by Eswaran et al. (1993), however, Batjes (1996) reported a relatively lower result of 384–403 Pg C. Li and Zhao (2001) also indicated that the amount of SOC in tropical and subtropical China is around 5.7–7.5% of the world's tropical areas. Based on this study, there is a total of about 0.16 Pg of stored SOC in upper 100 cm for the rural soils.

## 3.2 SOC accumulation with soil age

With increasing population in the world, additional land is expected to be converted to irrigated farming or reclaim for agriculture (Bruinsma, 2003). However, extremely few field survey data are available, and quantifying of impact of cropped lands on dynamic transformation of SOC is limited (Lal et al., 1999; Follett, 2001). Paustian et al. (1998) indicated that SOC increases linearly with increased additions of crop residues and root organic matter, however, suggesting that irrigated farming will increase soil C with time, which also consisted with Lal et al. (1998). For example, irrigated agriculture has been shown to increase SOC by 1.66 Mg/ha within the top 30 cm of soil after 15 yr (Lueking and Schepers, 1985). In general, SOC declines at the beginning of irrigation, approaches a steady state in 25 to 50 yr, and shows an evident increase in about 50 yr after conversion of native soil to agricultural land (Swift, 2001; Janzen et al., 1998; Lal et al., 1998). This pattern suggests that time is an important factor for C sequestration in irrigated cropland.

As a whole, SOC contents in topsoils of rural soils in Taiwan increased with irrigated age from 1950 to 1994 according to the legacy data (Table 5). The increase of SOC could probably be attributed to cultivated systems and fertilizer addition. By compared with the mean values of SOC, about 0.2% to 1.2% of SOC increased from 1950 to 1994 in Taiwan excluding Beinan and Dashe areas, where was long-term upland cultivation (Table 5). Agreed with Guo et al. (1995), we also considered that rotation of paddy and upland field cultivation, wildly land use in rice-growing and long-term applying of chemical and organic fertilizers are major reasons of increasing SOC contents in rural soils in Taiwan. Wu et al. (2008) also indicated that SOC stocks increased 0.5-1 times after five decades of irrigated farming in California, USA.

Table 5. Changes of soil organic matter content in rural soils in some counties in Taiwan from 1950 to 1994. Values are shown as mean ± standard deviation (sample number).

| Location | Soil organic matter content (%) | | | |
| --- | --- | --- | --- | --- |
| | 1950 | 1967 | 1981 | 1994 |
| Sinchen (Hualian) | 2.30±0.38 (7) | 2.34±0.88 (142) | 2.52±0.93 (21) | 2.60±1.17 (213) |
| Jian (Hualian) | 2.35±0.33 (3) | 1.44±0.41 (273) | 2.21±0.57 (21) | 2.24±0.66 (494) |
| Hihshang (Taitung) | -[a] (0) | 2.69±0.57 (160) | 2.89±0.63 (19) | 3.39±1.04 (493) |
| Beinan (Taitung) | 2.83±0.94 (18) | 2.10±0.75 (160) | 2.89±0.82 (19) | 2.64±0.88 (502) |
| Dashe (Kaohsiung) | 1.81±0.43 (4) | 1.36±0.49 (161) | 1.57±0.75 (8) | 1.34±0.61 (220) |
| Yongkang (Tainan) | 1.21±0.52 (6) | 1.00±0.36 (303) | 1.10±0.42 (5) | 1.61±0.56 (308) |
| Changhua (Changhua) | 2.53±0.31 (6) | 1.80±0.83 (426) | 2.44±0.63 (20) | 2.93±0.96 (469) |
| Hemei (Changhua) | 1.49±0.36 (7) | 1.92±0.56 (329) | 2.06±0.54 (42) | 2.66±1.40 (522) |

[a] Not available.

Additionally, we also estimated the SOC sequestration rate in upper 100 cm of rural soils in Taiwan (Figure 2). Although the sample number is small (n = 24); however, the time scale is long and ranges from 3,000 yrs to 480,000 yrs. The results show that SOC sequestration rate dramatically dropped from 12.4 $g/m^2$ per year to 1.14 $g/m^2$ per year within about 1000 yrs, and then toward to be stable about <0.50 $g/m^2$ per year over than 1000 yrs.
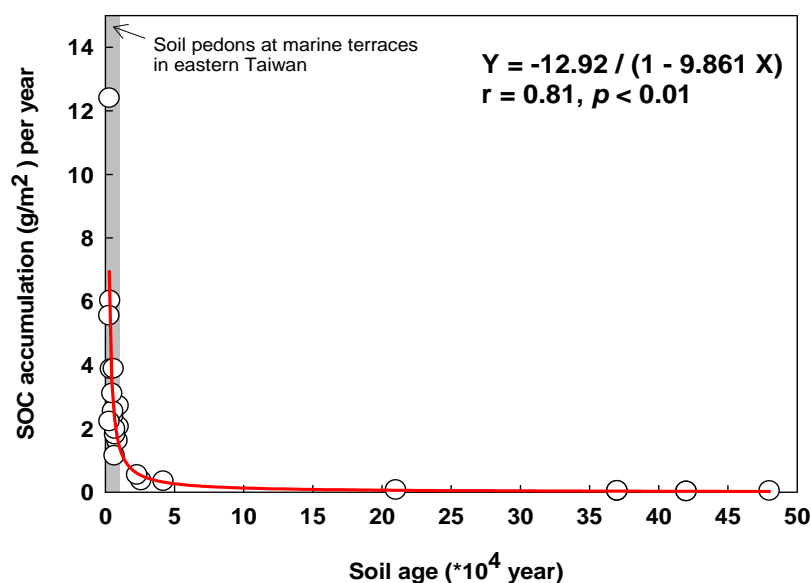
Figure 2. SOC accumulation rate with soil age on the river and marine terraces of Taiwan. The points in grey zone are SOC accumulation rate at marine terraces; others in white zone are SOC accumulation rate at river terraces.

The SOC sequestration rate is well fitted into equation of Y = -12.92 / (1-9.861X) (r=0.81, $p$<0.01). Schulp et al. (2008) indicated that C sequestration rate could be increased by 9-16% in 2030 relative to 2000 when they estimated the future C sequestration in Europe. About 0.03% decreased sequestration rate of SOC in rural soils in Taiwan within 30 yrs, which is different from the results of Schulp et al. (2008),will be occurred based on the estimation of our results. The difference could be attributed to scale of time in calculating C storages.

### 3.3 Comparison of SOC pools in different land uses

In general, different land uses have been indicated to lead to change of SOC storages (Purakayastha et al., 2008; Jelinski and Kucharik, 2009). With increasing population and food requirement in the world, conversion of native soils to cropland soils is needed to increase food production (Bruinsma, 2003). However, conversion of forests or pastures into croplands will decrease the SOC storages and the opposite situation usually lead to increase of SOC storages. The SOC sequestration could be positively or negatively influenced by land use change from native soils to cropland soils, which depended on the management policy of those converted cropland soils, e.g. tillage systems, frequently alternative cultivation, and fertilizer application.

From the viewpoint of SOC changes caused by different land uses, Table 6 and Table 7 list the SOC storages of rural soils in Inceptisols and Ultisols with different land uses, which exclude the temporal factor in Taiwan. The SOC storage in 30 cm depth (6.27-8.13 kg/m$^2$ in Inceptisols and 6.28-9.70 kg/m$^2$ in Ultisols) in rice-growing and fallow soils were greater than those in sugarcane planting soils, as well as in 50 cm and 100 cm depth. Figure 3 also presents the same trend in Entisols, Inceptisols and Ultisols of cropland soils. This trend could be probably ascribed to long-term flooding in those soils in spite of soils in fallow. Furthermore, to consider dynamic changes of SOC storage in different land uses, the estimation of SOC storage in different land uses from 1969 to 2002 was conducted in Tainan county where is a high potential productivity area of agriculture in Taiwan. As shown in Table 8, permanent rice-growing practice led to increase of SOC storage in the depth of 30 cm from 4.92 ± 0.74 kg/m$^2$ to 6.74 ± 0.91 kg/m$^2$ in past 33 years, however, the increase of SOC storage was insignificant in the depth of 50 cm but decrease in the depth of 100 cm. Change of land

use from rice-growing to fallow and upland cultivation (sugarcane planting) decreased SOC storage from $6.36 \pm 1.64$ kg/m$^2$ to $4.87 \pm 2.44$ kg/m$^2$ and $5.92 \pm 0.80$ kg/m$^2$ to $5.75 \pm 0.01$ kg/m$^2$, respectively, in the depth of 30 cm, as well as in the depth of 50 cm and 100 cm. In addition, no obvious change of SOC storage in permanent upland cultivation; however, SOC storage will obviously increase with ceasing to plant sugarcane.

Table 6. The rural SOC stocks with different depths in Inceptisols with different land uses of Taiwan

| Land use | 0-30 cm | | | 0-50 cm | | | 0-100 cm | | | Ratio[1] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | CV | n | Mean | CV | n | Mean | CV | n | A | B |
| | kg/m$^2$ | % | | kg/m$^2$ | % | | kg/m$^2$ | % | | % | % |
| Rice | 6.27 | 43 | 10 | 8.90 | 44 | 10 | 14.8 | 29 | 10 | 42 | 60 |
| Sugarcane | 5.88 | 42 | 10 | 8.40 | 42 | 10 | 12.5 | 41 | 10 | 47 | 67 |
| Fallow | 8.13 | 43 | 8 | 11.2 | 40 | 8 | 15.2 | 43 | 8 | 53 | 73 |

[1]A stand for the ratio of the soil organic carbon stock of 0-30 cm divided by in the 0-100 cm zone; B stand for the ratio of the soil organic carbon stock of 0-50 cm divided by in the 0-100 cm zone.

Table 7. The rural SOC stocks with different depths in Ultisols with different land uses of Taiwan

| Land use | 0-30 cm | | | 0-50 cm | | | 0-100 cm | | | Ratio[1] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | CV | n | Mean | CV | n | Mean | CV | n | A | B |
| | kg/m$^2$ | % | | kg/m$^2$ | % | | kg/m$^2$ | % | | % | % |
| Rice | 9.70 | 40 | 11 | 13.5 | 39 | 11 | 20.0 | 39 | 11 | 49 | 68 |
| Grass | 6.28 | 31 | 6 | 9.24 | 32 | 6 | 14.3 | 27 | 6 | 44 | 75 |
| Fruit | 4.34 | 74 | 6 | 6.49 | 79 | 6 | 9.12 | 81 | 6 | 48 | 69 |

[1]A stand for the ratio of the soil organic carbon stock of 0-30cm divided by in the 0-100cm zone; B stand for the ratio of the soil organic carbon stock of 0-50cm divided by in the 0-100cm zone.
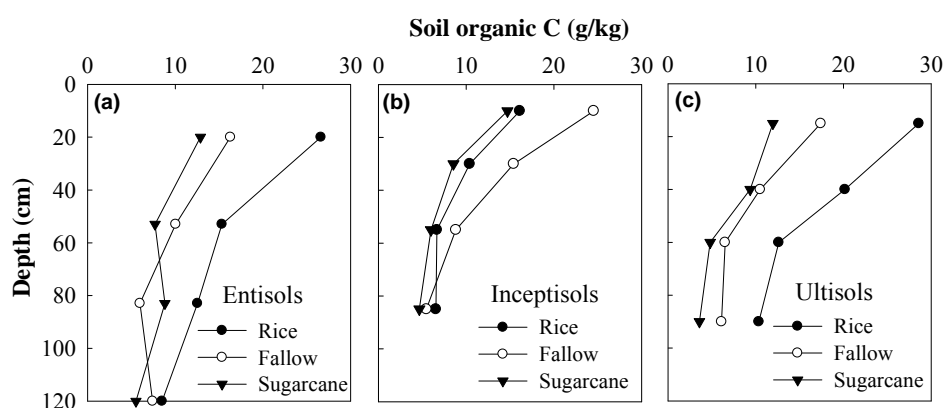


Figure 3. Vertical distribution of SOC content in selected rural soils with different land uses in Taiwan: (a) Entisols (n=30), (b) Inceptisols (n=28), (c) Ultisols (n=23).

Table 8. The SOC storages in the croplands of Tainan with different land uses in 1969 and 2002

| Land use change | | Sample | 1969 SOC storages (kg/m$^2$) | | | 2002 SOC storages (kg/m$^2$) | | |
|---|---|---|---|---|---|---|---|---|
| 1969 | 2002 | number | 0-30 | 0-50 | 0-100 | 0-30 | 0-50 | 0-100 |
| | | | ----------------------------------- cm ----------------------------------- | | | | | |
| Rice | Rice | 5 | 4.92 ± 0.74 | 8.26 ± 1.93 | 17.3 ± 6.98 | 6.74 ± 0.91 | 9.13 ± 1.78 | 13.5 ± 3.84 |
| Rice | Fallow | 6 | 6.36 ± 1.64 | 10.0 ± 2.27 | 16.1 ± 4.35 | 4.87 ± 2.44 | 6.88 ± 4.42 | 11.9 ± 5.41 |
| Rice | Sugarcane | 2 | 5.92 ± 0.80 | 9.38 ± 1.44 | 15.5 ± 1.15 | 5.75 ± 0.01 | 9.05 ± 0.69 | 16.2 ± 0.28 |
| Sugarcane | Sugarcane | 1 | 3.09 ± -[a] | 3.66 ± - | 4.89 ± - | 3.02 ± - | 4.77 ± - | 6.58 ± - |
| Sugarcane | Fallow | 3 | 2.55 ± 0.55 | 4.29 ± 0.67 | 7.19 ± 1.53 | 2.79 ± 1.39 | 3.82 ± 1.70 | 6.09 ± 1.49 |

[a] Not available.

From the legacy data, Figure 4, 5 and 6 present distribution of SOC storage of different soil depths in Tainan County, Taiwan. The investigated soil pedons with different land uses in 1969 and 2002 were also shown in the Figure 5, 6 and 7. In Tainan county, we found that SOC storage in the west part was greater than that in the eastern part, which could be probably attributed to more rice-growing soils in area there. The spatial distribution of SOC storage consisted with the data listed in Table 8 mentioned above. The range of SOC storage (45-65 Mg/ha) in the depth of 30 cm in the north-western Tainan were enriched as comparing the paddy soils in China (Li and Zhao, 2001), especially in northern Tainan. With permanent rice-growing from 1969 to 2002 in northern Tainan, SOC storage increased and with extended area in northern Tainan (Figure 4). Long-term application of fertilizer or manure could be the major reason for increasing SOC storage in the upper 30 cm with time. In addition, incorporation of residues and roots after rice harvesting could also increase SOC storage in the rice-growing soils (Lal et al., 1998; Wu et al., 2008). On the contrary, the SOC storage in the upper 50 cm and 100 cm seem to decrease (Figure 5 and 6).
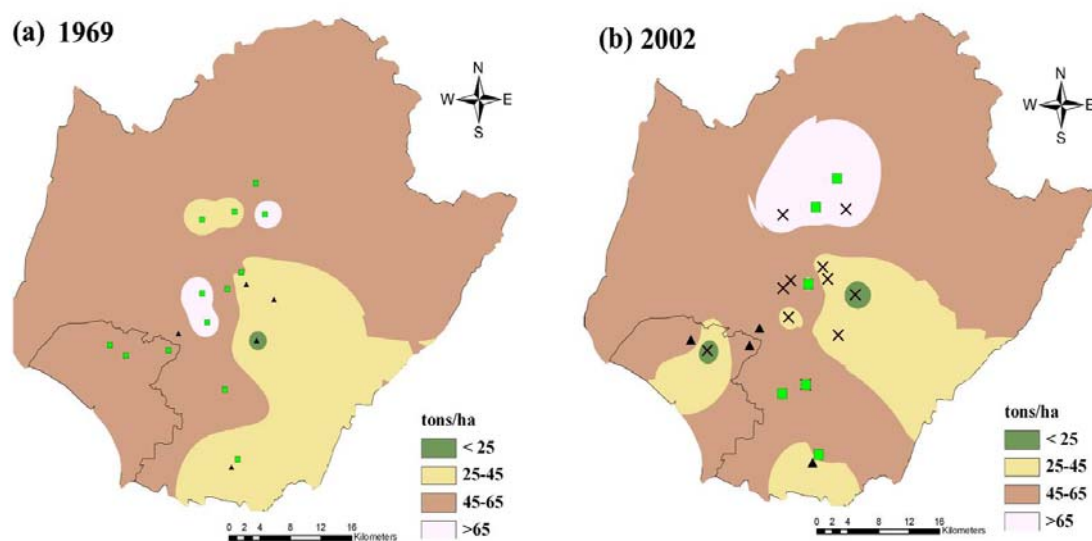


Figure 4. The distribution of soil organic carbon storage (Mg/ha) for depth of 0-30 cm in Tainan County of Taiwan in 1969 and 2002. The different land uses are represented by different notations. Green squares mean rice-growing soils; triangle means sugarcane-growing soils and cross means fallow.
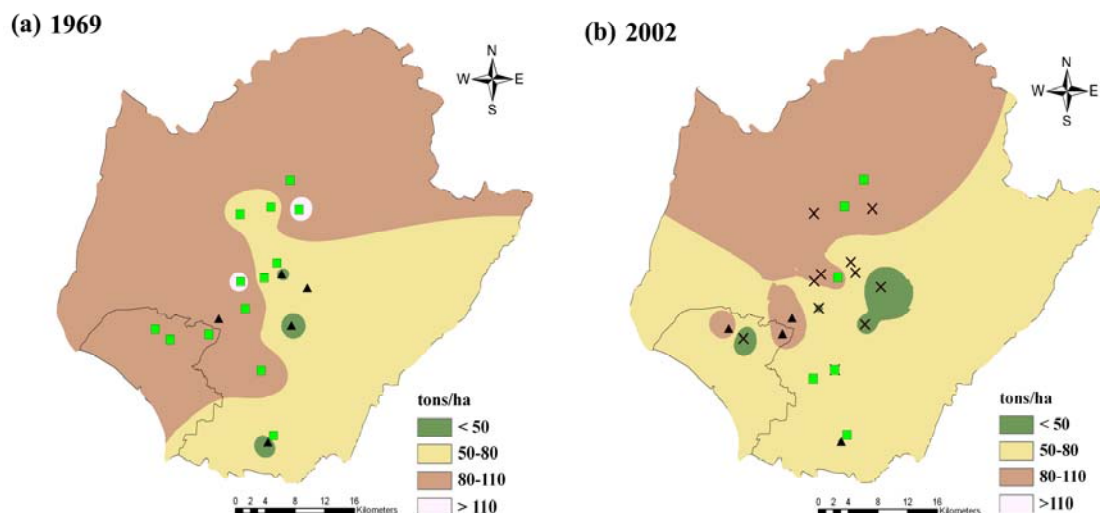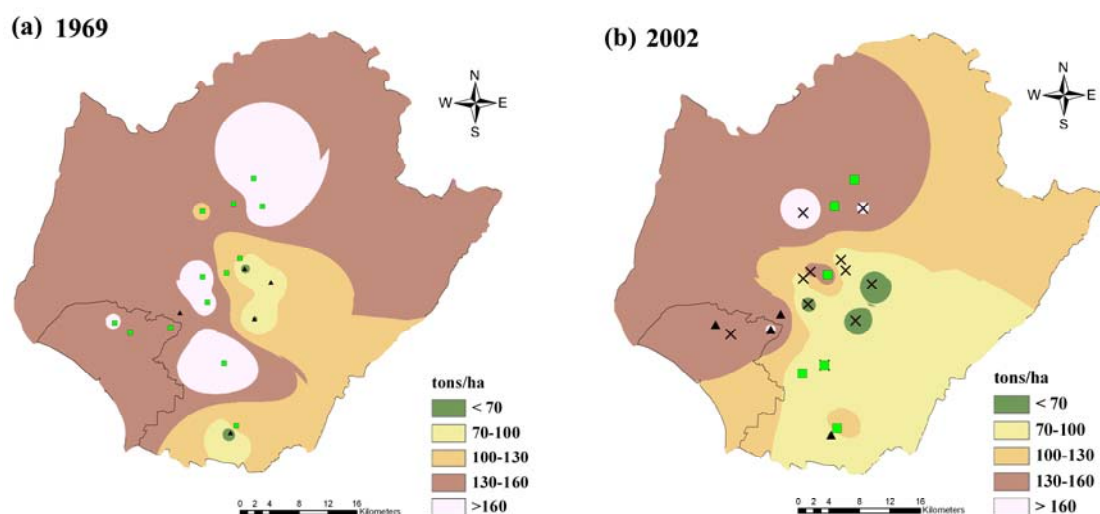
Figure 5. The distribution of soil organic carbon storage (Mg/ha) for depth of 0-50 cm in Tainan County of Taiwan in 1969 and 2002. The different land uses are represented by different notations. Green squares mean rice-growing soils; triangle means sugarcane-growing soils and cross means fallow.



Figure 6. The distribution of soil organic carbon storage (Mg/ha) for depth of 0-100 cm in Tainan County of Taiwan in 1969 and 2002. The different land uses are represented by different notations. Green squares mean rice-growing soils; triangle means sugarcane-growing soils and cross means fallow.

## 3.4 Strategies of SOC sequestration in the rural soils

Several managements of agricultural soils to conserve eroded and degraded soils in USA have been archived by the Conservation Reserve Program (CRP) (Ogle et al., 2003). Post and Kwon (2000) conducted a meta-analysis of average global C sequestration rates on land converted from agricultural production to grassland and reported the average SOC sequestration rate was 0.33 Mg/ha per year. With performing conservation tillage including continuous no-till, high-residue crop rotation, and high

organic matter inputs. In Southeastern USA, Franzluebbers (2010) indicated that SOC sequestration rate was $0.45 \pm 0.04$ Mg/ha per year. From this study (Table 8 and Figure 4, 5 and 6), permanent rice-growing increased SOC storage and the sequestrated rate was $0.55 \pm 0.35$ Mg/ha per year from 1969 to 2002. changing land use from rice-growing to fallow or upland cultivation decreased the SOC storage in rates of $-0.45 \pm 0.87$ Mg/ha and $-0.02 \pm 0.17$ Mg/ha per year, respectively. Consequently, long-term fallow will decrease the SOC storage in the rural soils of Taiwan. Sequestration of C in soils has also been promoted as strategy to mitigate the effects of increasing emissions of greenhouse gases in the atmosphere (Lal et al., 1998; Lal, 2001; Janzen, 2004). Sequestration of SOC can be increased through a wide range of management measures, including reduced tillage (to decrease mineralization), improved rotations, and manure application (Freibauer et al., 2004).

Overall, prolonging waterlogged duration of paddy soils and efficiently reusing crop residues for all rural soils were proposed as good ways to sequester SOC in Taiwan based on our results. Additionally, remote sensing techniques could be also applied to determine the area of each land use in Taiwan and approximate SOC storages of different land uses or whole SOC storage in Taiwan could be therefore estimated.

## 4. Conclusion

In Taiwan, more than 30% of the total area is croplands; it is therefore important to estimate the SOC storage for cropped soils to evaluate the SOC sequestration and emission potential of greenhouse gases of rural soils. According to investigated results, the SOC contents in topsoils gradually increase from 1950 to 1994. For a unique site study, we also found that SOC storage of croplands increase from 1969 to 2002 in Tainan County, especially in the depth of 30 cm. According to previous studies conducted in USA, Europe and China, land use change led to modification of SOC storage. In Taiwan, the SOC storage with paddy rice was higher than that with upland practice like pineapple or sugarcane cropping. Regarding SOC sequestration rate, the SOC storage in permanent rice-growing soils significantly differs from those in fallow and upland cropping soils. Positive sequestrated rate was found in permanent rice-growing soils, and therefore, the strategies by prolonging waterlogged duration of paddy soils and by efficiently incorporating crop residues for all rural soils proposed good ways to sequester SOC.

## 5. References

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47:151-163.

Blake, G.R., and Hartge, K.H., 1986. Bulk density. In: Klut A. (Ed.), Methods of soil analysis, Part 1. Physical and mineralogical methods. ASA and SSSA, Madison, WI. Agronomy Monograph No. 9, 383–411.

Bruinsma, J. 2003. World agriculture: Towards 2015/2030, an FAO perspective. Earthscan Publ., London.

Buringh, P. 1984. Organic carbon in soils of the world. In: Woodwell, G.M. (ed.) The role of terrestrial vegetation in the globe carbon cycle. Measurements by remote sensing. pp. 91-109. SCOPE 23. John Wiley & Sons, New York.

Chen, Z.S., C.Y. Lin, H.Y. Lai, T.A. Fu, S.H. Jien, C.C. Tsui, C.J. Huang, S.W. Su, W. C. Lao and C.C. Lin. 2005. Basic soil characteristics of Taichung and Nantou soils. COA Project report (contract no. COA-94-AS-1.3.3-F-Z2(1), code no. 941780). (In Chinese)

Chen, Z.S., D.Y. Lee, C. M. Lai, S.P. Ho, R.S. Chung, C.C. Tsai, H.S. Lin, and C.L. Chen. 2002. Sustainable soil management system of Taiwan soils (2/3). COA Project report (contract no. COA-91-AS-1.1.1-F-ZA(1), code no. 913043). (In Chinese)

Chen, Z.S., D.Y. Lee, C. M. Lai, S.P. Ho, R.S. Chung, C.C. Tsai, H.S. Lin, and M.R. Lin. 2003. Sustainable soil management system of Taiwan soils (3/3). COA Project report (contract no. COA-92-AS-1.1.3-F-Z2(1), code no. 921920). (In Chinese)

Chen, Z.S., D.Y. Lee, C.M. Lai, S.P. Ho, R.S. Chung, C.C. Tsai, H.S. Lin, C.L. Chen, K.W. Juang, T. L. Liu, and J. C. Chen. 2001. Sustainable soil management system of Taiwan soils (1/3). COA Project report (contract no. COA-90-AS-1.1.1-F-ZA(1), code no. 901283). (In Chinese)

Chen, Z.S., D.Y. Lee, C.Y. Lin, T.L. Liu, C.H. Lee, C.C. Tsui, C.J. Huang, S.W. Su. 2006. Basic soil survey of soil characteristics and soil productivity. COA Project report (Contract No. COA-95-AS-1.3.3-F-Z2(3), Code No. 952033). (In Chinese)

Chen, Z.S., Hseu Z.Y. 1997. Total organic carbon pool in soils of Taiwan. Proc Natl Sci Council ROC Part B Life Sci 21:120-7.

Chen, Z.S., Z.Y. Hsu, H.Y. Lai, S.H. Jien, S.P. Wu, C.H. Lee, H.S. Lin, and M.R. Lin. 2004. Basic soil characteristics of Taichung and Nantou soils. COA Project report (contract no. COA-93-AS-1.3.3-F-Z2(1), code no. 931032). (In Chinese)

Eswaran, H, Van den Berg E and Reich P. 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57:192-194.

Falloon, P., Smith, P., Bradley, R.I., Milne, R., Tomlinson, R.W., Viner, D., Livermore, M., Brown, T.A.W., 2006. RothCUK-a dynamic modelling system for estimating changes in soil C from mineral soils at 1-km resolution in the UK. Soil Use and Manage. 22:274-288.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 6:77–92.

Franzluebbers, A.J. 2010. Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. Soil Sci. Soc. Am. J. 74:347-457.

Freibauer, A., Rounsevell, M.P.A., Smith, P., Verhagen, J. 2004. Carbon sequestration in European agricultural soils. Geoderma 122:1-23.

Guo, H.Y., Chu, C.L., Chiang, C.F. and Wu, H.G. 1995. Soil organic matter contents and application of organic amendments in Taiwan. pp. 72-83. In: Taiwan Agricultural Research Institute (editor). Special issue of reasonable application of organic fertilizers. Taichung, Taiwan.

Guo, H.Y., Liu, T.S., Chu, C.L., and Chiang, C.F. 2008. Development of Soil Information System and its application in Taiwan. pp. 141-157. In: Ichiro Taniyama (editor). Monsoon Asia Agro-Environmental Research Consortium (MARCO) Workshop: A New Approach to Soil Information System for natural Resources Management in Asian Countries. Organized by National Institute for the Agro-Environmental Sciences (NIAES) and Food and Fertilizer Technology Center (FFTC). Tsukuba International Congress, Japan, Oct 14-15, 2008.

Guo, H.Y., Liu, T.S., Chu, C.L., Chiang, C.F. and Yeh, M.J. 2002 Soil information of Taiwan and its development. p.1-38, In Proceeding of Conference of soil information application, Taipei, Taiwan. (In Chinese)

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8:345-360.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil Tillage Res. 47:181–195.

Jelinski, N.A. and Kucharik C.J. 2009. Land use effects on soil carbon and nitrogen on a U.S. Midwestern floodplain. Soil Sci. Soc. Am. J. 73:217:225.

Knops, J.M.H., and D. Tilman. 2000. Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. Ecology 81:88–98.

Kucharik, C. 2007. Impact of prairie age and soil order on carbon and nitrogen sequestration. Soil Sci. Soc. Am. J. 71:430-441.

Kucharik, C.J., K.R. Brye, J.M. Norman, J.A. Foley, S.T. Gower, and L.G. Bundy. 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: Potential for SOC sequestration during the next 50 years. Ecosystems 4:237-258.

Lal, R., Griffin, M., Apt, J., Grave, L.,Morgan, M.G., 2004. Managing soil carbon. Sci. 304:393.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI.

Lal, R., R.F. Follett, J.M. Kimble, and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54:374–381.

Lettens, S., Orshoven, J.v., Wesemael, B.v., Muys, B., Perrin, D., 2005. Soil organic carbon changes in landscape units of Belgium between 1960 and 2000 with reference to 1990. Global Change Biology 11:2128-2140.

Li, Z. and Zhao Q. 2001. Organic carbon content and distribution in soils under different land uses in tropical ad subtropical China. Plant and Soil 231:175-185.

Lueking, M.A., and J.S. Schepers. 1985. Changes in soil carbon and nitrogen due to irrigation development in Nebraska's sandhill soils. Soil Sci. Soc. Am. J. 49:626–630.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H., Keeney D.R. (Eds.), Methods of soil analysis, Part 2. Chemical and microbiological properties. ASA and SSSA, Madison, WI. Agronomy monograph, No. 9. 539–577.

Paustian, K., C.V. Cole, D. Sauerbeck, and N. Sampson. 1998. $CO_2$ mitigation by agriculture: An overview. Clim. Change 40:135–162.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Global Change Biol. 6:317–327.

Purakayastha, T.J., Huggins, D.R. and Smith J.L. 2008. Carbon sequestration in native, perennial grass, no-till, and cultivated Palouse silt loam. Soil Sci. Soc. Am. J. 72:534-540.

Rejineveld, A., van Wensem, J., Oenena, O. 2009. Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004. Geoderma 152:231-238.

Schlesinger, W.H., Andrews, J.A. 2000. Soil respiration and the global carbon cycle. Biogeochem. 48:7–20.

Schulp, C.J.E., Nabuurs, G.J., Verburg, P.H. 2008. Future carbon sequestration in Europe-effects of land use change. Agri. Ecosys. Environ. 127:251-264.

Soil Survey Staff. 2006. Keys to Soil Taxonomy. 12th ed., NRCS, USDA, Washington DC.

Sombroek, W.G., Nachtergaele, F.O. abd Hebel, A. 1993. Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils. Ambio. 22:417-426.

Sundquist, E. 1993. The global carbon dioxide budget. Sci. 259:934-941.

Swift, R.S. 2001. Sequestration of carbon by soil. Soil Sci. 166:858–871.

Tsai H, Huang WS, Hseu ZY, Chen ZS 2006: A river terrace soil chronosequence of the Pakua tableland in central Taiwan. Soil Sci., 171, 167–179.

Tsai, C.C., Tsai, H. Hseu, Z.Y. and Chen, Z.S. 2007. Soil pedogenesis along a chronosequence on marine terrace in eastern Taiwan. Catena 71: 394-405.

Wu, L.S., Wood Y., Jiang P.P., Li L.Q., Pan G.X., Lu J.H., Chang A.C. and Enloe H.A. 2008. Carbon sequestration and dynamics of two irrigated agricultural soils in California. Soil Sci. Soc. Am. J. 72:808-814.