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Original Research

Effect of Agricultural Land-Use Patterns on Soil Organic Carbon Stock in the Upper Vietnamese Mekong Delta

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Abstract

In the mitigation strategies of climate change, improving soil carbon storage is considered as one of the main tasks to enhance agricultural sustainability and sequester atmospheric carbon dioxide. Agricultural patterns have been changing significantly and causing many impacts on soil organic carbon (SOC) storage in the upper Vietnamese Mekong Delta (VMD). Therefore, this study aims to evaluate how typical agricultural pattern changes are affecting SOC by estimating the SOC stock and identifying the correlation with soil physic-chemical properties. Soil samples were collected in both depths of 0-20 cm and 20-50 cm and analyzed physic-chemical properties such as soil texture, bulk density, pH_{KCl}, EC and SOC. In topsoil layers, the SOC stock of the wetland forest was the highest in the opened depression of floodplain (24.42±1.38 kg C m^{-2}; $p<0.05$) while that of paddy rice was the richest at depth of 20-50 cm (27.69±2.97 kg C m^{-2}; $p<0.05$). In other agro-ecological areas, SOC stock in croplands was lower than forest and grassland in topsoil layer, especially in mountainous areas. SOC stock correlated positively with SOC content, clay, bulk density, and EC ($p<0.05$) but had a negative correlation with sand and pH_{KCl} ($p<0.05$). The decrease in SOC stock in dry cultivating patterns indicated the impact of agricultural management practices and soil fertility on SOC storage. Thus, improving SOC stock

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is needed to maintain sustainable soil management. That can be done by increasing C input and decreasing C loss in the atmosphere.

Keywords: carbon dynamics, climate change, cropping patterns, land-use change, Mekong Delta, soil degradation

Introduction

Soil is a key compartment for climate regulation as a source of greenhouse gases (GHGs) emissions and as a sink of carbon (C). Soil carbon sequestration is one of the three main approaches to carbon dioxide removal and storage through the management of terrestrial ecosystems [1]. Soil is the largest reservoir of C, storing approximately 53% of the terrestrial C [2]. Changes in soil organic carbon (SOC) stocks is one of the most important parameters related to ecosystem quality and sustainability and the net GHG balance [3]. Thus, soil carbon stock should be considered alongside reduction strategies for other GHG emissions. The total SOC stock can be influenced by natural and anthropogenic factors, consisting of soil properties, land-use changes, agricultural management practices, and climate changes [4, 5]. On this basis, agricultural land-use patterns changes are considered as key drivers of SOC dynamics that affect soil nutrients as well as soil organic matter concentrations [6].

The Mekong Delta in Vietnam is the downstream area of the Mekong River before reaching into the Vietnam East Sea and the Gulf of Thailand. This area covered approximately 4 million hectares of natural area of Vietnam and was mainly formed by deposits of eroded sediment from the upper basin of the Mekong River [7]. Two upstream provinces of the Vietnamese Mekong Delta (VMD), Dong Thap and An Giang provinces, have diverse agro-ecological regions, namely mountainous areas, opened depression of floodplain, fluvial plain and closed depression of floodplain [8-10]. Unlike down-stream and middle-stream provinces, Dong Thap and An Giang have not been impacted by salinity intrusion yet, these zones still face annual flooding in the monsoon season. In order to control floods, many high dike systems have been constructed by the two provincial governments in recent decades [11]. Due to being less affected by floods in dike areas, agricultural patterns are becoming more and more diversified (e.g., triple-rice crops, orchards, upland crops, and aquaculture), and they account for a large proportion of land use (more than 85% land area) [12]. Thus, the agricultural land-use change in these provinces is among the most dynamic ones in the region. The development history of these eco-regions is associated with agricultural cultivation and the development of canal systems. In the years after *Doi Moi* (Renovation) was launched, the national agricultural strategies focused on implementing food security and economic development. Some policies pushed investments for agricultural intensification, especially rice farming systems [13]. This caused gradually narrowing the area of natural island-wetlands in the Plain of Reeds and Long Xuyen Quadrangle. Since the early 1990s, land use in the VMD evolved towards intensive rice farming. In the upper VMD, the area devoted to double rice cropping and triple rice cropping quickly expanded, while seasonal rice diminished by 28% [14]. Besides, thanks to the high dike system and good drainage, some areas along the Mekong River (also known as Tien River) and Bassac River (also known as Hau River) converted from rice fields into orchards or other upland crops in recent years [15, 16]. Currently the conversion of agricultural land-use patterns is still happening due to the influence of agricultural policy, market prices, infrastructure, dike system, and changes in hydrological regime. These agricultural land-use patterns changes caused some impacts to carbon storage and nutrient in the topsoil layer.

In the VMD, several studies on carbon stocks have been conducted in coastal mangrove forests [17, 18], and *Melaleuca* forests [19-21]. These studies showed that above-ground carbon stocks were close related to the biomass, density, age of forest and soil characteristics. To our current knowledge, no study assessing the impact of different agricultural land-use patterns on SOC stocks in the upper VMD area, have been reported. In this context, for achieving sustainable development goals, it is extremely relevant to quantify the sources of SOC on the largest and most dynamic agricultural area in the upper VMD. The results will provide scientific basis for the development of climate change mitigation and food security policies. This study therefore aims to: (1) quantify soil carbon stock under selected agricultural land-use patterns in agro-ecological areas, and (2) evaluate the extent of agricultural land-use patterns impact on carbon dynamics in the upper VMD.

Materials and Method

Study Area

The study area is in the upper Vietnamese Mekong Delta, south-western Vietnam (10°07′N-10°58′N, 104°47′E-105°56’E), and it is within the tropical climate zone (Fig. 1), covering about 6,912.15 km^2 with an elevation ranging from 1 m to 710 m above sea level. The area has two distinct seasons including the rainy

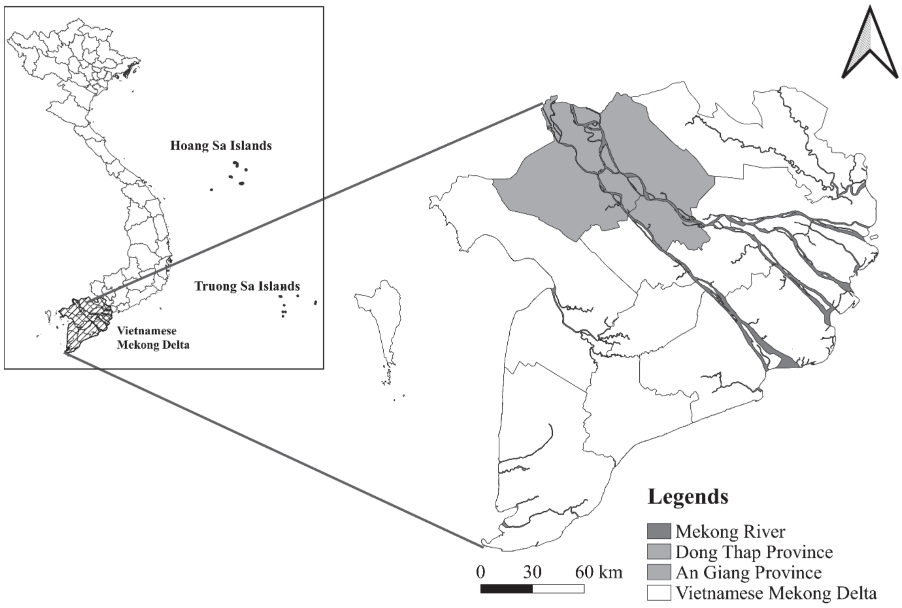

Fig. 1. Map of the study area.

season from May to November and the dry one from December to April next year. Average temperature ranges from 26ºC to 28ºC and average annual rainfall varies between 1,170 mm and 1,520 mm, of which about 90 - 95% occurs in the rainy season. This climate feature is relatively favorable for agricultural production.

Based on the topographical features, the depth of inundation in the flood season and soil conditions, An Giang and Dong Thap provinces were divided into four main ecological areas including mountainous area, opened depression of floodplain, fluvial plain, and closed depression of floodplain [8, 9]. Firstly, the mountainous area slopes around 15° - 35°, consisting of many mountains with the highest peak of 710 m in Cam mountain. All these hills and mountains are composed of granitic rocks. In addition, the fields go around the foot of the mountain, have an elevation of 5 to 10 m and not inundation in the flood season. The mountainous soil was classified into two main types by FAO/UNESCO, namely Leptosols and Arenosols. Secondly, the opened depression of floodplain in this study is a part of Long Xuyen Quadrangle surrounding two districts of Tri Ton and Tinh Bien. This area slopes gently from the Bassac River to the Gulf of Thailand. Due to low topography and upstream position, it is flooded annually for 3-4 months with a depth of inundation over 0.5 m. The soil type in this area is mainly heavy acid sulphate soil, as Thionic Fluvisols by FAO/UNESCO. Then, the fluvial plain that is located along Mekong and Bassac Rivers has geomorphological units such as natural levees, sandbars and back-swamps with depth of inundation over 0.5 m. Soils in the study area are developed from alluvial deposits and classified as Fluvisols by FAO/UNESCO. The last ecological area to be surveyed was closed depression of floodplain (located within an important wetland known as the Plain of Reeds), enclosed by sand ridges in the East, the natural levee of the Mekong River in the southwest and the old alluvial terraces in the north. During the flood seasons, this area is flooded up to 3 m. The dominant soil type in closed depression of floodplain is acid sulfate soil (Thionic Fluvisols) (Fig. 2).

Soil Sampling and Household Survey

Soil samples were collected from two depths (0-20 cm and 20-50 cm) for typical agricultural land-use patterns in four agro-ecological areas with 238 plots (10 m x 10 m for each one) from 2019 to 2021. Total soil samples collected were 476 (238 plots x 2 soil depths). For each plot, five-soil subsamples were taken; one at the center and others in each direction from the center (north, east, west and south) within a 10 m x 10 m area. Collected subsamples were mixed to obtain one homogenized sample per plot. These samples were stored in zip bags and taken for soil nutrient analysis. Soil samples were air-dried, manually ground in a mortar, and sieved to pass through a 2 mm sieve screen. To estimate stocks of SOC, an undisturbed soil core of each soil depth was taken at the center of each plot for bulk density determination by using a cutting ring with an inner diameter of 5.0 cm, volume of 100 cm^3. The collection ensured plots that are well distributed over the study area and are representative of local farming practices.

A household survey of the farmers managing the respective fields used for plot sampling was also conducted. A questionnaire was designed to collect information regarding agricultural management practices, the amount, type and timing of organic matter

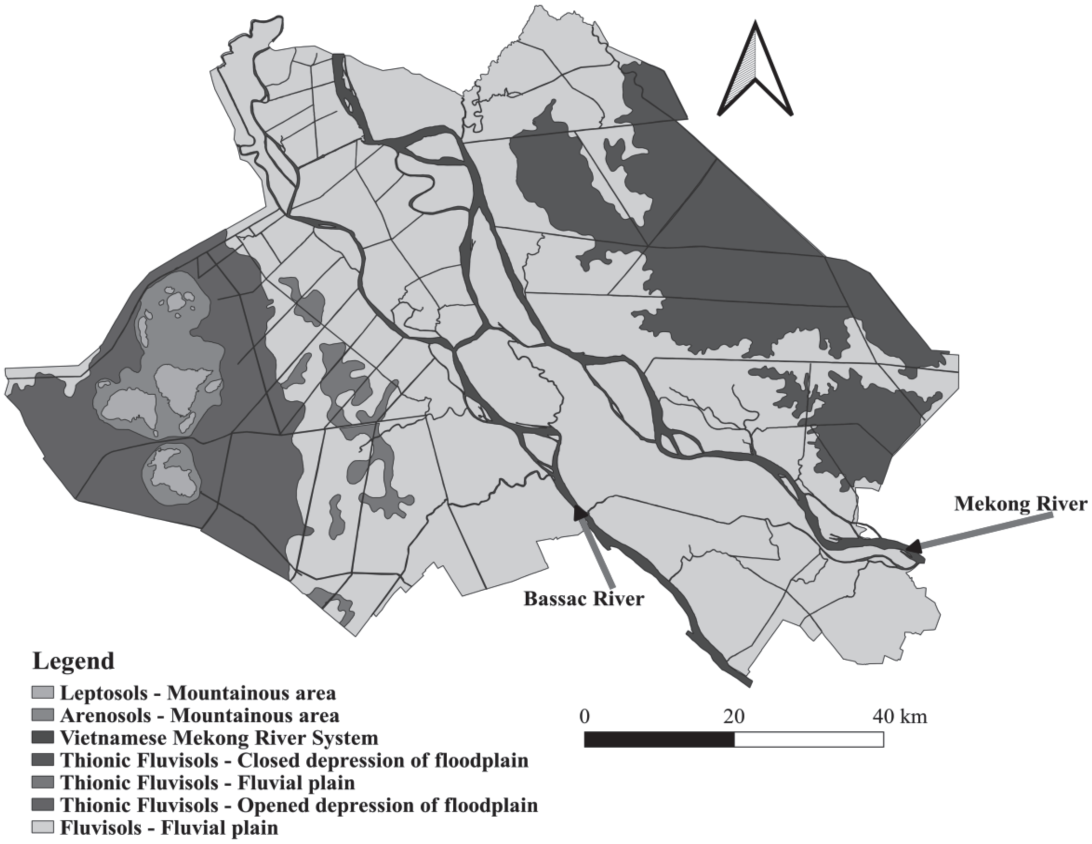

Fig. 2. Map of soil distribution in the study area.

inputs, chemical fertilizers and other farm household data.

Laboratory Methods

Soil texture was analyzed by the Robinson method. To measure soil bulk density, the soil samples were oven-dried at 105ºC until a constant weight was obtained (approximately 24 hours). Soil bulk density was calculated as the proportion of the dry weight of soil (g) per unit volume of soil (cm^3). The soil samples were extracted by KCl 1N to determine pH_{KCl} by a pH meter with a ratio of soil: KCl = 1:5 and extracted by demineralized water to determine EC by an EC meter with soil: demineralized water = 1:5.

To estimate the soil organic matter (SOM) content, soil samples were analyzed using dry combustion method at 830ºC, and a conversion factor of 0.58 between SOM to soil organic carbon (SOC) [22, 23]. In this case, concentrations of soil organic carbon (%) were calculated as:

$$\text{SOC (\%)} = 0.58 \times \text{SOM (\%)} \quad (1)$$

For each depth interval, the SOC stock (SOC stock, kg C m^{-2}) was determined by the product of the SOC content (%), the soil bulk density (BD, g.cm^{-3}), and the soil depth (D, cm) [24, 25]. Eq. (2) was used to calculate SOC stock:

$$\text{SOC stock (kg C m}^{-2}\text{)} = \text{SOC (\%)} \times \text{BD (g.cm}^{-3}\text{)} \times \text{D (cm)} \times 10 \quad (2)$$

Statistical Analysis

One-way analysis of variance (ANOVA) was used to compare the differences of soil texture, bulk density, pH_{KCl}, EC in four agro-ecological areas; and to compare the effects of different land-use patterns on SOC stock, organic carbon at the two soil depths separately. The significant differences between means were assessed by Duncan's test at $p<0.05$. Pearson's correlation analysis was performed to verify the association degree of the measured variables. All statistical analyses were performed using a standard software package – SPSS, version 21.

Results and Discussion

Soil Characteristics in Different Agro-Ecological Areas

Overall, the soils in four agro-ecological regions in the upper VMD have varied soil texture composition because they were formed in different processes (Fig. 3). Soils in the mountain area were Leptosols and Arenosols that had higher sand components than

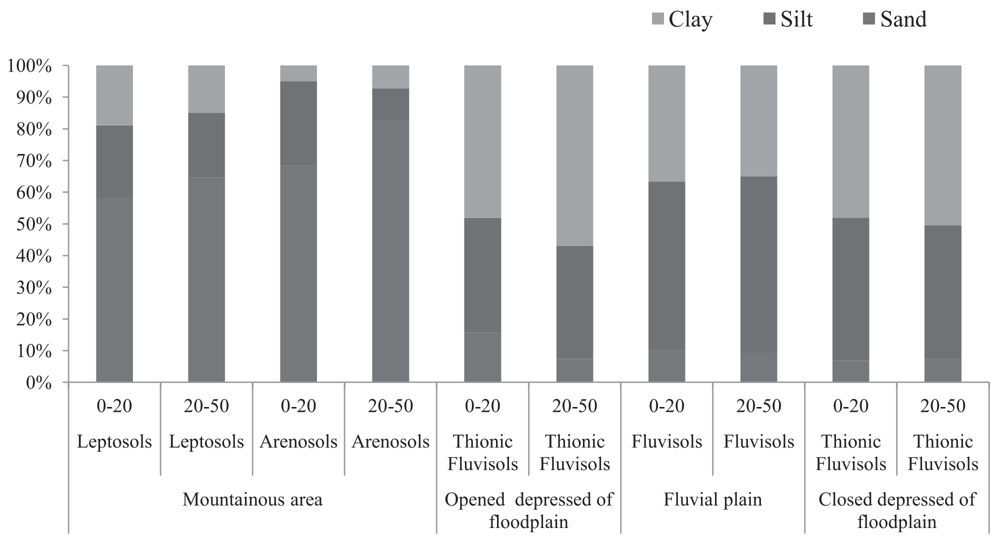

Fig. 3. The soil texture in different agro-ecological areas.

others. Leptosols and Arenosols distributed mainly on the slopes and the foothills and were formed by the in-situ weathering of rocks. Thus, the soil contained a high amount of sand, ranging from 58.33±1.83% to 82.30±2.88% at the 0-20 cm and 20-50 cm depths (p<0.05), respectively. In the fluvial plain, Fluvisols were mainly distributed along the Mekong and Bassac Rivers. Because of forming by deposited sediments every year, the soil had mainly characteristic that the silt component was higher than sand and clay in both depths 0-20 cm and 20-50 cm (p<0.05). In contrast with other agro-ecological areas, the opened depressed of floodplain and closed depressed of floodplain were the same as back-swamp areas that are distributed far from the Mekong and Bassac Rivers. Therefore, the soil features contained a higher amount of clay than sand and silt. The clay ranged from 49.13 ±0.87% (0-20 cm depth) to 57.54±1.21 % (20 50 c depth) in the opened depressed of floodplain, and from 46.95±1.84% (0-20 cm depth) to 50.38±1.12 % (20-50 cm depth) in the closed depressed of floodplain (p<0.05).

In addition, the soil in the fluvial plain was assessed to be more fertile than the soil in the mountainous area, opened depressed of floodplain and closed depressed of floodplain (Table 1). Bulk density of Arenosols in mountainous areas was the highest in the two soil depths, following the bulk density of Thionic Fluvisols in the opened depressed of floodplain. The pH_{KCl} value of the soil in the opened and closed depressed of floodplain was assessed as highly acidic in both two depths (pH<4.5) (p<0.05). The soil in these areas contained acid sulfate soil materials. In the process of oxidation, H^+, Fe^{3+}, Al^{3+} and SO_4^{2-} were formed, thus the pH is low. Besides, the mean values of EC in the soil of the opened and closed depressed of floodplain were higher than in the soil of the mountainous and fluvial plain areas (p<0.05). At the same time, because of the low soil pH in these two areas, the ions of Fe^{2+}, Fe^{3+}, Al^{3+} and SO_4^{2-} were released to high concentrations. Therefore, the EC value was also higher than the other areas (Table 1).

SOC at Different Soil Depths for Different Agricultural Land-Use Patterns

SOC content differed across agricultural land-use patterns. The difference among agricultural land-use patterns in the SOC contents occurred in both soil of depth 0-20 cm and 20-50 cm. At the same depth (0-20 cm), the SOC contents reached the highest value in wetland forest (*Melaleuca* forest) in opened depression of floodplain (9.64±0.58%), followed by flooded grassland in closed depression of floodplain (6.84±0.51%) (p<0.05) (Fig. 4). The SOC contents varied from 1.41±0.12% to 6.07±0.34% for rice crop, 2.23±0.32% to 4.45±0.88% in the orchard and agro-forest areas, 2.36±0.14% to 4.67±0.36% in the cash crops field. The SOC contents also differed by agro-ecological regions. In the mountainous area, the lowest SOC value was identified in rice fields. The lowest SOC content was found in soils with cash crops in the opened depression of floodplain. In the fluvial plain, SOC seems to change slightly between agricultural land-use patterns and differ significantly with the opened depression of floodplain and closed depression of floodplain (p<0.05). Meanwhile, the lowest content of SOC was found in orchards in the closed depression of floodplain.

The SOC concentration in the depth (20-50 cm) tended to be lower than the surface layer (0-20 cm). However, in some agricultural land-use patterns, the SOC content showed the opposite trend, e.g., in the rice fields and cash crops in the opened depression of floodplain. The results showed that the SOC of the rice field located in the opened depression of floodplain in the soil layer (20-50 cm) has significantly enriched,

Table 1. Soil characteristics in different agro-ecological areas.

Agro-ecological areas	Soil types	Soil depth (cm)	Bulk density (g/cm^3)	pHKCl	EC (µS/cm)
			Mean±Std.E		
Mountain	Leptosols	0-20	0.99±0.01c	5.24±0.05b	88.45±5.28d
		20-50	1.02±0.02d	5.19±0.05b	70.73±4.83d
	Arenosols	0-20	1.67±0.08a	5.84±0.06a	198.72±12.92bc
		20-50	1.74±0.06a	5.89±0.07a	187.56±16.07bc
Opened floodplain	Thionic Fluvisols	0-20	1.25±0.03b	4.26±0.07c	564.13±51.92a
		20-50	1.28±0.03b	4.16±0.06c	551.25±40.63a
Fluvial plain	Fluvisols	0-20	0.98±0.02c	5.31±0.06b	117.74±7.52cd
		20-50	1.03±0.01cd	5.27±0.07b	120.49±9.80cd
Closed floodplain	Thionic Fluvisols	0-20	1.07±0.03c	3.96±0.03c	205.39±20.39b
		20-50	1.15±0.03bc	3.81±0.06c	220.87±22.74b

Note: At the same soil layer, values followed by dissimilar letters (a,b,c,d) under the same column are significantly different at $p<0.05$.

while in the mountainous areas, the SOC of the rice field has greatly reduced ($p<0.05$) (Fig. 5).

SOC Stock at Different Soil Depths for Different Agricultural Land-Use Patterns

The distribution of the SOC stocks of the topsoil layer were different between agricultural land-use patterns, as well as in the agro-ecological areas. The average SOC stock (0-20 cm soil depth) was significantly higher in the wetland forest ecosystems of opened depression of floodplain than other agricultural patterns, while rice crop in the mountainous had the lowest SOC stock ($p<0.05$) (Fig. 6). In the opened depression of floodplain, the average SOC stocks per agricultural land-use type can be ranked as, wetland forest (24.41±1.38 kg C m^{-2}) ($p<0.05$), rice crop and orchard (13.10±0.74 kg C m^{-2} and 11.85±2.02 kg C m^{-2}), cash crop (10.04±1.54 kg C m^{-2}). In the closed depression of floodplain, SOC stock showed significant

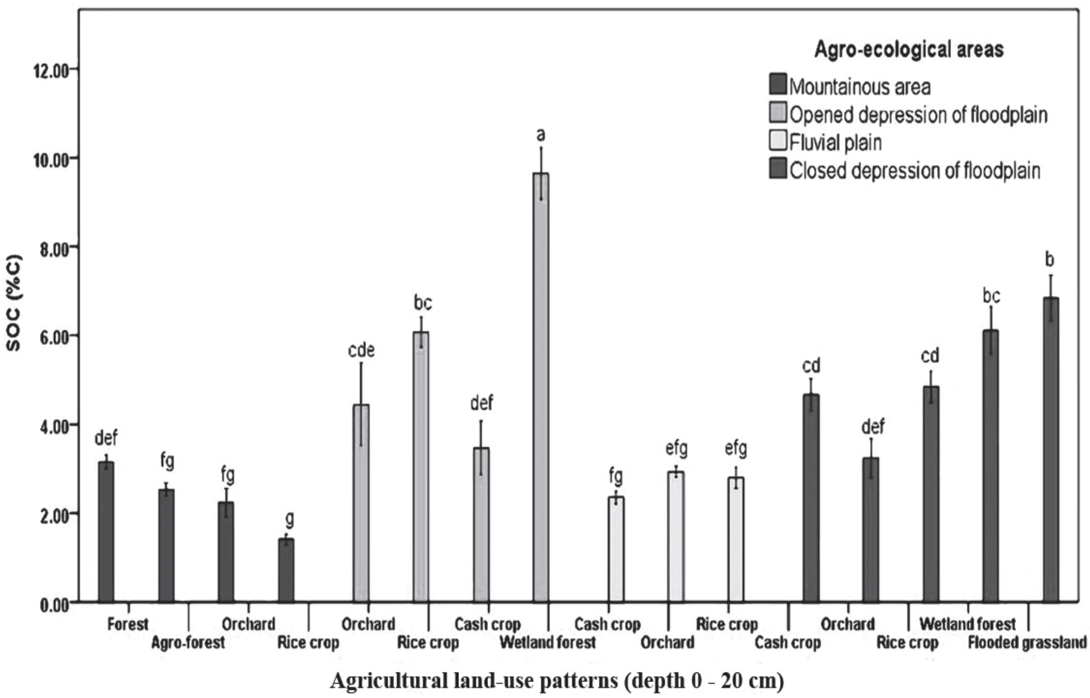

Fig. 4. SOC of depth 0-20 cm in agricultural land-use patterns.

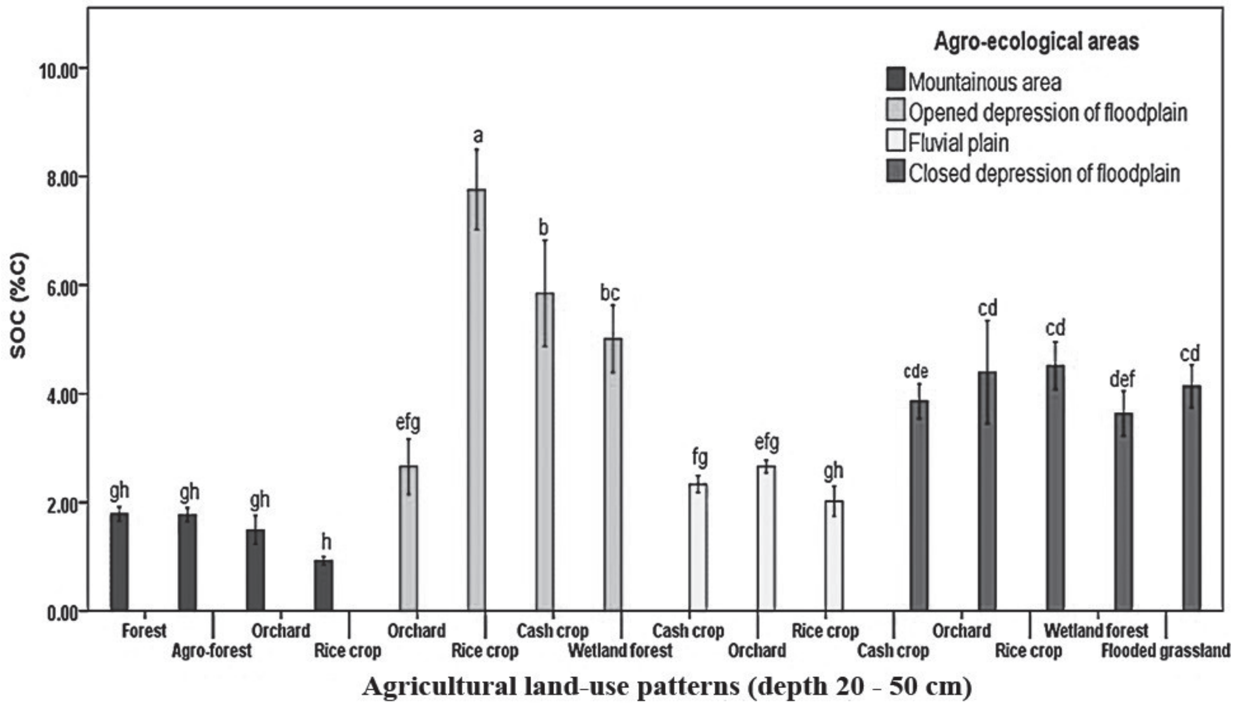

Fig. 5. SOC of depth 20-50 cm in agricultural land-use patterns.

differences in flooded grassland (14.68±1.33 kg C m^{-2}) (p<0.05). However, the difference between other agricultural patterns was not different significantly in this same area, namely wetland forest (11.50±1.25 kg C m^{-2}), cash crop (9.38±1.04 kg C m^{-2}), rice crop (7.75±0.70 kg C m^{-2}), and orchard (6.67±0.95 kg C m^{-2}) (p>0.05). In the mountainous and fluvial plain area, the mean SOC stocks of agricultural patterns were low in surface soil. SOC stock of the cash crops in the fluvial plain area was 6.00±0.32 kg C m^{-2} and was not different significantly with SOC stocks of forest and agro-forest in the mountainous area, respectively, 5.80±0.25 kg C m^{-2} and 5.33±0.30 kg C m^{-2}. While SOC stocks changed slightly in forest and agro-forest of the mountainous, orchard and rice crop of fluvial plain areas, and orchard of the closed depression of floodplain, varied from 5.33±0.40 kg C m^{-2} to 6.67±0.95 kg C m^{-2} (p>0.05).

Similarly, SOC stock in layer 20-50 cm also showed differences between the agricultural land-use patterns in agro-ecological areas and followed a similar trend to SOC concentration (Fig. 7). Rice crop in the opened depression of floodplain accumulated the highest SOC stock of depth 20-50 cm, while this pattern stored the lowest SOC stock in the mountainous area (p<0,05). In the forest ecosystems, the lowest SOC stock was found in the forest of the mountainous area (5.59±0.45 kg C m^{-2}) and increased in wetland forest of the closed and opened depression areas, respectively 12.88±1.61 kg C m^{-2} and 19.84±2.54 kg C m^{-2} (p<0.05). In the orchard and agro-forest, SOC stored the highest stocks in the closed depression of floodplain (13.81±2.67 kg C m^{-2}), while it stored the lowest stocks in the mountainous area (4.64±0.72 kg C m^{-2}) (p<0.05). In terms of cash crops, SOC stocks decreased from opened depression of floodplain (23.70±3.67 kg C m^{-2}) to closed depression of floodplain (12.82±1.01 kg C m^{-2}), and fluvial plain (7.07±0.54 kg C m^{-2}).

In the mountainous area, the SOC stocks varied from 4.27±0.71 kg C m^{-2} in rice crop to 5.86±0.46 kg C m^{-2} in agro-forest (p>0.05). Similarly, in the fluvial plain, the effects of agricultural land-use patterns to SOC stocks in the depth 20-50 cm were not significant. Meanwhile, in the closed depression of floodplain, the SOC stocks were significantly affected by flooded grassland (p<0.05), while the influence of other land-use patterns was relatively mild. Especially, in the opened depression of floodplain, rice crop cultivation increased SOC stocks of depth 20-50 cm (27.69±2.97 kg C m^{-2}), but orchard decreased SOC stocks sharply (11.52±1.87 kg C m^{-2}) (p<0.05).

Effect of Agricultural Land-Use Patterns on SOC and SOC Stock

The SOC promotes nutrient retention, maintains optimal soil structure, and increases water holding capacity [26]. Thus, the loss of SOC does not only contribute to an increase of GHGs in the atmosphere but also has negative impacts on agricultural productivity [27]. The dynamics of SOC stock can be significantly affected by various factors such as agricultural land-use conversion, climatic conditions, vegetation composition and management practices. Especially, in the agricultural land-use patterns, the rate of SOC loss is caused by inappropriate agricultural practices

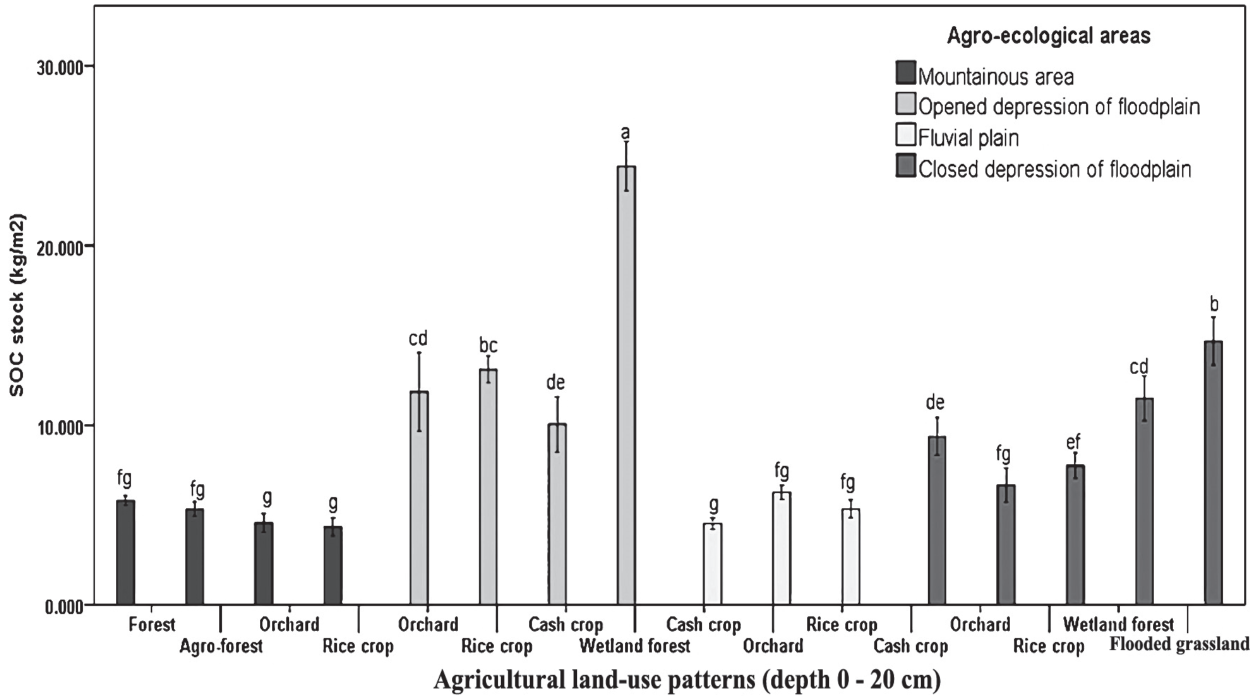

Fig. 6. SOC stock of depth 0-20 cm in agricultural land-use patterns.

and expansion of agricultural land to meet the need of food security and economic development [28, 29]. In this study, SOC content and SOC stock varied across different land-use types. In particular, in the topsoil layer, forest and flooded grassland have higher SOC concentration and SOC stocks than other agricultural land-use types in the same agro-ecological areas. SOC content build-up under any land-use types is the balance between C inputs and C losses which related to the turnover and decomposition of vegetable residue and the respiration by soil organisms [28]. The *Melaleuca* forest is a typical type of wetland forest in the opened depression of floodplain and the closed depression of floodplain. Most of the *Melaleuca* forests in the study

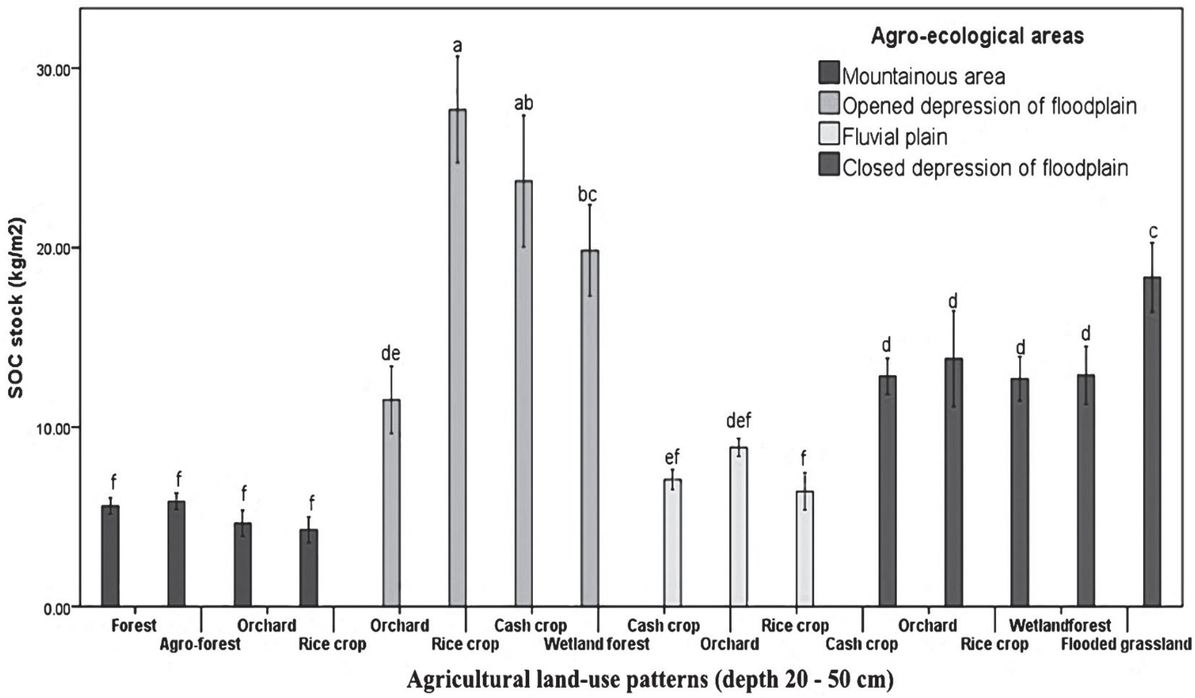

Fig. 7. SOC stock of layer 20-50 cm in agricultural land-use patterns.

area are distributed in Tram Chim National Park (in Dong Thap province) and Tra Su *Melaleuca* forest (in An Giang province). They are two protected forest areas, therefore, human activities that remove plant residues from the soil are not allowed. As a result, in depth 0-20 cm, higher SOC stock in these wetland forest types may link to a high level of C inputs, such as leaf litter and root biomass from the forest trees. In addition, these two areas are also highly inundated in the flooding season every year (about 6 months). Periodic anaerobic conditions occurred in the inundation habitats, which may have slowed the decomposition of organic matter. There is evidence that pieces of fine woody debris buried 20 cm below the soil surface in conditions of higher moisture decomposed 5-10% slower per year, on average, when compared to similar pieces placed on the soil surface [30]. In recent years, to prevent the risk from fire, the *Melaleuca* forests in Tram Chim National Park have been enhanced protection by keeping water inundated all year round. This management practice may cause lower SOC stock in the 0-20 cm soil depth in Tram Chim than the Tra Su *Melaleuca* forest due to the slower decomposition rate by microorganisms.

In the mountainous area, forest was the lowest SOC stock due to the soil's aeration and slope topographic. The decomposition of SOC in this area have happened faster than in opened depression of floodplain and closed depression of floodplain. Furthermore, organic matter was also removed easily from the soil in the rainy season by slope topography. For the flooded grassland in the closed depression of floodplain, total SOC concentration and total SOC stock were higher than in wetland forest in both two soil layers, increasing by 12.55% (for SOC concentration) and 35.41% (for SOC stock). The grassland has long been considered a land-use type that increases soil C stocks (for soils with >45% clay content) when compared with soils of forest areas due to grassland's higher net primary production and contributions to soil structure maintenance [29]. Moreover, residues' recalcitrant nature from *Melaleuca* prevents microbial decomposition. Meanwhile, residues from flooded grassland are biomass of annual herbs, thus the carbon capacity is returned over from dead organic matter to accumulated soil carbon easier and faster.

The agricultural land-use patterns change organic matter decomposition and soil carbon dynamics through alterations of plant species and management practices. Changing in the agricultural practice can lead to substantial gains or losses in system-level carbon. The history of agricultural cultivation impacts soil organic matter decomposition through soil nutrient status, pH, or decomposer community [28]. At present, most of the cultivated areas in the upper VMD are used for rice, cash crop and orchard cultivations [16]. The fluvial plain was exploited by farmers before Vietnam's transition towards an open market economy (Doi Moi policy) in 1986 because of its advantages such as fluvial deposition, irrigation, and well-drained soil. Meanwhile, parts of the opened and closed depressions of floodplain areas are only exploited for agricultural cultivation after Vietnam's transition because of the urgent need of food security and economic development in Viet Nam. Moreover, these cropping land-use patterns in the fluvial plain undergo regular agricultural practices which thereby reduced the input of C to the soil, i.e., in depth 0-20 cm. In agricultural systems, where soil and plant residues are often intensively manipulated, human impact on decomposition is especially pronounced [31]. Management practices such as tillage, cover crops and returning residues, and application of fertilizers can modify the rate of soil organic matter decomposition by their effects on soil moisture, soil temperature, aeration and composition [32]. The higher SOC stock in rice paddies than other cropping patterns in our present study has been ascribed to favorable water regimes during the cultivating time. In addition, after rice harvesting, some farmers took part of the rice straw, and at the same time left the stubble of the previous rice crop. Before planting the next crop, the soil is prepared by tillage to turn over the soil from the depth layer into the topsoil and bury the stubble of the rice crop into the soil for decomposing. These practices increased SOC stock in layer 20-50 cm and prevented soil degradation.

Effect of Soil Characteristics on SOC Stock

Pearson's coefficient revealed a significant correlation ($p<0.05$) of SOC stock with SOC content, soil texture, bulk density, pH and EC (Table 2). At the regional level, changes in SOC stock were most positively related to SOC content, silt, clay, bulk density, and EC in both two layers ($p<0.05$) but negatively related to sand and pH_{KCl}. In our result, SOC stocks are positively related to SOC content not only in small agro-ecological areas but also in the whole study region in two soil layers ($r\geq0.790$; $p<0.05$). In principle, the amount of SOC stored in a given soil is dependent on the equilibrium between the amount of C input and the amount of C output. Locally, C can also be lost or gained through soil erosion or deposition, leading to the redistribution of soil C at local, landscape and regional scales [33]. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e., the input of organic C to the soil system) and minimizing the soil C losses. Furthermore, SOC stabilization through its interaction and association with soil minerals affected SOM persistence [34]. A high SOM content provides nutrients to plants and improves water availability which enhances soil fertility and improves food productivity [35].

Differences in SOC stock are reported to be attributable to soil parameters such as texture, clay mineral type, land-use change type, temperature and precipitation [36]. The soil texture was assessed as the most prominent predictor for the topsoil SOC stock, especially its fine particles (silt and clay). The clay and silt are considered important agents accounting for the

Table 2. Correlation of SOC stock with soil characteristics.

Agro-ecological areas	Layer (cm)	SOC content	Sand	Silt	Clay	Bulk density	pH_{KCl}	EC
All	0-20	.911**	-.293**	.100*	.385**	.388**	-.453**	.306**
	20-50	.951**	-.371**	.266**	.392**	.380**	-.429**	.402**
Mountainous area	0-20	.849**	-.317**	.284**	.151	.170*	-.041	-.023
	20-50	.913**	-.145	.296**	-.041	.337**	.243**	.106
Opened floodplain	0-20	.908**	.007	-.031	.016	.047	-.656**	-.194
	20-50	.952**	-.331*	.241	.011	.115	.069	-.057
Fluvial plain	0-20	.869**	-.555**	.061	.373**	.632**	-.338**	-.330*
	20-50	.940**	-.124	-.109	.174*	.552**	-.533**	-.131
Closed floodplain	0-20	.790**	.181	.018	-.159	.638**	.171	-.416**
	20-50	.830**	-.029	-.363**	.309**	.361**	-.164	.007

**. Correlation is significant at the 0.01 level (2-tailed) and * at the 0.05 level (2-tailed).

difference in SOC through the role of organic matter adsorption [37, 38]. In accordance with previous studies, the silt and clay were recorded to have a positive correlation with SOC stock in our study (Table 2) [39, 40]. Clay content is beneficial to the protection of SOM from decomposition by adsorption and aggregation, slowing turnover, and effectively increasing SOC [41]. Moreover, increasing clay content also increases the water holding capacity, thus clay content interacts with water regime to control the accumulation of SOC in the opened depression of floodplain and the closed depression of floodplain areas. This process may explain the significant correlation found between SOC stock and clay content at a large area in our research. However, Table 2 shows that clay content has little effect on the SOC stock under similar climatic conditions at smaller agro-ecological areas. These trends may be explained in terms of difference of SOC content (e.g., the vegetation diversity, litter input, and root exudates), pH_{KCl}, bulk density and EC under similar climate conditions.

Soil bulk density characterizes the compaction of soil and its water permeability and is therefore an important index used to assess SOC [42]. However, the soil surface and soil bulk density are prone to change due to erosion or deposition of material, swelling or compaction, and anthropogenic activities [43]. In agreement with the findings from Gebrehiwot et al. (2018) [44], our results showed that SOC stock had a significant positive correlation with soil bulk density, especially in fluvial plain area and closed floodplain (p<0.05). Increasing the soil bulk density to the appropriate level stimulates plant production by enhancing the water holding capacity and thereby intensifying C inputs to soil. The suitable soil bulk density for cash crops and orchard plants is from 1.0-1.1 g/cm^3, but low bulk density causes harm to rice because the soil will not be able to hold water. In general, soil bulk density >1.2 g/cm^3 (>1.4 g/cm^3 in the plow pan) is very suitable for rice growth.

In addition, the relationship of soil pH and SOC stock is a negative correlation in both the whole study region and typical agro-ecological areas (p<0.05). Soil pH is a fundamental soil property that affects soil acidification and soil organic matter decomposition [45]. Higher soil acidity can cause significant changes in microbial composition and lead to lower microbial activity in the soil. This impact regulates multiple biogeochemical processes in soil carbon cycling, especially SOM decomposition [46]. Finally, EC also has a positive effect on SOC stock in the study region (r = 0.306 in depth 0-20 cm and r = 0.402 in depth 20-50 cm, p<0.05). However, in the fluvial plain and closed floodplain, we found a negative effect of EC on SOC stock in the 0-20 cm depth.

Conclusions

The study revealed the SOC stock distribution in agricultural land-use patterns and the impact of these patterns on carbon dynamics in the upper Vietnamese Mekong Delta. Lower SOC concentration and stock were found in the topsoil layer, but the SOC concentration and stock significantly increased in a depth of 20-50 cm in cropping patterns. In areas that had almost no or fewer impacts of agricultural cultivation (i.e., forest in the mountainous area, wetland forest and grassland in the opened and closed depression of floodplains), SOC stock trended opposite. However, this trend did not increase remarkably. The notable variability in SOC stock between dry croplands and rice paddies in agro-ecological areas indicated that the changes in SOC stock were influenced by changes in agricultural cultivation, especially differences in vegetation types and practical management in agriculture. Furthermore, other factors such as texture soil and some physicochemical characteristics also contributed to the differences in SOC stock between agro-ecological areas. The correlation of SOC stock and other soil factors (BD, soil pH, sand content, clay content, and EC) contributed to interpreting how C changes over spatial distribution and soil depth in the study area. Thus, improving SOC stock is needed to maintain sustainable soil management in cropping patterns, especially in the topsoil layer. Based on these findings, we concluded that increasing organic matter input and maintaining suitable water regimes in crops were appropriate management practices to enhance carbon storage and fertility in the soil, and at the same time mitigate global warming.

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Conflict of Interest

The authors declare no conflict of interest.

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