

Review

Soil Organic Carbon in Sandy Paddy Fields of Northeast Thailand: A Review

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Abstract: Soil organic carbon (SOC) improvement has become a sustainable strategy for enhancing soil resilience and reducing greenhouse gas (GHG) emissions in the rice cropping system. For tropical soils, the SOC accumulation was limited by the unfavorable environment, likely the sandy soil area in Northeast (NE) Thailand. This review aims to quantify and understand SOC in sandy paddy fields of NE Thailand. The existing research gap for alternative management practices is also highlighted to increase ecological and agronomic values. We review previous studies to determine the factors affecting SOC dynamics in sandy paddy fields, in order to enhance SOC and sustain rice yields. High sand content, up to 50% sand, was found in 70.7% of the observations. SOC content has ranged from 0.34 to 31.2 g kg⁻¹ for the past four decades in paddy rice soil of NE Thailand. The conventional and alternative practice managements were chosen based on either increasing rice crop yield or improving soil fertility. The lack of irrigation water during the mild dry season would physically affect carbon sequestration as the soil erosion accelerates. Meanwhile, soil chemical and microbial activity, which directly affect SOC accumulation, would be influenced by nutrient and crop residue management, including chemical fertilizer, manure and green manure, unburned rice straw, and biochar application. Increasing SOC content by 1 g kg⁻¹ can increase rice yield by 302 kg ha⁻¹. The predicted carbon saturation varied tremendously, from 4.1% to 140.6% (52% in average), indicating that the sandy soil in this region has the potential for greater SOC sequestration. Our review also suggests that broadening the research of rice production influenced by sandy soil is still required to implement adaptive management for sustainable agriculture and future food security.

Keywords: soil organic carbon; sandy soil; carbon saturation; rice paddy; Northeast Thailand

1. Introduction

Over the past decades, research on the multifunctionality of soil has been increasingly recognized as a resolute direction for sustainable soil management [1,2]. Beyond the basis for agriculture, soil provides ecological functions, including balancing nutrients and water cycles, biomass production, biodiversity preservation, and carbon (C) sequestration [2,3]. According to the Sustainable Development Goals (SDGs) of the United Nations, the soil is linked to many goals as an important resource not only for providing food production and quality of life but also explicitly for ecosystem services [4,5]. The challenge of sustainable management in cropping systems under degrading land [6,7] and climate variation [8–11] has led many researchers to focus on the capacity of soils to accumulate organic C [12–15].

Soil organic carbon (SOC) storage is the key function of agricultural soil, as it interacts with other functions, e.g., soil fertility, nutrient cycling, temperature, and pH balance [16,17]. It is also related

to sustainable strategies to mitigate the emission of greenhouse gases (GHGs) [18,19]. Autotrophic organisms use atmospheric gases, such as CO₂ and CH₄, as the main C sources of organic materials syntheses. Then, organic C from the death and residues of plants and animals is incorporated into the soil through the activities of heterotrophic microorganisms [20]. Finally, decomposition of plant and animal residues results in the formation of SOC in soil. In the agroecosystem, the SOC retention potential of soil depends on several factors, including C input level, elevation, practical management, and vegetation type [1]. Many management practices to improve SOC have been suggested, such as no-tillage management, crop rotation, manure or crop residue addition, biochar, and other amendments [21–27]. The SOC also contributes to “soil resilience”, which is the ability of soil to recover after a deterioration event such as drought conditions [28].

Sandy soil, which is a light-textured soil with low organic matter and water-holding capacity, occupies about 86,000 km² in Asia [6]. Because of the high proportion of drainage pores, water and dissolved substances can be lost rapidly through sandy soil particles, due to both natural and anthropogenic processes. In terms of productivity, it is difficult to maintain soil fertility and irrigation efficiency on these soil types, particularly at the higher temperatures and precipitation rates of tropical areas. In tropical soil, the nutrients are concentrated in the topmost humic deposits and are quickly recycled [29]. Compared to other soils, tropical sandy soils tend to have a low potential of C storage and are hypothesized to be very weak in the role of mitigation of GHGs emissions [30,31]. Nonetheless, increasing populations and food security requirements push forward the exploitation of more arable cropping areas. Hence, comprehensive research on sandy soils should be implemented to develop soil utilization sustainably.

In Thailand, approximately 46% of the agricultural area was used for fields of paddy rice (*Oryza sativa* L.) [32], which were mostly found in the Northeast (NE) region, where the soil is mainly characterized as sandy soil with low organic C content and high salinity. Most of the rice paddies in this region are grown annually as a rainfed system, due to low precipitation and lack of irrigation water. As a result, low yield has been a problem in this region for decades. That is why rice cultivation in NE Thailand was not recommended. A decline in arable land area threatens food security, leading to sandy soils as a potential option to enhance food production capacity. In order to do so, there is a need to quantify and understand the properties of sandy soils across NE Thailand, particularly SOC concentrations and factors affecting SOC levels. Therefore, this review aims to quantify and understand SOC in sandy paddy fields of NE Thailand and has three objectives: (1) to review the mechanisms of factors affecting SOC in sandy paddy fields; (2) to estimate SOC content and carbon saturation for sandy soil in NE Thailand; and (3) to point out the challenges in sustaining SOC in sandy paddy fields in NE Thailand.

2. Data Compilation and Systematic Reviews

Data were collected by searching existing peer-reviewed literature. The articles were collected and sorted by using the electronic databases of ISI Web of Science, Scopus, and Google Scholar. We searched for articles published up to December 2019 that studied SOC and rice production in NE Thailand. We used “soil organic carbon”, “sandy soil”, “rice paddy”, “management practices”, and “Northeast of Thailand” as the search keywords. The literature search was restricted to studies pertaining only to the NE region of Thailand and that discussed soil physical and chemical properties, management practices of rice-based cropping, rice yield, and SOC in the articles. If any published articles did not fully provide all mentioned data, they would be excluded. Therefore, there were 40 articles that could be used for the synthesis of this review by extracting the data from contents, tables, and figures in the articles. The topsoil data (within the range of 0–40 cm depth) were considered and extracted. If any published articles collected soil samples more than 40 cm deep, the data were not included in this review.

Soil physical and chemical properties, management practices, rice yield, and SOC were extracted from the collected literature search. Data were then summarized, synthesized, and presented in the form of tables and figures. Statistical analyses of the data were performed by using SPSS (Version 20.0,

Chicago, IL, USA). The data plots and graphics were constructed by using the R package ggplot2 [33] implemented in R 3.6.1. The mean and standard deviation values of data were calculated. Simple linear regression analysis was used to find the relationship between SOC and rice yield.

Carbon saturation (maximum protective capacity) is the amount of SOC that can be associated with clay and silt particles, which was calculated by using to the equation developed by Hassink [34]:

$$C_{sat} = 4.09 + 0.37(\text{Clay} + \text{Silt}) \quad (1)$$

where C_{sat} is the C saturation (g C kg^{-1}) expressed as the C content of the clay plus silt fraction on a whole-soil basis, and Clay + Silt is the clay ($0\text{--}2 \mu\text{m}$ particles) and fine silt ($2\text{--}20 \mu\text{m}$ particles) contents (%), respectively.

Theoretically, the maximum concentration of SOC is referred to the upper limit of soil C saturation capacity [35]. Thus, the difference between the existing SOC concentration and the C saturation is defined as the C saturation deficit [36] and represented the potential for SOC sequestration. In this review, we calculated the C saturation deficit as follows:

$$\text{C saturation deficit} = C_{sat} - \text{SOC} \quad (2)$$

Soil which has the amount of SOC associated with clay plus silt fraction exceeding the maximum protective capacity means the capacity level associated with clay plus silt was saturated; thus, more SOC accumulation will be associated with the macro-particles (fine sand to coarse sand) [37].

3. Topography and Climatic Condition in Northeast Thailand

Naturally, topographical features and climate controlling the size and flux of sediment can play a crucial role in SOC distribution [38–40]. By weathering, SOC is partly eroded and transported through the air and hydrological systems [41,42]. The NE region of Thailand is a saucer-shaped basin that is composed of a dissected peneplain surface mainly divided into the Korat and Sakon Nakhon basins. These basins consist of undulating features, including flat-topped mountains surrounded by isolated remnants of high mountains, e.g., Phu Phan and Phnom Donk Rak mountains [43]. Elevation varies from 200 to 2075 m a.s.l., with relatively gradual slopes (Figure 1). The region is influenced by wet–dry monsoonal or tropical savanna climate. The rainfall is lower in the west and middle part, which ranges between 1000 and 1400 mm, while a higher range (1500–2300 mm) is found in the east and the north [44]. However, the precipitation rate occurred erratically, with long dry periods in some area, such as in Khorat basin [43].

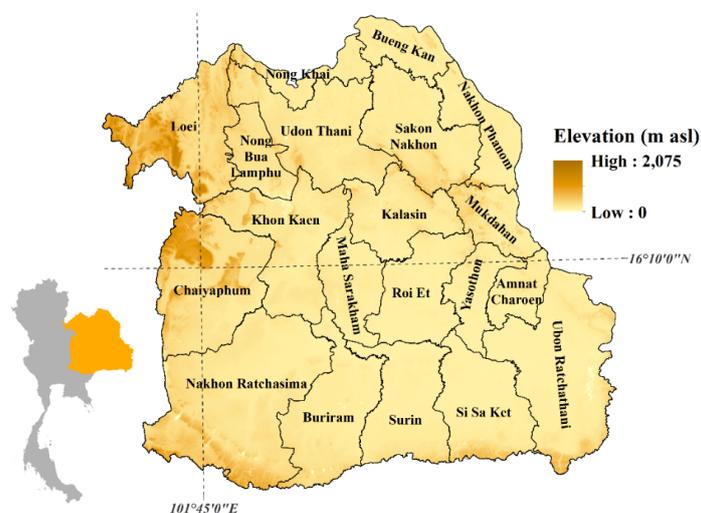


Figure 1. Topography of Northeast Thailand.

Of the few studies in NE Thailand, SOC was found to differentiate with elevation gradients. Within a toposequence, both SOC and the clay content of lowland rainfed paddy fields generally declined with ascending relative elevation within the mini watersheds [45,46]. Soil organic C concentration in the lowermost area of the paddy rice field was found as the highest amount of C sequestration, due to effects of erosion and accumulation. The higher rate of C sequestration at in the lower positions was described as the result of deposition of eroded finer particles with organic matter [47]. Moreover, the variability of SOC was associated with both average annual rainfall and distance from the steam network in Laos, which is influenced by the same climate as the NE Thailand. Due to soil weathering, higher SOC stocks, soil fertility, and decreased clay contents were also found near steams systems [48]. However, physical and chemical properties are often discussed relating to soil fertility in each soil type. The limiting factors for NE Thailand's soil are mainly determined by the parental materials and tropical savanna climatic environment [49]. Notwithstanding these observations, the wide scale of the topography and climate condition effect on SOC distribution in the region, especially the agriculture area, is still lacking. Further research considering SOC storage ability in a wide-range variation of regional terrain and still required for providing guidelines for agriculture activities in the appropriate location. The SOC distribution in rice-based cropping systems in NE Thailand was in the range between 0.34 and 31.2 g kg⁻¹ ($n = 89$), varying from site to site (Figure 2).

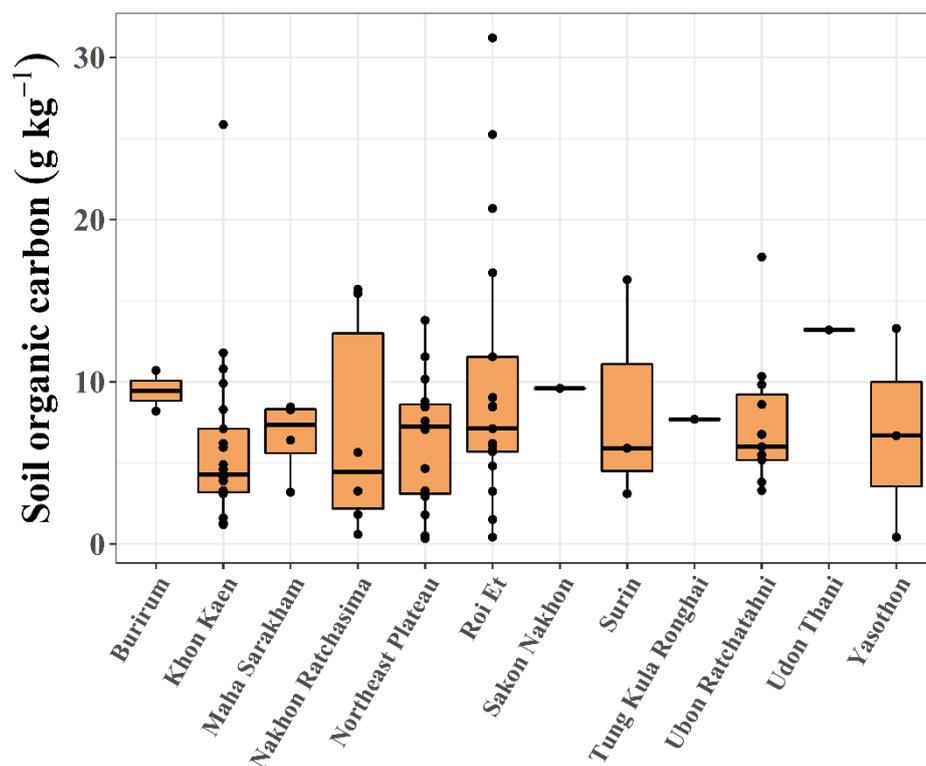


Figure 2. Overview on soil organic carbon (g kg⁻¹) (within the range of 0–40 cm depth) distribution in rice-based cropping systems of each area in Northeast Thailand ($n = 89$) [41,49–70].

4. Soil Properties Effect on Soil Organic Carbon

4.1. Physical Properties

The stabilization of SOC is dependent on soil texture and mineralogy [71,72]. The topsoils of the Northeast plateau, Thailand, have a strong sandy texture that has relatively low fertility [43]. The texture classes of surface soils (0–40 cm) of paddy fields varied in a wide range, from sand to silty clay, and were mostly found as sandy loam and sand (26% and 20% of 109 reference samples, respectively). Theoretically, the fine fraction of soil serves as a useful measure for potential SOC

storage [1]. The low clay content of the soil tends to be poor in soil aggregation stability [73] and water holding, due to low cohesion forces between elementary particles that affect the porosity [74]. Soils in this region have bulk densities between 1.1 and 2.0 g cm⁻³ (Table 1), which is also an indication of the variability in soil compaction. Many studies show the negative correlation between soil bulk density and SOC content, either in NE Thailand [63] or other countries [75–77]. The increase of soil bulk density by reduction of porosity results in a limitation of SOC accumulation. Sriwichai et al. [68] revealed the influence of soil aggregate sizes on SOC stability. It was found that labile organic carbon (LOC), which is an easily decomposed composition, mostly binds with the macroaggregate, soil particle size > 0.25 mm. Thus, aggregation of small particles likely to microaggregate soil tends to be more stable by physical and chemical protection in the soil [68,78]. This research also suggests that the non-LOC ratio in aggregated soil could be the essential indicator for SOC stability in all the particle sizes. In order to compare the SOC accumulation by soil textural characteristic, 45 literature samples which collected in NE Thailand were interpreted as Figure 3. The soil samples' texture can be classified into three groups: sand (85%), sandy loam (11%), and clay (4%). Generally, the larger surface areas of clay particles have a high ability to protect organic matter, owing to soil weathering and microbial decomposition due to bonds between the surface of clay particles and organic matter that slow down the decomposition process; moreover, higher clay content in soil assists the macroaggregate formation [70,79,80]. Furthermore, more clay content in soil provides more polyvalent cations (Ca²⁺, Fe²⁺, and Al³⁺), which play a vital role as an ion bridge for the attachment of SOC on the clay surface of the soil [68]. However, Figure 4 showed that the highest SOC (13.9 g kg⁻¹) sample contained only 17.2% sand particle. The fluctuated SOC concentration (0.34 and 13.9 g kg⁻¹) in sandy soil is due to sand particles having a low capacity to store C and being susceptible to the driver factors. These results indicate that, not only can the fine particle fraction affect the stability of SOC storage in the paddies' soil, but chemical features are also possible influential factors.

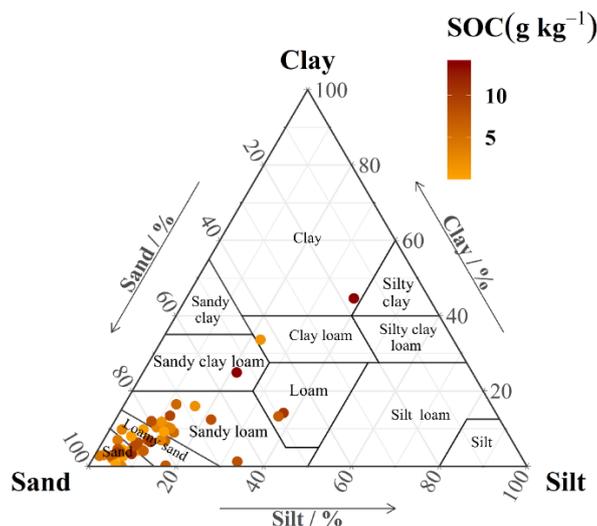


Figure 3. Overview on texture of analyzed referenced soil samples and soil organic carbon ($n = 45$) of rice-based cropping system in Northeast Thailand (within the range of 0–40 cm depth) [45,50–52,54,57,61,63,65,66,68,69,81,82].

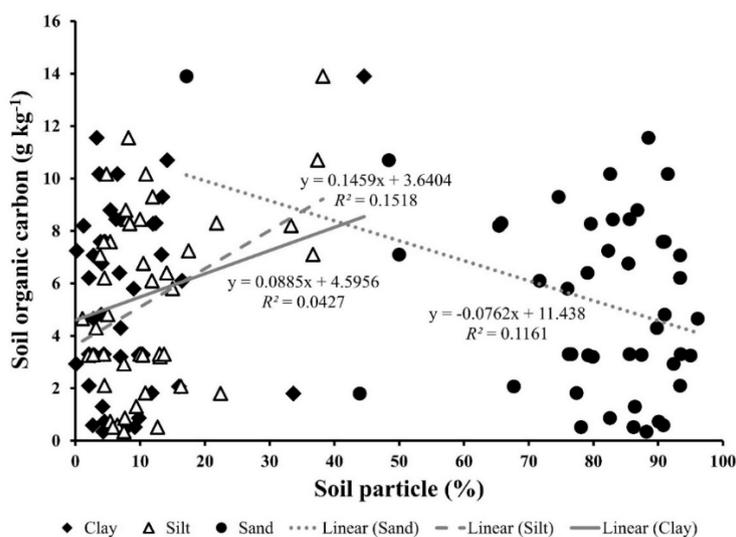


Figure 4. Overview on soil organic carbon (g kg^{-1}) of paddy fields from Northeast Thailand ($n = 45$) (within the range of 0–40 cm depth) [45,50–52,54,57,61,63,65,66,68,69,81,82].

4.2. Chemical Properties

The pH variation owing to wet and dry alternative conditions is a special characteristic of paddy soils [83]. Likewise, the pH of NE Thailand paddy soils ranges between 3.9 to 9.6 (Table 1). The references were mostly to acidic soil, which relates to the chemical stabilities of sulfides and ferrous iron [83]. Meanwhile, the EC in the region is highly variable. A negative correlation between pH and SOC ($p < 0.01$) was found in the study of Islam et al. [63], especially in the presence of high sand percentage and high concentrations of Na^+ . Soil pH in paddy field conditions has the effect of either optimizing or inhibiting the rice growth and may increase from weakly acidic to neutral upon flooding condition, due to the reduction process. While SOC affects the pH due to the production or consumption protons (H^+) during biodegradation, the reduction of inorganic oxidized agents results in pH variations [84]. The pH of paddy soils of NE Thailand, in addition, was found to be differentiated by other factors such as elevation [85] and N-fertilization [60]. Although the previous studies detected the correlation between pH and SOC in paddy sandy soil of NE Thailand, the further studies are needed to answer the questions about which pH condition have an optimizing effect and which pH condition have an inhibiting effect on SOC.

Both electrical conductivity (EC) and cation exchangeable capacity (CEC), the important fertility characteristics, as well as pH, have relationships with the other factors, e.g., soil texture, base saturation, and clay content [86]. Very low to moderately low CEC values, ranging from 0.5 to 20.75 cmol kg^{-1} , were found in almost all the reference paddy soils in NE Thailand (Table 1). The cations in the soil are generally held by the negatively charged clay and organic matter particles through electrostatic forces. The cations on the CEC of soil particles are easily exchangeable with the others, which is an essential property for plant nutrient availability. In rice production, management practices, such as fertilization, are dependent on the soil's CEC. Unlike soils with high CEC that are typically more fertile and can hold more plant nutrients, sandy soils require more frequent fertilizer applications due to lower CEC. Previously, the CEC of the sandy soil was indicated to positively correlate with SOC content. Due to the long-term effect of the various organic matter management strategies, low SOC content and humus in the sandy soils resulted in CEC consistently below the level considered to pose salinity effects on rice production [85]. In contrast, in Islam et al. [63], CEC was found to have a significantly negative effect on sand content and C sequestration (Table 2). The high sand content in the soil is commonly influenced by particles to have no charge, which results in low CEC. Unlike sand content, soil C sequestration was also possibly affected by other factors, e.g., the amount and type of clay minerals, parental material, soil salinity, and weathering [63]. Similarly, EC indicates soil salinity

and the electric current capacity of the soil's aqueous solution. The studies of Arunrat et al. [65] showed high EC, which positively correlates with SOC ($p < 0.01$). It was hypothesized that the surface soil was mostly affected by salinization. Rice production is adversely affected, both physically and chemically, by excess salts in some soils of NE Thailand [49,50,63–65,87].

Base saturation (BS) is another important soil measurement which represents the soil fertility by the percentage of base cations Ca^{2+} , Mg^{2+} , and K^{+} . A great variation of %BS was found among some studies of NE Thailand (Table 1). The high BS of soil reflects high soil fertility; however, other cation compositions in these soils should be examined in more detail. For instance, exchangeable sodium (Na^{+}), which is mostly found in high concentration in many areas of NE Thailand's soil, causes the dispersion of soil aggregates and accelerated organic matter loss [63]. Nonetheless, there is a lack of data for many key metal cations, such as Al^{3+} and Fe^{3+} , that play the role of a cationic bridge between SOC's functional group and clay minerals [88,89]. Furthermore, the position of the field in the region [85] and management practices mainly effect the distinction of exchangeable cations and electrical conductivity, as discussed in previous studies [53,60,69,82,90].

Table 1. Overview on physicochemical characteristics of sandy soil in Northeast Thailand (within the range of 0–40 cm depth).

Location	%Sand	%Silt	%Clay	BD	pH	CEC	EC	BS	SOC	References	
Buriram	48.42–65.42	33.32–37.4	1.26–13.3	1.50–1.54	5.23–5.28 ^a	4.32–5.24			8.2–10.7 ^d	Sriwichai et al. [68]	
	42.2	28.6	24.3	1.36	5.14 ^b				10.8 ^g	Knox et al. [91]	
Chaiyaphum	50.1	24.2	24.6	1.37	5.02 ^b				9.7 ^g	Knox et al. [91]	
Kalasin	48.7	24.2	24.8	1.38	5.15 ^b				9.6 ^g	Knox et al. [91]	
Khon Kaen	89.8–90.8	3.2–18	2.7–12.4		5.2–8 ^(1:2.5)	2.2–15.7	0.3–11.5 ^(1:5w)	76.8–1627.3	0.59–4.3 ^h	Patcharapreecha et al. [50]	
	46.2	26.7	24.1	1.37	5.19 ^b				10.3 ^g	Knox et al. [91]	
	78.5–93.4	4.5–12.5	2.1–9	1.45–1.75	5.18–5.5 ^b	3.53–5.14			6.2–7.9 ^d	Vityakon et al. [57]	
				1.557	5.77 ^b	4.07					Clermont-Dauphin et al. [85] ^d
	59.1–67.9	25.9–35.6	4.9–6.3	1.55–1.84	3.67–4.28 ^(KCl)		2.7–54.1 ^(ECe)		3.2–4.1 ^e	Quantin et al. [59]	
	40–66	18–30	16–30		4.2–4.5 ^a				3.9–11.8 ^d	Naklang et al. [54]	
	11.4–61.6	20.3–29.9	17–54.4		5.12–6 ^b	4.8–9.75	6.1–16.8 ^(1:1w)	53.5–116.96	1.19–5.96 ^e	Wongpokhom et al. [61]	
	93.4	4.5	2.1	1.45	5.5 ^b	3.5			2.1 ^d	Samahadthai et al. [81]	
	90	5	5	1.45	5.5 ^b	3.5				Puttaso et al. [92] ^d	
	49.5	36.2	14.4						25.86 ^d	Ro et al. [62]	
50	36.7	13.3	1.17–1.45	4.6–5.1 ^a	11.2–16.8			7.1 ^d	Thammasom et al. [82]		
65.8	21.9	12.4	1.39	4.4–4.6 ^a	3.32–3.51			9.9–10.8 ^g	Phiwdaeng and Kaewpradit [67]		
					7.5–8.5 ^a					Kumputa et al. [69] ^d	
					3.91–4.36 ^b					Inubushi et al. [93] ^d	
Loei	51.2	24.1	25.2	1.37	5.13 ^b				10.4 ^g	Knox et al. [91]	
Mahasarakham	44.2	28.6	23.1	1.37	5.27 ^b				10.5 ^g	Knox et al. [91]	
	84	5	11	1.504						Suzuki et al. [94] ^d	
					4.3–9.6 ^b		82.53–0.13 ^(ECe)		8.27–8.44 ^d	Saisema and Pagdee [64]	
	79.5	13.6	6.9					3.2–6.4 ^g	Kunlanit [66]		
Mukdahan	51.6	22.7	24.9	1.38	5.04 ^b				9.7 ^g	Knox et al. [91]	
Nakhon Phanom	50.2	23.2	24.6	1.39	5.08 ^b				9.4 ^g	Knox et al. [91]	
Nakhon Ratchasima	49.8	36.6	13.6		6 ^b	4.5		95.8		Miura et al. [95] ^h	
	42.1	28.2	25.3	1.36	5.3 ^b				11.0 ^g	Knox et al. [91]	
	31	22	47		4.6 ^b				15.7 ^d	Naklang et al. [54]	
	25–70.5	12.8–22.9	15.3–49.1		6.3–6.9 ^b	5.18–19.01	5.6–6.5 ^(1:1w)	73.4–96.1	0.59–5.64 ^e	Wongpokhom et al. [61]	
	77.4–79.2	10.4–10.8	10.4–11.8	1.65	6.5 ^a	4.86			1.82–3.26 ^g	Islam et al. [63]	
1.6	85.24	13.14		5.6 ^(1:2.5)				15.45 ^e	Zhou et al. [70]		
Nong Khai	51.1	23.4	23.7	1.4	5.07 ^b				9.4 ^g	Knox et al. [91]	
Roi Et	47.7	39.9	12.4		6.1 ^b	5.77		95		Miura et al. [95] ^h	
	79.5	12.5	8			5.47 ± 5.01			7.12 ^e	Nakamura and Matoh [51]	
	43.8	30.3	21.8	1.37	5.27 ^b				11.1 ^g	Knox et al. [91]	
	86.1–89.8	6.7–8.8	3.5–6.6		4.87–5.46 ^c			10.52–77.78	0.42–8.5 ^g	Ruaysoongnern and Noble [58]	
	37.8	25	34.8		7.1 ^b	11.67	1 ^(1:1w)	90.8	1.51 ^e	Wongpokhom et al. [61]	

Table 1. Cont.

Location	%Sand	%Silt	%Clay	BD	pH	CEC	EC	BS	SOC	References
Sakon Nakhon	50.3	22.8	24.5	1.41	5.19 ^b				9.4 ^g	Knox et al. [91]
	73	25	2		4.1 ^b				9.6 ^d	Naklang et al. [54]
Sri Sa Ket	44.7	28.2	23.2	1.37	5.24 ^b	0.25–20.75	0.89–0.45 _(ECe)	16.9–52.5	10.6 ^g	Knox et al. [91]
	32.6–84.6	6.9–33.9	9.9–37.8	1.8–2	4.5–6.3 ^b				0.34–31.99 ^g	Saenya et al. [96]
Surin					4.7 ^b	2.2				Jermasawatdipong et al. [97] ^f
	43.6	28.9	23.2	1.37	5.24 ^b				10.8 ^g	Knox et al. [91]
	78	14	8		4.0 ^b				5.9 ^d	Naklang et al. [54]
	52–59	25–33	14–19	1.5–1.58	4.3–5 ^b	3.1–3.8	9.2–3.4 _(1:1w)	3.1–16.3 ^e	Thuithaisong et al. [98]	
Ubon Ratchathani	85.4	10.5	4.1		4.2 ^b	1.53–1.85	5	31.8	3.81–16.76 ^d	Naklang et al. [53]
	48.7	24.2	24.5	1.38	5.14 ^b				9.4 ^g	Knox et al. [91]
	80–88	8–12	4–8		4.1–4.2 ^b				5.2–6 ^d	Naklang et al. [54]
	58–84	12–31	4–28		4.42–6.12 ^b				5.7–31.2 ^e	Suriya-Arunroj et al. [55]
	69	17	8		5.53 ^b				4.6 ^d	Mochizuki et al. [60]
	74–81	9.4–15	9.1–11					3.3–17.7 ^d	Homma et al. [45]	
					4.1–4.8 ^b			5.17–10.34 ^d	Seto et al. [99] ^e Sansen et al. [100]	
Udonthani	65.6	29.9	4.5		4.8 ^b	8.02		83.7		Miura et al. [95] ^h
	50.4	23.4	24.5	1.39	5.11 ^b				9.2 ^g	Knox et al. [91]
	54	28	18		5.7 ^b				13.2 ^d	Naklang et al. [54]
						14.2–4.7 _(1:5w)			Supparattanapan et al. [87] ^d	
Yasothon	76.3–90.8	5.4–12.1	2.4–11.6		4.72–5.21 ^c	0.107–1.718		10.24–65.04	0.42–6.68 ^g	Ruaysoongnern and Noble [58]
	44.9	27.8	23.4	1.37	5.21 ^b				10.5 ^g	Knox et al. [91]
	46.29	22.57	31.14	1.48	6.33–7 ^b				13.3 ^g	Sudjarit [101]
Northeast Plateau	67.7–96.1	1.1–17.5	0.1–16	1.32–1.77	4.7–6.5 ^b	0.97–4.63		32–89	0.34–13.8 ^g	Kheoruenromne et al. [49]
	43.3	22.1	33.2		6.3 ^b	10.54		96.9	1.8 ^e	Wongpokhom et al. [61]
	89	8	3		4.6 ^b				7.7 ^d	Naklang et al. [54]

* BD = bulk density (g cm⁻³); SOC = soil organic carbon (g kg⁻¹); CEC = cation exchange capacity (cmol kg⁻¹); EC = electrical conductivity (dS m⁻¹); BS = percent base saturation (%);
^a (pH_{1:5w}), ^b (pH_{1:1w}), and ^c (pH_{1:10 Ca 0.002M}); ^d(0–15 cm soil depth), ^e (0–20 cm soil depth), ^f (0–25 cm soil depth), ^g (0–30 cm soil depth), ^h (0–36 cm soil depth), and ⁱ (0–40 cm soil depth).

Table 2. Overview on correlation of soil organic carbon with soil physical and chemical properties under sandy soil conditions of Northeast Thailand (within the range of 0–40 cm depth).

Reference	Factor	Correlation	Significance
Islam et al. [63] ^g	Bulk density	–	$p < 0.05$
Sriwichai et al. [68] ^d	Soil Microaggregates	+	
Zhou et al. [70] ^e	%Clay	+	
Zhou et al. [70] ^e , Arunrat et al. [65] ⁱ	%Silt	+	$p < 0.05$
Arunrat et al. [65] ⁱ	%Silt + %Clay	+	$p < 0.05$
Samahadthai et al. [81] ^d	C/N	–	$r^2 = 0.84$
Vityakon [57] ^d	C/N	–	$r^2 = -0.61$
Manguiat et al. [52] ^e , Arunrat et al. [65] ⁱ	Total N	+	$p < 0.01$
Samahadthai et al. [81] ^d	%N	+	$r^2 = 0.88$
Clermont–Dauphin et al. [85] ^d	CEC	+	$p < 0.05$
Islam et al. [63] ^g , Arunrat et al. [65] ⁱ	CEC	–	$p < 0.01$
Arunrat et al. [65] ⁱ	EC	+	$p < 0.01$
Islam et al. [63] ^g	pH	–	$p < 0.01$
Arunrat et al. [65] ⁱ	pH	+	$p < 0.01$
Islam et al. [63] ^g	%Exchangeable sodium (ESP)	–	$p < 0.01$
Islam et al. [63] ^g	Sodium adsorption ratio (SAR)	–	$p < 0.05$
Thuithaisong et al. [98] ^e	Microbial biomass	+	
Samahadthai et al. [81] ^d	OM diameter	+	$r^2 = 0.89$
Manguiat et al. [52] ^e	Soluble carbohydrates	+	

* OM = organic matter; CEC= cation exchange capacity (cmol kg^{-1}); EC = electrical conductivity (dS m^{-1}); ^d (0–15 cm soil depth), ^e (0–20 cm soil depth), ^f (0–25 cm soil depth), ^g (0–30 cm soil depth), ^h (0–36 cm soil depth), and ⁱ (0–40 cm soil depth).

5. Influence of Management Practices on Soil Organic Carbon and Rice Yield in Northeast Thailand

Rice production in NE Thailand is typically in the lowlands of rain-fed (rely on precipitation only) and irrigated (using both precipitation and irrigation water) areas [102]. Normally, the availability of water to support rice cultivation in NE Thailand depends on precipitation, except in the dry season, from May to October, when irrigation water is required [103]. Many studies have identified water management in NE Thailand, as shown in Table 3. According to the literature data, a single rice crop was mostly grown in the rainy season (monsoon), with yields ranging from 0.49 to 6.05 t ha⁻¹. In rainfed conditions, the soil dries in periods of poor rainfall, when the standing water disappears. In these drying conditions, rice was grown aerobically by draining the surface water. Suriya-Arunroj et al. [55] identified nutrient limits under different water conditions for growing rice. It was found that the nutrient omission response to the soil when in standing water disappears from the paddies. However, submerge conditions lead to chemical changes that noticeably stimulate SOC dynamics under O₂ limited conditions [19,104]. Via many processes of an oxidation-reduction reaction, SOC dynamics change soil pH, reduction of C, nitrogen (N), sulfur (S), and redox potential in a waterlogged rice field [105]. By these, the effect of flooding may influence the availability of SOC in terms of accelerating decomposition. Furthermore, some studies report that soil chemistry is different under varying irrigation conditions. In flooded paddies, the ferric iron (Fe²⁺) in soil solution is increased due to the intensity of the reduction reaction of the soil organic matter by anaerobiosis [59]. Meanwhile, the microbial biomass and activities are probably inhibited in highly saline conditions. Seto et al. [99] suggested that the availability of phosphorus (P) for rice growing in the rain-fed rice field, particularly sandy soil area, can be physically limited by mild soil drying. It was found that the uptake of phosphorus (P) under the rain-fed conditions was significantly lower than in flooded conditions [99]. The rain-fed condition inhibited the P diffusion into the rice's root surface with the effect of reducing P uptake. Therefore, fertilizers and additional nutrients applied to improve the rice yield are important for rice cultivation in some regions, especially in rain-fed paddies. From 89 literature data (Figures 5 and 6), a higher trend of SOC contents and rice yield were found in irrigated-paddy soils, while the ranges varied in different nutrient management practices. The nutrient management practices biochar application (BC), chemical fertilizer application (CF), no adding nutrient supplement (control), green manure application (GM), intercropping other plant with rice (IN), NPK fertilizer application (NPK), organic materials such as plants residues application (OM), and rice straw application (RS) were highlighted as soil amendment and nutrients supplies in rice-based cropping system. Among these management practices, combining biochar and chemical fertilizer led to the highest SOC (Figure 5) and rice yield (Figure 6) in irrigated areas. Biochar is known as a carbon-rich exogenous organic matter, and along with chemical fertilizer, it can enhance the rice plant biomass, when rice residues remain in the soil; thus, it could increase the SOC. Moreover, under anaerobic conditions in an irrigated area, it can also retain SOC. In rainfed areas, using biochar alone resulted in the highest SOC (Figure 5) and rice yield (Figure 6). In dry soils, biochar plays an important role by increasing water-holding capacity; then it can form the large-size aggregates in soil, increase large surface area of soil particles, and thereby increase the rate of SOC accumulation, finally resulting in increased rice production [21,25,65].

Table 3. Rice yield and alternative management practice of rice-based cropping under sandy soil conditions of Northeast Thailand.

Soil Type	Crop System	Rice Species	Treatment		Rice Yield (ton ha ⁻¹)	References
			Typical Practice	Alternative Practice		
Coarse-loamy, saline soil	Rain-fed paddy	RD6	Control	RS, manure	0.48–2.99	Supparattanapan et al. [87]
Loamy sand	Irrigated paddy	Pathum Thani 1	CF	BC, BC+CF, RS, RS+CF	2.46–6.05	Thammasom et al. [82]
Sandy loam	Rain-fed paddy	Pitsanulok 2	CF	BC, RS	6.25	Kumputa et al. [69]
Sand, sandy loam, loamy sand	Rain-fed paddy	KDML105, RD8	NPK	NPK+ GM	1.5–2.3	Nakamura and Matoh [51]
Loamy sand	Irrigated, Rain-fed paddy	KDML105, RD6, SPR 60	No GM	GM, NPK	1.29–3.78	Arunrat et al. [65]
Loamy sand	Rain-fed paddy, Rice-stylo	KDML105	No CF	CF, intercropping, GM	1.53–2.89	Homma et al. [45]
Sandy loam, fine sand, loamy fine sand	Rain-fed paddy	KDML105	Farmer practice	Mechanized dry direct-seeding, SSNM	2.50–2.58	Sansen et al. [100]
Loamy fine sand	Rain-fed paddy	KDML105	No CF, No stubble	CF, OM, stubble	1.9–2.8	Jermawattadipong et al. [97]
Infertile acid sandy soil	N/A	KDML105	No leaf litters, No stubble	Leave litters, stubble	1.545–2.7	Whitbread et al. [90]
Sandy silt	Rain-fed paddy	KDML105	No CF, No incorporate	CF, Incorporate	1.68–2.58	Mochizuki et al. [60]
Loam, sandy loam	Rain-fed paddy	KDML105	Control	CF, GM, RS	2.16–3.48	Thuithaisong et al. [98]
Sandy loam	Rain-fed paddy	RD6	RS burn	RI, RI+OM	4.0	Clermont-Dauphin et al. [85]

BC = biochar; RS = rice straw; CF = chemical fertilizer; SSNM = site-specific nutrient management, OM = organic material; RI = rice straw incorporation; GM = green manure; N/A = no data available.

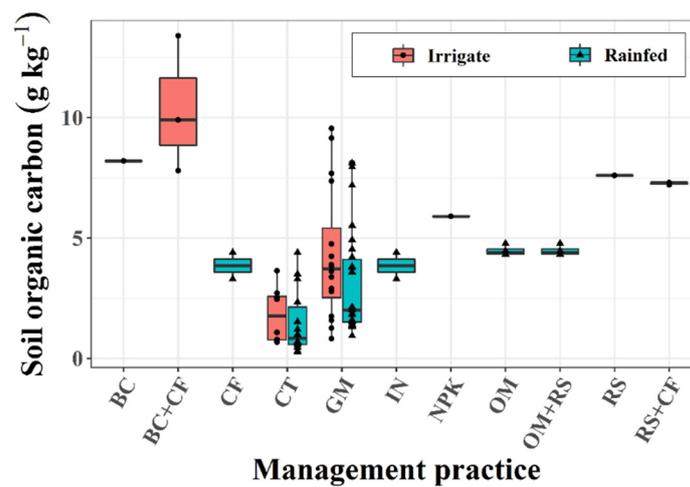


Figure 5. An overview of soil organic carbon in relation to management practice at the rice paddies of Northeast Thailand ($n = 89$) (within the range of 0–40 cm depth) [41,49–70]. * BC = biochar, CF = chemical fertilizer, CT = control, GM = green manure, IN = intercropping, NPK = nitrogen, phosphorus, and potassium fertilizers, OM = organic material, RS = rice straw.

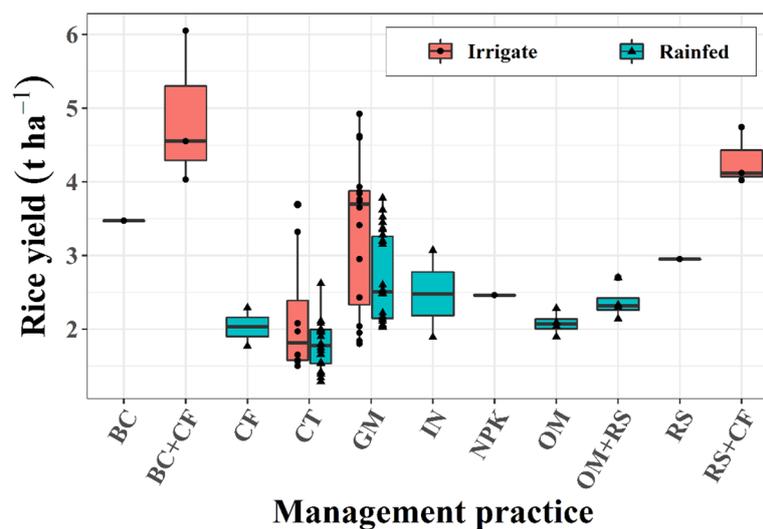


Figure 6. An overview of rice yield in relation to management practice at the rice paddies of Northeast Thailand ($n = 89$) (within the range of 0–40 cm depth) [41,49–70]. * BC = biochar, CF = chemical fertilizer, CT = control, GM = green manure, IN = intercropping, NPK = nitrogen, phosphorus, and potassium fertilizers, OM = organic material, RS = rice straw.

6. Tillage Management in Northeast Thailand

Moldboard plow or traditional plowing is the conventional tillage practice in South Asia, including Thailand. In rice production, the plow is used for the initial cultivation. During this operation, the soil seedbed recommended for rice is produced, whereby previous crop residues are incorporated, breaking soil aggregates are broken down, and SOM is exposed. However, reduced tillage or no-tillage has been suggested by many studies, to minimize SOC loss by erosion [16,106–108]. Less intensely disturbed soil under no-tillage tends to have higher aggregation, which positively relates to SOC accumulation [109]. Plowing to incorporate soil along with fertilization, in Thailand, is suggested for rice production practice [110]. Nevertheless, the alternative practice in the previous studies was rarely concerned about the effect of incorporation on SOC. Mochizuki et al. [60] showed that SOC and rice yield increased with the incorporated of chemical fertilizers or pond sediment. Their suggestion was demonstrated as the practical technique for increasing clay content and organo-mineral complexes to

improve the soil N, CEC, and stability of SOC (Table 3). Further research may be necessary to expand more information about the importance of soil incorporation in the rice cultivation system.

7. Crop Residue Management in Northeast Thailand

To increase crop yield and SOC sequestration in low-fertility soils, crop residue and other organic amendments can be added to the soil (Table 4). Studies have investigated the use of low-cost organic residues of varying quality as organic matter amendments to rice crops in NE Thailand. Many plant residues, including farmyard manure (FYM) such as rice straw, groundnut stover, dipterocarp, and tamarind, applied for soil amendment significantly increased SOC accumulation [53,56,66,81,90,92]. Because the organic material applied was associated with increased microbial biomass, the metabolic quotient (qCO_2), an important indicator of the effectiveness of residues to contribute to SOC buildup, tends to decrease during later stages of decomposition. In soil amendment improvement, the organic residues with sufficient N content, low cellulose content, and moderate amounts of lignin and polyphenols, such as tamarind residues, were found as the most effective [92]. Meanwhile, the high indigenous SOC content residue application tends to improve the dissolved organic carbon (DOC) composition in the soil. In contrast, the high cellulose residues with low amounts of lignin and polyphenols, likely from rice straw, may negatively affect SOC accumulation [66,69,92]. High cellulose composition in the rice straw leads to low-molecular-weight-DOC production, which has low adsorption affinity. Moreover, the quality and chemical composition of the applied organic residues tended to affect the long-term SOC accumulation, depending on the fraction of soil particles (soil texture), in which clay and silt particles play an important role. Decomposition resistance, organic matter, free existing particle organic matter (POM), and bonds in the soil matrix were partly consequences of SOC content. Vityakon et al. [56] stated that the C/N in plant residue application was negatively correlated to SOC in soil particle sizes smaller than 1 mm, due to the promotion of N mineralization for microbial decomposition. The products of decomposition and the C/N ratio of plant residues have positive effects on the soil aggregation [81]. On one hand, Naklang et al. [53] and Whitbread et al. [90] evaluated the results of leaf litter and rice stubble addition for SOC and rice yield improvement in the rain-fed paddies. Although it was found that the plant residue application was not significantly related to soil organic content, the residues act as a covering, slowly decomposing and protecting the soil surface from the environment. The application of biochar (BC) and rice straw (RS) in the soil led to SOC increases [82]. Biochar, a C-rich form of charcoal, increases the amounts of stable C components such as lignin and fixed-C in the soil, which slows down the microbial decomposition. Furthermore, the combined BC–RS material application in paddy soil has been found to be more beneficial in improving productivity and reducing GHG emissions [69]. The application of bentonite, volcanic ash locally quarried and used commercially in prawn farming, to significantly improve the structural stability of the soil, which relates to high water-holding capacity, has also been linked to the rate of SOC accumulation [94].

Table 4. Overview on correlation between soil characteristics (within the range of 0–40 cm depth) or rice yield with management practices of rice-based cropping under sandy soil condition of Northeast Thailand.

Management Practice	Soil Properties											Yield	References	
	P	N	K	C/N	Fe ²⁺	pH	EC	BD	CEC	WHC	LOC			SOC
Leaves litter	(+)*	(+)*	(+)*									(+)*	(+)*	Naklang et al. [53] ⁱ , Whitbread et al. [90] ⁱ
Stubble	(+)*	(+)*	(+)*									(+)		Naklang et al. [53] ⁱ , Whitbread et al. [90] ⁱ
Straw		(+)		(-)								(+)		Vityakon [57] ^d ; Puttaso et al. [92] ^d
Plant residues		(+)		(-)*										Vityakon [57] ^d ; Puttaso et al. [92] ^d
Organic matters application					(+)									Quantin et al. [59] ^e
Land elevation			(+)*			(+)*	(+)*							Clermont-Dauphin et al. [85] ^d
Incorporate (tillage)		(+)*							(+)**			(+)*		Mochizuki et al. [60] ^d
Bentonite										(+)*				Suzuki et al. [94] ^d
Relay-intercropping (3 years)												(+)*		Homma et al. [45] ^d
Biochar	(+)**	(+)**	(+)**					(-)	(+)**			(+)**	(+)	Thammasom et al. [82] ^d , Kumputa [69] ^d
Flooded condition		(+)**	(+)**		(+)									Quantin et al. [59] ^e , Seto et al. [99] ^e

* Significant difference at $p < 0.05$; ** significant difference at $p < 0.01$; BD = bulk density (g cm^{-3}); LOC = labile organic carbon (g kg^{-1}); SOC = soil organic carbon (g kg^{-1}); CEC = cation exchange capacity (cmol kg^{-1}); EC = Electrical conductivity ($\mu\text{S cm}^{-1}$); WHC = water-holding capacity (unit); rice yield (t ha^{-1}); ^d (0–15 cm soil depth), ^e (0–20 cm soil depth), ^f (0–25 cm soil depth), ^g (0–30 cm soil depth), ^h (0–36 cm soil depth), and ⁱ (0–40 cm soil depth).

8. Nutrient Management in Northeast Thailand

Nutrient management is the most important practice which contributes to rice production. In NE Thailand, many alternative management practices have been applied in rice production to maximize nutrient-use efficiency; N, P, K, C/N, and Fe^{2+} mainly come from crop residues and biochar (Table 4).

Variations in site-specific differences in soil fertility, irrigation, and rice variety were hypothesized as vital factors of inconsistent responses to fertilization in the NE Thailand region [54,111]. Chemical fertilization (CF) application is generally suggested for enhancing the rice grain yield. Nonetheless, NPK 40–12–10 kg ha^{-1} is the only existing uniform recommendation of nutrient management guidelines for all rain-fed lowland paddies in NE Thailand [111]. Haefele and Konboon [111] proposed a site-specific nutrient management approach based on toposequence and field-specific ingenious nutrient supply to choose the most optimum fertilizer for the farmers. The adoption of site-specific nutrient management combined with mechanized dry direct-seeding in the rainfed lowland area, as studied in Sansen et al. [100], shows high potential for decreasing the cost of rice cultivation. In sandy soils with a clay content below 5%, the response to inorganic fertilizer is often lower than in the finer texture soils [112]. However, the increase of SOC through nutrient management is still unclear. Thuithaisong et al. [98] found that the addition of neither green manure (GM) nor chemical fertilizer (CF) treatment could increase nutrient stocks in the soil sufficient to support rice production. Moreover, whether the plot had applied CF or organic materials, the essential macronutrients, such as NPK or SOM, as well as improvement in both total and plant available fractions, were also less than adequate for paddy soils (20 g kg^{-1}). Similarly, in the long-term, Clermont-Dauphin et al. [85] assessed on-farm organic matter management effect on responsible properties of soil. The various organic matter management did not result in differences in soil C content, pH, EC, exchangeable cations, or bulk density. In another study, Homma et al. [45] used the biomass of *Stylosanthes guianensis* as GM in the rain-fed lowland paddies, to support the relay-intercropping as the forage system. The SOC content of the relay-intercropping in the upper toposequence area was significantly increased after three years. However, it was not suggested as an effective practice, because the use of GM did not significantly increase the rice yield. An integrated nutrient-management strategy that uses organic materials, legume crops in rotation, and balanced application of chemical fertilizer can increase SOC and improve the sustainability of rice-based production systems.

9. Carbon Saturation for Sandy Soil in Northeast Thailand

In theory, the C saturation proposed by Hassink [34] mentioned that if the amount of SOC is below the maximum protective capacity level, adding organic matter to the soil will mostly increase SOC in clay plus silt fraction, until reaching the saturation level. The SOC will then accumulate in coarse size fractions [37].

For sandy soil in NE Thailand, the SOC in clay plus silt fraction (particle size $<20 \mu\text{m}$) varied tremendously, from 4.1% to 140.6% of the predicted C saturation (range 5.5–34.7 g C kg^{-1}) (Figure 7), while the C saturation deficit ranged from 0.05 to 23.0 g C kg^{-1} . The SOC of sandy soil of NE Thailand has accumulated about 52% in average of C saturation, indicating that this soil has potential for greater SOC sequestration. Hence, the challenge is how to promote C sequestration in the sandy soil of NE Thailand. Due to the physical structure of sandy soils, they have large pores (macropores: diameter $>0.08 \text{ mm}$) that expose the active SOC pool (turnover in months to few years) to more rapid microbial decomposition and accumulate slowly in passive SOC pools (turnover in 100 to >1000 years). As a result, any organic material inputs that are added to the topsoil of sandy soil are converted to the active SOC pool, and that is rapidly degraded into CO_2 and is respired back to the atmosphere [113,114]. Although adding more organic materials can increase more active SOC pool and release nutrients to the soil, it is not considered as carbon sequestration due to short turnover time [115]. Sanchez [116] indicated that apply the manure helps to improve soil fertility by increasing the active SOC pool, but it is unlikely to fill the C sequestration. In contrast, organic materials with high lignin and low nitrogen contents are recommended, because once those materials are decomposed, they will be sequestered

into the slow (turnover in 10 to 100 years) and passive SOC pools, and that helps to increase the SOC at the topsoil and fill the carbon saturation deficit. Wang et al. [117] found that, although returning rice straw was an effective practice to increase SOC in the short-term, it might not have effects in the long-term. Meanwhile, biochar application is recommended from various studies (e.g., rice straw biochar for paddy soil [118] because it is more resistant to microbial decomposition unless management practices change. In cultivated sandy soil like paddy field in NE Thailand, SOC is often lost due to tillage, crop residue removal, and fallow land after harvest; as a result, SOC is lower than the maximum protective capacity level.

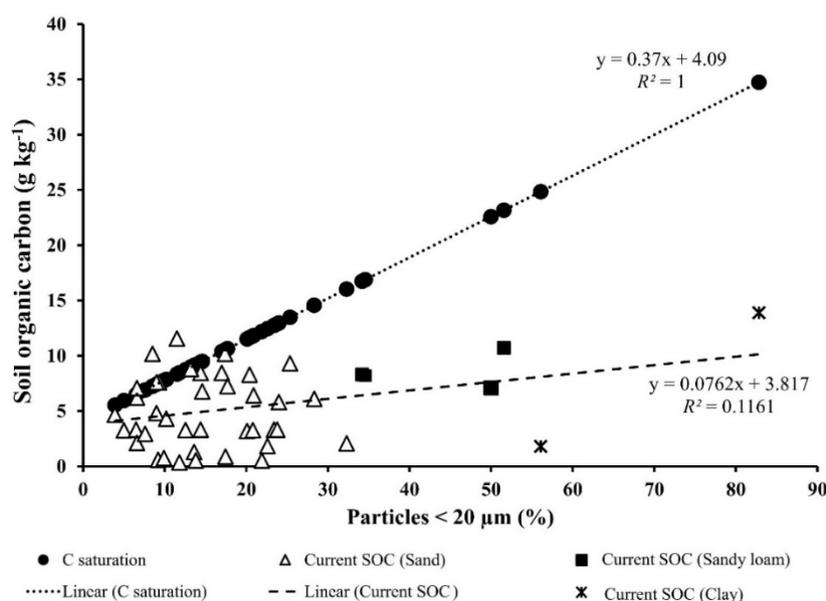


Figure 7. Relationship between C in the particle size fraction $> 20 \mu\text{m}$ (g kg^{-1} soil) and the percentage of particles $< 20 \mu\text{m}$ in sandy soil of Northeast Thailand ($n = 45$) (within the range of 0–40 cm depth) [45,50–52,54,57,61,63,65,66,68,69,81,82].

It should be noted that the equation of Hassink [34] was developed under the range of soils in temperate and tropical regions, which indicates that the predictive equation needs to be adjusted under the soil and climatic conditions in Thailand. More importantly, although the C saturation and deficit were roughly predicted in this review that can be guided for understanding how much C in sandy soil of NE Thailand can sequester, how fast it can be sequestered, and how long sequestration will arise after applying organic materials (e.g., manure, straw, and compost) are required for more research.

10. Challenges in Sustaining Soil Organic Carbon of Paddy Fields in Northeast Thailand

Even though the NE region is the largest rice cultivation area in Thailand that covers approximately 61.5% of the overall rice paddies area, in 2018, it was found to have the lowest rice crop yield, as 1.98 t ha^{-1} , while the average of the whole country was 2.62 t ha^{-1} [119]. In this review, we emphasize the linear correlation of SOC on rice production yield (Figure 8). By 89 reference observations, the results show that rice yield was significantly increased with SOC ($r^2 = 0.68$), indicating that increasing SOC content by 1 g kg^{-1} can increase rice yield by 302 kg ha^{-1} . However, the SOC examination in sandy paddy fields of more than 40 cm soil depth was still limited, which should be investigated in future research. Meanwhile, the SOC of paddy fields in NE Thailand was illustrated (Figure 9). The SOC account in NE Thailand paddy soil fluctuates with time. This reflects the instability of SOC in the sandy soil, which should cause concern. Patrick et al. [120] proposed important factors such as climate, topography, texture, and land-use management that are related to establishing SOC thresholds. Thresholds of SOC could be different in various specific sites, crops, and nutrient balances. Moreover, N fertilizer

addition was revealed as a key driver to critical SOC range for the production yield. To expand rice production in NE Thailand, SOC improvement under the inefficient conditions of sandy soil should be further upgraded through the farmer's management practices. Therefore, it is a challenge to indicate the critical SOC and N fertilizer level of the highest efficiency and optimal crop yield. Broader studies to provide appropriate improvements of SOC content, as far as its stabilization, will be beneficial for planning or decision making by farmers.

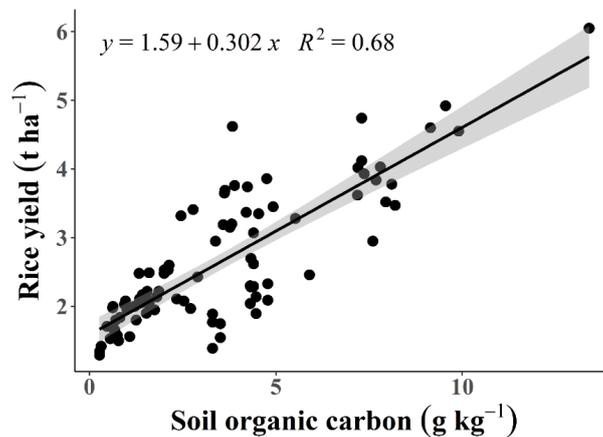


Figure 8. Correlation of soil organic carbon of rice-based system paddies and the production yield by reference observations in Northeast region, Thailand ($n = 89$) (within the range of 0–40 cm depth) [41,49–70].

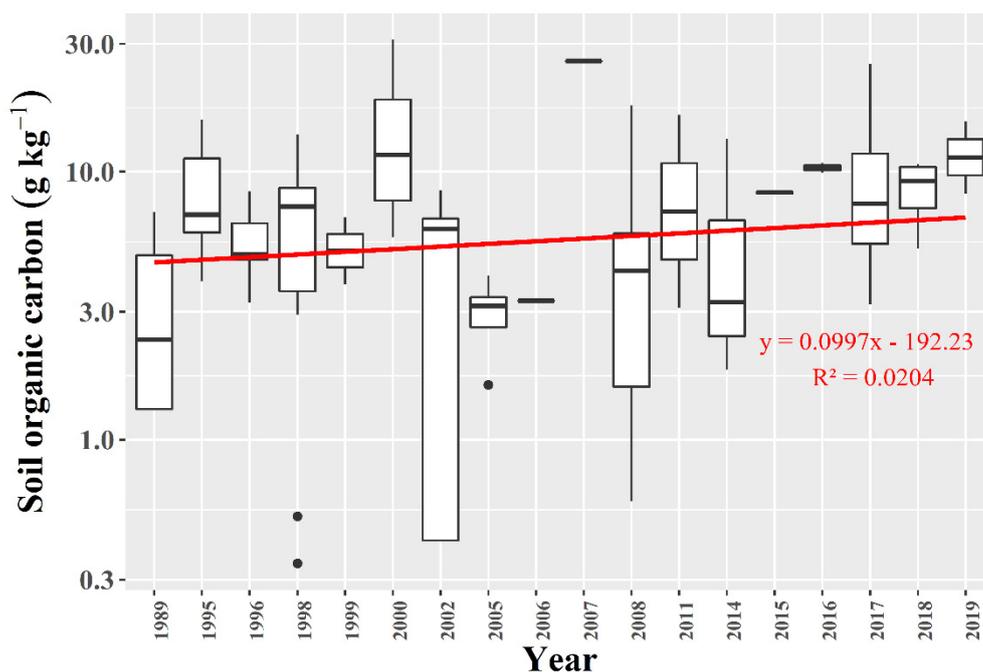


Figure 9. Overview on soil organic carbon (g kg^{-1}) observed data from 1989 to 2019 in Northeast Thailand ($n = 89$) (within the range of 0–40 cm depth) [41,49–70].

11. Conclusions

Conservation of SOC is a key strategy for rice cultivation for its potential roles in increasing soil fertility, nutrient balance, and crop productivity. The influences of undulating topography and wet–dry monsoon climate contributed to the harsh environmental conditions, as well as NE Thailand rice paddy fields being generally found as rain-fed areas with strongly sandy soil texture profile could be the

considerations for increasing rice productivity effectively. The low soil fertility of these soils is also described by low CEC and pH, which dynamically changed by exchangeable ions in the soil solution. The lack of irrigation water and the low precipitation in NE Thailand are the controlling factors which accelerate decomposition processes, resulting in large losses of SOC. Additionally, different management practices, such as tillage, crop residues, and fertilization, that are specifically used to increase soil fertility and rice yield production also influence SOC accumulation. It is notable from the previous work that SOC significantly enhances rice production in NE Thailand. Therefore, beyond the current rice production improvement strategies, SOC should be the key priority of management of rice paddies' soils due to maintaining the soil resilience and reducing GHG emissions. Determining the critical SOC level is the challenge of the optimal management practice in specific conditions, owing to rice production development. Moreover, further studies of the sandy soil in the agroecosystem of NE Thailand are still required to implement the active planning and management policy for the local life quality development, as far as future food security.

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