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Original research article

Depth Profiles of Soil Carbon Isotopes as Influenced by Crop Residues

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ABSTRACT

Soil organic carbon (SOC) is an important component for the sustainable maintenance of soil fertility. SOC supply to the cultivated soil may vary in each cover crop species which should be taken into account in the plant residues management. Studies have documented a strong relationship between decreased SOC and increased $\delta^{13}C$ with soil depth. Therefore, the present study investigated whether SOC is influenced by different crop residue amendment by determining $\delta^{13}C$ in soil profiles. Soil samples were collected during 2016-2018 from banana crop land, rice paddy with straw retention, and rice paddy with straw burning prior to crop rotation practice of Sunnhemp *(Crotalaria juncea* L*)*. Depth profiles of 0-3, 3-9, 9-12, 12-15, 15-18, 18-21, 21-24, 24-27, and 27-30 cm were determined on $\delta^{13}C$ for each sampling site. The $\delta^{13}C$ values ranged as follows -27.11‰ to -23.27‰ for banana plantation, -29.52‰ to -26.37‰ for rice straw retention, and -24.63‰ to -16.81‰ for rice straw burning prior to harvest of Sunnhemp, a legume rotation crop. These results indicate a strong relationship between the types of plant residues, including charred rice straw and its isotopic values. It is thus explained that $\delta^{13}C$ values of SOC will shift towards the $\delta^{13}C$ values of plant residues. Results revealed that $\delta^{13}C$ increased with soil depth due to the age of the biomass while SOC decreased. Further research should be conducted to determine the effect of crop residue incorporation with different soil textures, water contents, and climate conditions.

Keywords: Crop residue management; Cultivated soil; Soil organic carbon; Stable carbon isotopes

1. Introduction

The implications of land degradation, water resources scarcity and climate change will impact agriculture in different levels, ecological zones and production systems. Increased use of agro-chemicals has played a major role in the negative effects on agriculture's natural resource base, including land degradation, water resources contamination, build-up of pest resistance and the loss of biodiversity. As of previous studies, 33 % of the world's farmland is moderately to highly degraded. In general, land degradation is an impediment to

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realizing food security and reducing both economic and environmental terms. Growth in agricultural land degradation will be decelerating, partly owing to the improved performance of agricultural practices [1-2].

The most common practices to improve soil fertility are crop residue amendment instead of using chemical fertilizers, as well as crop rotations. Such practices provide essential nutrients to soil and improve other soil properties, such as water-holding capacity, nutrient-holding capacity and microbial activity of soil [3-5]. Generally, plant biomass (above and below ground residues) is the primary source of carbon input into soil organic carbon (SOC) which acts as basic elements of green agriculture. When biomass decomposes, it is incorporated into SOC, of which carbon is stored in soil for a long time. Whereas legume-based rotations have been shown to be an effective strategy for improving soil fertility, water use efficiency, minimizing plant diseases and other pest infestation, and improving the productivity of subsequent cereals [5]. Soil stable carbon isotopes ($\delta^{13}C$) values correspond closely to the $\delta^{13}C$ of plant residues entering the system through litter fall and residue amendment. Microbial composers use crop residues and lead to the isotope fractionation of initial $\delta^{13}C$ in plant residues. Also, initial plant $\delta^{13}C$ values are modified by biochemical compositions that comprise soil organic matter. Therefore, processes affecting soil $\delta^{13}C$ over time are carbon input vegetation and biological decay [6]. Several traditional methods are used to determine SOC; however, the methods are inconvenient, time consuming and generate toxic wastes [7]. Soil carbon isotopic signatures $\delta^{13}C$ are widely used in ecological research to investigate sources of SOC. The application of $\delta^{13}C$ to study the SOC has been indicated to be effective, rapid and reliable. Especially, as it is a method that does not use toxic reagents which will be ideal in view of current environmental concerns [8-9].

The relationship of SOC to land use activity and its distribution along soil profile are the important issues that could be useful for estimating mitigation potentials and sustainable agriculture. This present study measured depth trends of $\delta^{13}C$ from paddy fields and banana plantation to evaluate the effects of two different crop residues retention (banana and rice straw) and crop rotation (Sunnhemp; *Crotalaria juncea*, L.) on SOC levels and its distributions.

2. Materials and Methods

2.1 Study area

The study area is located at Bang Krathum district, Phitsanulok, Thailand. The area lies between 16°34′30″N and 100°17′60″E with average temperature 27.9^{0}C, relative humidity 73.2%, and annual rainfall of 1,324 mm/y (Fig. 1).

Fig. 1. Location of the study area.

Total area of Bang Krathum district is 447 km^2 and its topography consists of flat, fertile lowlands. The Köppen-Geiger climate classification is Aw. The majority of agricultural holdings (94.6%) use fertilizer. Of those who use fertilizer, 91.8% use a combination of chemical fertilizer, organic fertilizer (compost based on crop residues, leaves litter, and animal manure) and bio-fertilizer. Of this group, about 69.8%, used only chemical fertilizer while 1.6% used only organic fertilizer and 0.5% used only bio-fertilizer [10-11].

2.2 Sample collection

Three sites of banana crop land, continuous monoculture rice paddy with straw amendment, and rice paddy with straw burning prior to cropping rotation of Sunnhemp (*Crotalaria juncea* L.) were selected. Soil profiles were collected during 2016-2018 and taken randomly by plant root auger (Eijkelkamp, Netherland) according to the European standard procedure LUCAS [12]. Each sampling site was overlaid by a 20 x 20 m grid which was subdivided in 25 cells of 4 x 4 m.

Fifteen soil cores were sampled in 15 cells selected by a random process (Fig. 2).

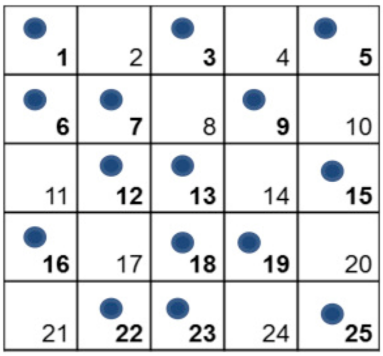

Fig. 2. Spots shown the 15 sampling cells.

The soil metallic cores of 8 cm diameter down to 30 cm depth were sliced at 3 cm intervals in the 0-3, 3-6, 6-12, 12-15, 15-18, 18-21, 21-24, 24-27, and 27-30 cm depths. Soil samples used for analysis were air dried and pulverized in an agate stone mortar and pestle (Mixer Mill RM 200, Retsh Germany). The samples were sieved through a 125 micron mesh sieve and stored in sealed plastic bags. A precisely weighted soil sample of 2 mg was transferred into 3.3 x 5 mm tin capsules.

2.3 Carbon isotopes analysis

Carbon isotope ratios ($^{13}C/^{12}C$) of the samples ($^{13}C/^{12}C$ sample) were determined using a Cavity Ring-Down Spectrometer Analyser Picarro model G2131-i (Picarro, USA). The precision of the instrument including sample preparation and analysis is better than 0.1‰. Periodic replicates were run, and internal standards were interspersed with every 10th sample. Average standard deviation for $\delta^{13}C$ of unknowns was 0.04‰.

The natural abundance of ^{13}C ($\delta^{13}C$, ‰ per mil), which is the ratio of $^{13}C/^{12}C$ based on international Vienna-Pee Dee Belemnite (V-PDB) standard was determined using the equation 1 [8]:

$$\delta^{13}C = \left(\frac{(^{13}C/^{12}C)\ sample}{(^{13}C/^{12}C)\ V-PDB} - 1\right) x\ 1000 \qquad (1)$$

2.4 Statistical analysis

One-way analysis of variance (ANOVA) was applied to determine the differences in $\delta^{13}C$ among soil samples at the level of 95%. Statistical analyses were performed using GraphPad Prism V.8 (GraphPad Software, Inc., La Jolla, California, USA). A probability of 0.05 ($p > 0.05$) was considered as significant in testing the null hypothesis of no differences in $\delta^{13}C$.

3. Results and Discussion

In soil of the three sites, the greater $\delta^{13}C$ values reported in this study were found in the surface layer (0-5cm) and gradually increased isotopic values along the profile. There was significant decrease in the amount of ^{13}C in the profile between layers 0-3, 3-6, 6-12, 12-15, 15-18, 18-21, 21-24, 24-27, and 27-30 cm, and this was reflected in the carbon values derived from crop residues and charred stubble. Banana plantation with crop residues retention exhibit isotopic carbon values ranging from -27.11‰ to -23.27‰ while continuous monoculture rice-fallow with rice straw amendment presented values of -29.52‰ to -26.37‰. The $\delta^{13}C$ values of rice-Sunn hemp *(Crotalaria juncea* L.*)* rotation with rice straw burning and Sunnhemp residues incorporated in soil after harvest were -24.63‰ to -16.81‰. It was observed that microbial composers used the new resource pathway provided by the addition of crop residues. These were revealed by decreased $\delta^{13}C$ values ($^{13}C/^{12}C$) in the crop residue treatment of rice straw compared with that of banana and legume.

Values found in this study were consistent with what is reported in the literatures wherein photosynthetic cycle C3 plant tissues (rice, wheat, banana, legume) exhibit lower $\delta^{13}C$ values ranging from -20.0 to -32.0‰, averaging -27.0‰, while the $\delta^{13}C$ values of C4 species (sugarcane, Sorghum, maize and grass) are larger, ranging from -9.0‰ to -17.0‰, with an average of -13.0‰. Variations of the $\delta^{13}C$ values of C3 biomass within this range are controlled by species, soil water deficit, irradiance, latitude and altitude, topographic location, and the degree of re-utilization of respired CO_2, including plant organ tissues [5, 6, 8, 9]. In the case of banana plantation, the banana tree was grubbed out at harvest, and pseudo-stems and roots of banana residues were returned to the banana crop field. While in the paddy field, rice stubble was taken out and only rice straw was amended. In the rice-Sunnhemp rotation, above and below ground plant parts of all Sunnhemp were harvested and fragmented into small pieces and incorporated into soil. The enriched $\delta^{13}C$ observed in the crop rotation paddy field and in banana soil can be explained that mixing between above- and below-ground biomass sources of carbon can also generate profile enrichment because root biomass is, on average, enriched in ^{13}C relative to aboveground biomass [13-14].

The results show that $\delta^{13}C$ in all the study soils become enriched with depth which was consistent with the typical trends observed in the previous studies [15-17]. It is noted that there was an overall similarity pattern in the vertical distribution in the $\delta^{13}C$ value of SOC among the banana residues incorporation, mono culture rice-fallow with straw retention, and rice-legume based Sunnhemp rotation (rice straw-stubble in-situ burning land).

Some authors indicated that the values of the $\delta^{13}C$ increased with soil depth due to the age of the SOC and to selective decomposition processes in which isotopically light carbon (^{12}C) is degraded first resulting in loss of ^{12}C atoms from the soil. The depletion of $\delta^{13}C$ in the topsoil (with newer crop residues) reflected the trend of $\delta^{13}C$ in the atmospheric CO_2. The enrichment of $\delta^{13}C$ in the subsoil (with older SOC) might be partly caused by the isotopic fractionation during SOC decomposition [5-6, 8-9, 13-17]. In fact, Wedin et al. [18] found that root litter can be more $\delta^{13}C$ enriched than leaves from the same plant with a maximum total difference of about 1.5‰. The $\delta^{13}C$ of root material is generally higher than that of above ground biomass, such as leaves, and so the $\delta^{13}C$ of SOC at the soil surface may be lower than deep soils. Because microbes, invertebrates, and other soil fauna are typically enriched in $\delta^{13}C$ compared to source-substrates, biological migration and physical mixing of soils may alter relationships between soil carbon concentrations and $\delta^{13}C$. Recent studies provide evidence confirming that soil $\delta^{13}C$ generally increases from shallow to deep mineral soils in relatively well-drained systems, concomitant with decreasing SOC concentrations. Therefore, SOC $\delta^{13}C$ tends to increase with depth along vertical soil profiles until it reaches a maximum value at which point a steady state is achieved or without input of fresh biomass. These trends result in a negative linear relationship between the log-transformed plot of SOC concentration and soil $\delta^{13}C$ [19].

Based on the values of soil $\delta^{13}C$, the incorporation of rice straw reflected the highest SOC followed by the banana residues, and among the residues, the straw burning-legume system led to the lowest

SOC content. This was partly due to the fact that the amount of carbon added in the straw burning-legume system was the lowest. Storage of SOC is a balance between carbon additions from non-harvested portions of crops including organic amendments, and carbon losses, primarily through organic matter decomposition and release of respired CO_2 to the atmosphere. Plant materials are basically composed of similar components, but differ in their proportions which influence the decomposition of residues. The quality of residues depends on the plant species. This observation shows that differences in residue quality (cellulose, lignin content) was likely to influence the level of carbon accumulation in soils. Increases in SOC were negatively correlated with cellulose content of residues and microbial respiration losses (CO_2-C) [19]. Sunnhemp had the highest cellulose content, which is a relatively labile carbon compound and is readily decomposed (i.e., high respiration losses) by a wide range of microorganisms. Low lignin and high cellulose content of Sunnhemp are crucial characteristics associated with the lack of resistance and stabilization of organic carbon (Table 1).

Table 1. Composition of untreated rice straw, banana stem-leaves and Sunnhemp expressed as percentage content on a dry weight basis [20-22].

	Percentage (%)			
Biomass	Cellulose	Hemi Cellulose	Lignin	Ash
Straw	32.1	28	19.6	11.3
Banana	39.1	72.7	8.9	8.2
Sunnhemp	78.4-81.7	5.7-6.4	10-13	0.3

Statistical analyses shown that the $\delta^{13}C$ value of SOC was significantly affected by site and depth ($p \leq 0.05$). This indicated that changes in isotopic signals were directly related to the type of vegetation contributing plant residues to the soil (Table 2). Apart from the quality of residues among rice straw, banana and Sunnhemp, the decomposition process of microbial in soil may affect the retention time [15]. In addition, charcoal in the rice straw burning site causes soil compaction and acidic soil which affected microbial activities and consequently lower SOC [23].

Table 2. Significant level from the analysis of variance from the main effects of crop residues retention.

Source of variation	$\delta^{13}C$	Depth	pH	Bulk density
Straw	***	***	**	**
Banana	***	**	**	**
Sunnhemp	***	***	***	***

where *, **, *** represent probability of > 0.05. ≤ 0.05, and ≤ 0.001.

Crop residue amendment to soil is documented as an effective measure to increase SOC and improve soil productivity. Crop retention and incorporation in to the soil is an essential management practice to handle residue; it plays a vital role in improving SOC sequestration including soil physical and chemical properties [2, 5]. Although most of the crop straw residues are burned to save time and labor, this study revealed that legume based Sunnhemp rotation with Sunnhemp residues incorporated in soil resulted in enhanced SOC.

Rice straw burnt by farmers annually during October-November leads to air pollution (particulates and green-house gases), respiratory problems, increase in the incidence of fog even in distant cities, and loss of soil nutrients. The burning of crop residue also affects human and animal health both medically, and by traumatic road accidents due to restricted visibility [24]. The results found in this study can be a strategy for maintaining or increasing SOC by either sufficient biomass carbon input or crop rotations. Crop residues amendment and forage-based rotations (groundnut legumes or Sunnhemp) not only stabilize soil but also increase SOC. However, the application of rice straw composting with effective microorganisms (EM) and manures is suitable to increase the N, P, and

K in the composting process [25]. The effect of cover crops on SOC is mostly an input-driven effect because they provide an additional source of aboveground and belowground crop residue carbon entering the soil [24-27].

Although the effects of crop residues and legume-rotation on SOC changes at the field scale are shown in this study, the variations between individual sites are large and the underlying mechanisms for these differences requires more focus in future research.

4. Conclusion

Crop residue retention and crop rotation are considered as a dual solution to improve soil quality and crop productivity through suppressing pests and avoiding pathogen infection. Legume-based cropping systems not only increase grain yields, but also improve soil fertility through SOC, and biological N2-fixation of legume plants. In this study, a $\delta^{13}C$ enrichment trend with depth was observed in all the studied soils which indicated more enriched older SOC at depth and more depleted recent SOC at the surface. The application of the ^{13}C technique indicated that changes in isotopic signals were directly related to the type of vegetation contributing plant residues to the soil. The observations revealed that rice straw retention provided the highest SOC followed by banana residues and straw burning-Sunnhemp rotation.

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References

[1] Peterson BJ, Fry B. Stable isotopes in ecosystem studies. Annu Rev Ecol Evol Syst 1987;18:293-320.

[2] Food and Agriculture Organization (FAO). The future of food and agriculture - trends and challenges. Rome: ISBN 978-92-5-109551-5; 2017. p. 180.

[3] Gross CD, Harrison RB. The case for digging deeper: soil organic carbon storage, dynamics, and controls in our changing world. Soil Syst 2019;3(28):1-24.

[4] Novara A, Rühl J, Mantia TL, Gristina L, Bella SL, Tuttolomondo T. Litter contribution to soil organic carbon in the processes of agriculture abandon. Solid Earth 2015;6:425-32.

[5] Li J, Liu K, Zhang J, Huang L, Coulter JA, Woodburn T, Li L, Gan Y. Soil-plant indices help explain legume response to crop rotation in a semiarid environment. Front Plant Sci 2018;9:871-83.

[6] Bai E, Boutton TW, Liu F, Wu XB, Hallmark CT, Archer SR. Spatial variation of soil $\delta^{13}C$ and its relation to carbon input and soil texture in a subtropical lowland woodland. Soil Biol Biochem 2012;44:102-12.

[7] Roper WR, Osmond DL, Heitman JL. Comparing four methods of measuring soil organic matter in north carolina soils. Soil Sci Soc Am J 2019;83:466-74.

[8] Zagal E, Munoz C, Espinoza S, Campos J. Soil profile distribution of total C content and natural abundance of ^{13}C in two volcanic soils subjected to crop residue burning versus crop residue retention. Acta Agr Scand B-S P 2012;62:263-72.

[9] Acton P, Fox J, Campbell E, Rowe H, Wilkinson M. Carbon isotopes for estimating soil decomposition and physical mixing in well-drained forest soils. J Geophys Res Biogeosci 2013;118:1532-45.

[10] Wikipedia. Bang krathum district [Internet]. [Cited 2020 Jan 3]. Available from:https://en.wikipedia.org/wiki/Bang_Krathum_District

[11] Agricultural Census Changwat Phitsa nulok 2013. National Statistical Office. Phitsanulok Provincial Statistical Office 2014, p. 158

[12] Tóth G, Jones A, Montanarella L (eds.). LUCAS topsoil survey. Luxembourg: Publications Office of the European Union; 2013.

[13] Severo FF, Aita NT, Marques LG, Souza da Silva L. Isotopic abundance of ^{13}C and contribution of eucalyptus biomass to soil organic matter conversion. Soil Sci 2017; 47(4):1-7.

[14] Diochon A, Kellman L. Natural abundance measurements of ^{13}C indicate increased deep soil carbon mineralization after forest disturbance. Geophys Res Let 2008;35(14):1-5.

[15] Wang J, Wang X, Xu M, Feng G, Zhang W, Yang X, Huang S. Contributions of wheat and maize residues to soil organic carbon under long-term rotation in north China. Sci Rep 2015;5:11409.

[16] Wang G, Jia Y, Li W. Effects of environmental and biotic factors on carbon isotopic fractionation during decomposition of soil organic matter. Sci Rep 2015;5:11043.

[17] Bostro B, Comtedt D, Ekblad A. Isotope fractionation and ^{13}C enrichment in soil profiles during the decomposition of soil organic matters. Oecologia 2007;153:89.

[18] Chen X, Hu Y, Feng S, Rui Y, Zhang Z, He H, He X, Ge T, Wu J, Su Y. Lignin and cellulose dynamics with straw incorporation in two contrasting cropping soils. Sci Rep 2018;8:1633.

[19] Wang C, Houlton BZ, Liu D, Hou J, Cheng W, Bai E. Stable isotopic constraints on global soil organic carbon turnover. Biogeosci 2018;15:987.

[20] Shawky BT, Mahmoud MG, Ghazy EA, Asker MMS, Ibrahim GS. Enzymatic hydrolysis of rice straw and corn stalks for mono sugars production. J Genet Eng Biotechnol 2011;9:59.

[21] Li K, Fu S, Zhan H, Zhan Y, Lucia LA. Analysis of the chemical composition and morphological structure of banana pseudostem. BioRes 2010;5(2):576.

[22] Liu M, Thygesena A, Summerscalesb J, Meyera AS. Targeted pre-treatment of hemp bast fibres for optimal performance in bio composite materials: A review. Ind Crops Prod 2017;108:660-83.

[23] Philippsen B, Olsen J, Sørensen SA, Måge B. δ13C values of wood and charcoal reveal broad isotopic ranges at the base of the food web. Radiocarbon 2019;61(6):2003.

[24] Kumari R, Singh R, Kumar N. Effect of crop residue management on soil organic carbon, soil organic matter and crop yield: An overview. J Nat Appl Sci 2019;11(3):712.

[25] Jusoh MLC, Manaf LA, Latiff PA. Composting of rice straw with effective microorganisms (EM) and its influence on compost quality. Iran J Environ Health Sci Eng 2013;10(17):1.

[26] Blanco-Canqui H, Shapiro CA, Wortmann CS, Drijber RA, Mamo M, Shaver TM, Ferguson RB. Soil organic carbon: The value to soil properties. J Soil Water Conserv 2013;68(5):129A.

[27] Bolinder MA, Crotty F, Elsen A, Frac M, Kismányoky T, Lipiec J, Tits M, Tóth Z, Kätterer T. The effect of crop residues,

cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. Mitig Adapt Strateg Glob Change 2020;25:929.