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Soil Organic Carbon Stock in Restored and Natural Forests in Northern Thailand

Nuttira Kavinchan[1], *Prasit Wangpakapattanawong*[1, 2,] *, *Stephen Elliott*[3], *Sutthathorn Chairuangsri*[3] *and Jitti Pinthong*[4]

[1]*Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*
[2]*World Agroforestry Centre (ICRAF) c/o Knowledge Support Center for the Greater Mekong Sub-region (KSC-GMS), Faculty of Social Sciences, Chiang Mai University, P.O. Box 267, CMU Post Office, Chiang Mai 50202, Thailand*
[2]*Forest Restoration Research Unit (FORRU), Biology Department, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*
[4]*Adjunct Professor, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*
**Corresponding author: Prasitwang@yahoo.com*

Abstract

In order to increase understanding of the role that tropical forest restoration might play in mitigating global climate change, soil organic carbon (SOC) was determined in a chrono-sequence of plots in northern Thailand; from a site undergoing unassisted natural forest regeneration (control); through 3 sites undergoing forest restoration by the framework species method, aged 2, 7 and 11 years since tree planting (R2, R7, R11); to a nearby area of relatively intact forest (NF). Forest restoration greatly increased SOC stocks compared with pre-restoration data, predicting a return to NF levels in less than 21.5 years after commencement of restoration activities. However, SOC stocks, measured in soil pits dug down to 2 m depth, did not increase in sequence with forest development, as expected: control 205.8 $tCha^{-1}$; R2, 254.4; R7, 251.1; R11, 161.8 and NF, 244.9. The incongruously low SOC in the 11 year-old restoration plot might be explained by the persistent, overriding, effects of land use history reducing SOC in the lower soil layers. Per cent organic carbon declined with soil depth, following reliable power functions (R^2 0.92-0.97): $\%SOC=k.DEPTH^p$ (k=7.7 to 22.2; p=-0.41 to -0.80). Comparison with other studies showed that forest restoration by the framework species method sequestered more soil carbon than monoculture plantations in the same region.

Keywords: *Chiang Mai*, *Climate change*, *Forest restoration*, *FORRU*, *Framework species method*

1. Introduction

The rapid increase in atmospheric CO_2, in the recent decades, and its effects on global climate change are well documented. The UN has recognized the substantial role that forest restoration could play in helping to reduce atmospheric CO_2 by including "enhancement of carbon stocks" within REDD++ ("Reduce Emissions from Deforestation and Forest Degradation": a set of policies and incentives being developed under the UN Framework Convention on Climate Change) . Forest restoration on degraded land substantially increases the carbon sequestered per unit area, both in the vegetation and in the soil (1) In Thailand, research on carbon sequestration by mature forests (2) and plantations (2, 3) has tended to focus on above-ground carbon. Little attention has been paid to the potential for forest ecosystem restoration to sequester carbon, particularly in the soil. Furthermore, soil organic matter (SOM) is a major contributor to the soil nutrient pool, required for maintaining soil fertility, plant growth and ultimately the capacity for forest regeneration. So, an increased understanding of SOM accumulation can ultimately lead to better forest restoration strategies.

Consequently, the research reported below focused on soil organic carbon (SOC) in forest restoration plots, established by the framework species method. This method was successfully developed to restore forest on degraded areas within Queensland's Wet Tropics World Heritage Site in Australia, using selected native tree species (4). In 1994, Forest Restoration Research Unit (FORRU) of Chiang Mai University started to investigate the possibility of restoring forests on degraded sites in northern Thailand, by adapting the technique to local conditions. The framework species method rapidly increases forest biomass and structural complexity, creating a variety of niches that accelerate biodiversity recovery, which enhances species interactions, leading to increased ecological functioning (e.g. pollination, seed dispersal, nutrient cycling etc.). The method involves planting mixtures of 20–30 pioneer and climax native tree species. Essential characteristics of framework species are: (i) high survival and growth rates when saplings are planted in open degraded site; (ii) dense, spreading crowns that shade out herbaceous weeds and (iii) provision of resources that attract seed-dispersing wildlife (e.g. fruits, nectar, nesting sites etc.) at a young age (1). The objectives of the research, reported here were i) to determine how soil carbon stocks change as forest development proceeds during restoration and ii) to investigate how soil organic carbon varies with soil depth.

2. Materials and methods

2.1 Study site

The study was carried out in a field trial plot system, set up to test the framework species method of forest restoration in the Upper Mae Sa Valley (18' 52^0N, 98' 51^0E, 1,207 – 1,310 m elevation) of Doi Suthep-Pui National Park (5). The study site was about 3-4 km from the large Hmong hill tribe community of Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province. Plots had been established annually, every rainy season since 1997, ranging in size from 1.4 to 3.2 ha y^{-1} and planted with varied combinations of 20 - 30 candidate framework tree species. The area had originally been covered with evergreen forest, which had been cleared approximately 30 years previously, to provide agricultural land.

Most of the study plots had previously been used for the cultivation of cabbages and carrots, prior to tree planting.

Study plots were selected in i) a control plot (not planted with trees) undergoing natural forest regeneration since 1997; ii) restoration trial plots of 3 different ages, since being planted with saplings of various mixtures of native tree species, being tested for their propensity to match the framework species criteria listed above (so-called "candidate framework species"): two years old (R2), 7 years old (R7) and 11 years old (R11) at the start of the study (planted in 2007, 2002, and 1998 respectively) and iii) in disturbed primary forest nearby (NF).

The control site was dominated by tall grasses: *Thysanolaena latifolia*, *Phragmites vallatoria* and *Imperata cylindrical* (6).

Restoration plots had been cleared of weeds by slashing and spraying with glyphosate, before being planted with saplings (30-50 cm tall) of 20-30 native forest tree species, grown from locally collected seed in local tree nurseries in 9 x 2½" polybags, in forest soil mixed with organic matter (50:50). Saplings were planted randomly across the plots, averaging 1.8 m apart (3,100/ha). Various fertilizer, mulching and weeding regimes were applied as experimental treatments during the first two rainy seasons after planting. Fire breaks were cut every January and fire prevention patrols worked throughout the dry season (1) .

Study plots were also located in degraded primary forest, east of Ban Mae Sa Mai representing the least disturbed forest in the vicinity. Although the forest had never been clear cut, it had been disturbed by local villagers, including selective tree felling for construction, fire wood collection and clearance of small patches for opium cultivation about 40-50 years previously. This "community" forest had been protected from disturbance for at least 20 years by local rules, enforced by the village environment committee. Situated at 1,300 m a.s.l., this forest was dominated by trees and seedlings of *Castanopsis diversifolia* (Fagaceae) (7). Throughout the paper, it is referred to as "natural forest" (NF) to distinguish it from "restored forest" (the "R" plots).

Tree densities in the R2, R7, R11 and NF plots were approximately 1,669 saplings/ha 1,400, 1,800, and 1,194 trees/ha, respectively (7).

The bedrock is mostly migmatite (87% of the area) of the Palaeozoic era with some Precambrian paragneiss (13% of the area).

Petrography of the area consists of 87% migmatites from Palaeozoic granites and 13% Precambrain paragneiss (8).

Soils are mostly Acrisols and Cambisols (9).

2.2 Soil sampling and soil organic carbon measurement

Soil samples were taken from pits dug down to a depth of 2 m. Soil samples of approximately 500 gm were collected by means of a soil auger oil auger at 4 points in each soil layer, at the following depths: 0 – 5, 5 – 10, 10 – 20, 20 – 30, 30 – 40, 40 – 60, 60 – 80, 80 – 100, 100 – 150 and 150 – 200 cm (10) in July, 2012. The 4 samples from each depth layer were bulked and 3 sub-samples removed for analysis. Organic matter was determined using the Walkley-Black method (11). A Van Bemmelen value of 0.58 was used to convert soil organic matter to soil organic carbon (12). Soil texture was determined using the hydrometer method (13). Soil organic carbon stock at depths ranging from 0 to 200 cm were calculated by the formula:

Soil organic carbon stock = OC (g/100g) x soil bulk density (g cm^{-3}) x soil depth (cm) (tC/ha)

Pre-restoration soil carbon data for the study site were obtained (14) for 16 samples collected in 1997 (1 year before tree planting commenced) across the area, which subsequently became the R11 and C plots in this study. Pre-restoration samples had only been taken from 0-15 cm depth (14) so comparison with the data collected during the current study was only carried out for this limited depth range.

2.3 Statistical analysis

Soil carbon data were analyzed for differences among the study sites, using one-way ANOVA (15). Tukey's test was used, in conjunction with ANOVA, to determine significant differences among means. The relationship between per cent organic carbon and depth was determined by curve fitting, using the Analysis ToolPak in Microsoft Excel.

3. Results and discussion

3.1 Increase in soil carbon over time

Eleven years of forest restoration significantly increased mean SOC levels by 30%, in the upper soil layer (0-15cm, $p<0.05$) compared with pre-restoration levels (14), although levels remained significantly lower than in natural forest (by about 22%, $p<0.05$, Table 1). SOC also increased in the non-planted control plots, but not significantly so.

If SOC in the R11 plot continues to accumulate at the same rate, it would return to NF levels within another 10.5 years, predicting full recovery of SOC in upper soil layers to natural forest levels within 21.5 years after commencement of forest restoration. However, it is likely that accumulation of SOC will accelerate and a return to NF levels will be achieved sooner. Our previous paper reported inputs of carbon into the soil via leaf litter of 0.81 tC/ha/y for the R11 plots and predicted a return to NF levels of litter carbon inputs by about 15 years after commencement of forest restoration (16). Since the input rate of litter carbon into the soil rose more sharply as restoration increased forest biomass and productivity, natural forest levels of SOC may actually be achieved much sooner than 21.5 years.

Table 1. Pre-restoration levels of soil organic matter (SOM) and soil organic carbon (SOC) (means ±SD, 0-15 cm depth) compared with the non-planted control, R11 and NF plots, 11 years after commencement of forest restoration

Soil property	Site			
	Pre-restoration in 1997 (14) (N = 16)	Control (this study) (N = 6)	11-year-old restoration (this study) (N = 6)	Natural forest (this study) (N = 6)
SOM (%)	5.35 ± 1.00 c	6.69 + 0.73 bc	6.93 ± 1.45 b	8.45 ± 0.21 a
SOC (%)	3.10 ± 0.58 c	3.88+ 0.42 bc	4.02 ± 0.84 b	4.90 ± 0.12 a

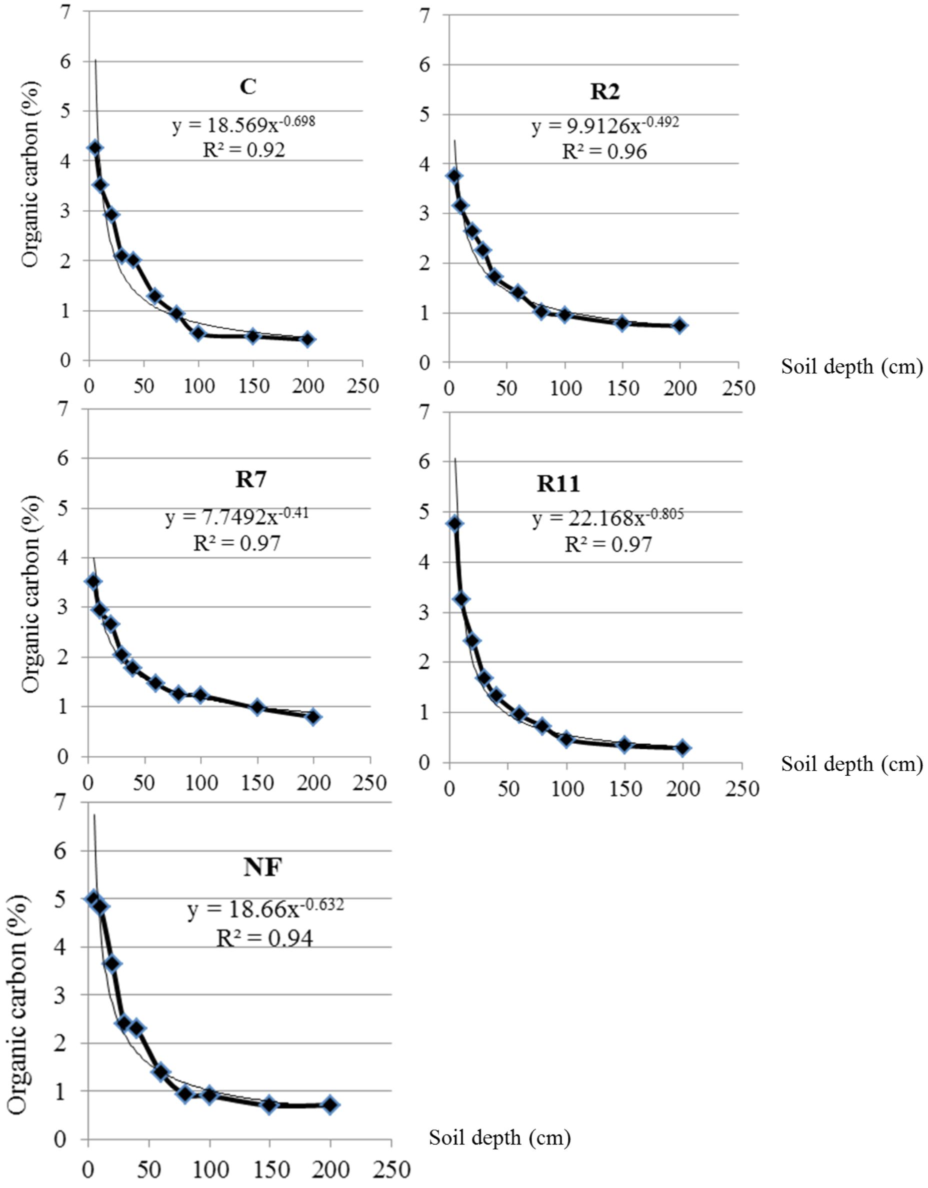
Values in rows not sharing the same superscript are significantly different (p < 0.05).

3.2 Relationship between %SOC and soil depth

%SOC (derived by multiplying % organic matter content by 0.58 (12)) declined sharply with increasing soil depth, through the upper soil layers, and less steeply lower down, closely following a simple power function (Figure 1):

$$\%SOC = k.DEPTH^{p}$$

… where depth is measured in cm and k and p are coefficients which vary for each site. k varied from 7.75 (R7) to 22.17 (R11), whereas p varied from -0.410 (R7) to -0.805 (R11). The coefficients of determination (R^2) for these relationships were very high (from 0.92 (control) to 0.97 (R7 and R11).



Figures 1. a – e Soil organic carbon at different depth at each study site (C = Control, R2 = 2007 plot, R7 = 2002 plot, R11 = 1998 plot, NF = Natural Forest)

This means that once k and p have been determined from measurements in upper soil layers %SOC can be reliably predicted down to a depth of 2 m. Most surveys estimate soil carbon stocks down to only 30 cm (17), the depth recommended by the International Panel on Climate Change.

A quick glance at the area beneath the curves in Fig 1 shows that such shallow measurements capture less than half of total SOC and would grossly underestimate the contribution that forest restoration could make towards mitigating global climate change. The power function appears to be a rapid, reliable way to estimate SOC down to 2 m, using easy-to-collect samples from the upper soil layers.

3.3 Effects of restoration on soil organic carbon stocks

Fig 1 shows significantly lower %SOC in the upper-most soil layers in the younger forest restoration plots (Fig 1b & c) compared with the control (Fig 1a). This may be explained by removal of herbaceous weeds (by weeding during the first 2-3 years following tree planting) and the relatively low biomass and productivity of the younger forest stages. This explanation is supported by our previous report of an initial decrease in inputs of organic matter into the upper soil layers, at the start of forest restoration activities in the R2 and R7 plots, (0.13 and 0.40 tC/ha/y respectively, compared with 0.51 for the control) (16). In contrast, %SOC had increased in the upper-most soil layers of the R11 pit, substantially above that of the control pit and closely approached NF levels. This was due to the higher biomass and productivity of the older restored plots, resulting in a previously reported, relatively higher, input of litter carbon into the soil of 0.81 tC/ha/y (16).

Looking at the lower soil layers (100-200 cm depth, Fig 1), we found that, %SOC levels in the control, R2 and R7 pits were similar to those in the NF pit, but in the R11 pit, it was much lower. Since SOC in lower soil layers responds slowly to land use changes, %SOC levels reflect a legacy from the previous land use. It may be that the R11 plots had been deforested and cultivated for much longer than the other plots, resulting in large carbon losses Furthermore, increased carbon inputs from forest restoration into the upper soil layers had not yet filtered down through the soil profile to 2 m depth. However, we could not obtain sufficiently reliable and detailed historical land-use information from the villagers to verify this explanation.

The anomalously low %SOC in the lower soil layers of the R11 pit meant that total soil organic carbon stocks, over the full 2 m depth, did not increase smoothly with forest development, as expected (Table 2). R2 and R7 *did* accumulate significantly more total SOC stock than the control (+24% and +22% respectively, $p<0.05$), with mean values slightly higher those in NF (but not significantly so). However, the R11 plot had significantly lower total SOC stock, over the full soil profile, compared with the control (-21%, $p<0.05$), despite higher %SOC in the uppermost layers and higher inputs of litter carbon (Fig 1d).

Table 2. Total soil carbon stocks, 0-2 m depth, at different sites, Mae Sa Mai village, Mae Rim district, Chiang Mai, Thailand.

Site	Soil organic carbon stock (tCha^{-1})		
	0 – 1 m	1 – 2 m	0 – 2 m
Control	156.10 c	49.78 c	205.88 b
R2	168.12 ab	86.28 a	254.40 a
R7	160.16 bc	90.98 a	251.14 a
R11	127.41 d	34.41 d	161.82 c
NF	172.99 a	71.97 b	244.96 a

Note: R2 = 2007 (2-year old in 2009), R7= 2002 (7-year old in 2009), R11 = 1998 (11-year old in 2009) and NF = Natural Forest sites. Values are means (n= 3). Values within columns not sharing the same superscript are significantly different ($p < 0.05$).

3.4 Comparison with other studies

Several other studies also reported poor or no relationship between forest age and SOC stocks in a teak plantation (18) and in secondary tropical forests (19, 20) (Table 3).

Table 3. Soil carbon studies in different regions of Thailand comparing with present study

Location	Land histories	Forest type	Soil organic carbon (tCha^{-1}) at 100 cm
Nan province, Northern Thailand (2)	Protected from logging for over half a century	Forest (hill evergreen and two mixed deciduous forest)	196.84
	Planted since 1979	Reforestation (native + exotic species)	146.83
	Cleared prior to 1957	Agriculture (fallow, orchard, paddy field and corn field)	95.69

FORRU, Doi Suthep –Pui National park, northern Thailand (This study)	**Degraded hill evergreen forest and agriculture before restoration**	**NF plot (hill evergreen forest)**	**172.99**
		Restored forest	
		-R11	**127.41**
		-R7	**160.16**
		-R2	**168.12**
		Control plot	**156.10**
Central Thailand (18)	Mixed deciduous forest before Planted since 1989	Teak plantation	
		-28-year-old	66.83
		-27-year-old	105.67
		-18-year-old	78.78
		-14-year-old	61.72
		-10-year-old	157.03
North – east (Nongkhai province) (21)	dry Dipterocarpus forest	Rubber plantation	
		-1-year-old	14.26
		-5-year-old	16.83
		-10-year-old	18.52
		-15-year-old	16.05
		-20-year-old	13.37

Most previous studies in Thailand investigated down to 100 cm soil depth. Therefore in Table 3 we compared measurements down to 1 m depth from this study with those of other studies, which went down to the same depth.

Our results are similar to those Pibumrung et al. (2008) (2), who recorded a SOC stock of 147 tCha^{-1}, close to the values of 160.16 – 168.12 tCha^{-1} recorded in the R7 and R2 plots. In contrast, SOC stocks in simpler plantations were much lower than those recorded in the present study; 61.72 -105.67 tCha^{-1} in teak plantations (18) and 13.36 - 18.52 in a rubber plantation (21). It is well known that diverse tropical forests have much greater capacity for partitioning carbon cycling and therefore higher carbon sequestration rates, compared with plantations (22) with simpler structure, lower biomass and lower primary productivity. This may account for the lower levels of SOC stocks in the latter two studies and re-affirms the higher value of restoring diverse forest ecosystems for maximizing carbon sequestration by forestry programs.

4. Conclusions

Even though carbon inputs into the upper-most soil layers increased, as forest restoration progressed, total soil carbon stocks did not increase with forest development as expected, due to lower %SOC in the lower soil layers of the R11 pit. This may have been a legacy from a longer period of clearance and cultivation prior to restoration compared with the other restoration plots.

One of the most practical outcomes from this study was the close fit of %SOC to soil depth, following reliable power function equations (Figure 1). This provides a useful rapid mechanism for calculating more complete soil carbon stock from upper soil layers, without having to dig down to 2 m.

This study confirms the superiority of forest ecosystem restoration over plantations as a way to sequester carbon and generate carbon credit income, particularly if carbon storage down to 2 m depth can be reliably predicted. However, more comparisons among different methods of forest restoration are needed to determine their effectiveness in influencing carbon inputs, soil organic matter, and total carbon stock.

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