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Effect of Long-term (13 Years) Application of Different Quality Plant Residues on Soil Organic Carbon and Soil Properties of a Sandy Soil of Northeast Thailand

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Abstract

We studied the effects of long term (13 years) annual applications of different quality organic residues on physical and chemical properties of an upland sandy soil as related to soil organic C (SOC) accumulation. At the end of year 13, SOC accumulation was highest in tamarind litter (intermediate contents of N, lignin (L) and polyphenol (Pp)) (8.41 Mg ha^{-1}) treatment, followed by the dipterocarp leaf litter (low N, high L and Pp), groundnut stover (high N, low L and Pp), and rice straw (low N, L and Pp but high cellulose), which were 7.06, 7.10 and 5.54 Mg ha^{-1}, respectively. Application of plant residues significantly reduced soil bulk density (Db) and increased mean weight diameter (MWD) (0.25-0.30 mm) over the control (0.21 mm). The infiltration rate under plant residues addition (1.54-2.87 cm min^{-1}) was higher than the control treatment (0.97 cm min^{-1}). In addition, the effective CEC (ECEC) was 2-5 times higher under the plant residue treatments than the control (1.58 cmol kg^{-1}). ECEC was highest under intermediate quality residue, like the tamarind but lowest under the rice straw. The SOC content was negatively correlated with Db (R^2= -0.49**) but was positively correlated with MWD (R^2= 0.57**), and ECEC (R^2= 0.89***). We concluded that long-term continuous application of organic residues especially those with intermediate contents of N, L and Pp, like tamarind, led to increase SOC accumulation, which, in turn, improve physical and chemical properties of tropical sandy soils.

Keywords: plant residue quality, soil organic carbon, sandy soil and soil property

1. Introduction

Sandy soils of Northeast Thailand are highly weathered and have intrinsically low fertility. This, coupled with land use and improper land management and conservation, have brought about soil degradation.

Land use change from forest to agriculture has been shown to further lower soil physical fertility as indicated by lower soil aggregation and chemical fertility as indicated by lower soil organic matter (SOM) and nutrients as compared to forest soil (Tangtrakarnpong and Vityakon, 2002). In addition, management practices that alter the living and nutrient conditions of soil organisms, such as repetitive tillage or burning of vegetation, result in degradation of their microenvironment (Bot and Benites, 2005). The declining SOM levels generally lead to deterioration of soil physical properties, notably soil aggregation, and bulk density and chemical, notably cation exchange capacity (CEC), properties. The SOM content and its conservation are deeply negatively affected by conventional practices (especially tillage), which not only decrease SOM but also infiltration rates resulting in increases in the potential for rainwater runoff and soil erosion. These are the consequences of destruction of natural soil aggregates and channels that connect the surface with the subsoil, leaving the soil susceptible to erosion. Soil organic C is commonly recognized as one of the key parameters of soil quality. Soil quality is defined as the capacity of a specific kind of soil to function effectively as a component of a healthy ecosystem. Soil chemical, physical, and biological properties have been proposed and are included as basic indicators of soil quality.

Maintaining residues on the soil is effective for improving soil quality. Several studies found that application of organic amendments, such as animal manure (Schjonning et al., 2002; Bhattacharyya et al., 2007), and compost improved soil physical properties as indicated by reduction in bulk density, increase in hydraulic conductivity, and improvement in soil structure and chemical properties as indicated by increase in SOC content and CEC. The relative contribution of clay and SOM to soil CEC is largely determined by the amount of SOM. SOM plays an important role in sorbing soil minerals; in addition, SOM is responsible for 25–90% of the total CEC of surface horizons of mineral soils (Van Dijk, 1971; Oades et al., 1989). Increase in CEC of soil resulted from increased organic C concentration. Thus, recycling of plant residues is important in maintaining SOC leading to maintenance and improvement of soil physical and chemical properties. Little information is available on SOC accumulation and its relations to soil physical and chemical properties especially sandy soils of North-east Thailand as affected by long-term application of plant residues varying in their chemical composition. Our hypothesis was that SOC and soil physical and chemical properties would be influenced by application of different quality plant residues; furthermore, the soil properties would be related to SOC content. The objectives of this study were to assess the effect of different quality plant residues applied annually for more than 10 years on physical and chemical properties of a sandy soil as related to SOC accumulation.

2. Materials and methods

2.1 Study site and soil

The study site was a long-term field experiment on soil organic matter located at a research station of the Office of Agriculture and Co-operatives of the Northeast at Tha Phra subdistrict of Khon Kaen province, Thailand (16°20′ N; 102° 49′ E). The experiment had been conducted for 13 years. Soil was Korat series (Oxic Paleustults). The soil textural class is sand (93.4% sand, 4.5% silt and 2.1% clay) (Vityakon et al., 2000).

2.2 Experimental design and treatments

The long-term field experiment was established in 1995 and the current evaluations were performed at the end of year 13 in late April 2008. A randomized completely block design (RCBD) with three replications were employed due to a gentle slope (approx. 1%). Manual weed control was employed at approximately monthly intervals. There were five treatments including (1) rice (*Oryza sativa*) straw and (2) groundnut (*Arachis hypogaea*) stover which were non-harvestable parts of the crops, (3) leaf litter of dipterocarp (*Dipterocarpus obtusefolius*) (4) leaf + petiole litter (7:1 leaf:petiole) of tamarind (*Tamarindus indica*) and control (no plant residue added). All plant residues were applied at the rate of 10 Mg ha^{-1} dry weight. The materials were air dried and cut into pieces of 5-10 cm size (rice straw and groundnut), while dipterocarp leaf litter was cut to a rectangular shape of approximate size of 5x10 cm^2. Chemical composition parameters of the plant residues used are determined as shown in Table 1. Groundnut was considered a high quality residue with high N and low lignin (L) and polyphenols (Pp) contents. On the other hand, dipterocarp was deemed low quality with its contents of three key chemical compositions in contrast to the groundnut. Meanwhile, tamarind had intermediate quality with its contents of N, L and Pp in a middle range between the groundnut and dipterocarp. Rice straw was considered in a category of its own with low N, L and Pp contents, but it had highest cellulose content. The organic residues had been incorporated into top soils at 15 cm depth in a 4x4 m^2 plot once a year in early May since 1995. Soil samples were randomly collected employing an auger at 52 weeks after residue application from the plots (at 0-15 cm depth) and composited.

2.3 Soil parameter measurements

Soil organic carbon (SOC) was determined on air-dried soil, sieved through a 1 mm mesh sieve, by dichromate oxidation (Allison, 1965). Exchangeable basic cation was determined by the ammonium acetate method (1*N* NH_4OAc). The cations, including Ca^{2+}, Mg^{2+}, K^+, and Na^+, were determined in the soil extract by atomic adsorption spectroscopy (AAS). Effective cation exchange capacity (ECEC) was the sum of basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and exchangeable acidity (Al^{3+} and H^+) (Thomas, 1982).

Soil infiltration rate was determined employing a double ring (ASTM, 1998). The double ring type constituted of an inner and an outer ring. The rate of fall of the water level in the inner ring was measured by a steel gauge (hook gauge). Soil bulk density (0-15 cm depth) was determined in undisturbed soil samples at 52 weeks after residue application.

Mean weight diameter (MWD): Twenty grams of an air dried soil sample that passed through an 8 mm sieve was gradually rewetted employing capillary rise. Then it was placed on the top sieve of a nest of sieves with opening sizes of 2, 1, 0.5, 0.25, and 0.106 mm and wet sieved for 30 minutes in a tumbler shaker (Daiki 2000). The mean weight diameter (MWD) of water stable aggregates was determined as the sum of the percentage of soil on each sieve multiplied by the mean diameter of the size classes (mm) i.e. MWD = ∑(percent of sample on sieve x mean diameter of the size classes) (modified procedure of Tangtrakarnpong, 2002).

2.4 Organic residues analysis

Plant residue analyses consisted of total C and total N by dry combustion (CN analyzer), lignin by acid detergent lignin method (Van Soest and Wine, 1968) and polyphenol (ratio of plant to 50% methanol was 1:50) by the recommended method in the Tropical Soil Biology and Fertility Handbook (Anderson and Ingram, 1993).

2.5 Statistical analysis

Analysis of variance was employed under RCBD, while mean comparisons of different treatments were done by least significant difference (LSD). Correlation analysis was conducted to study relationships between various factors. The statistical package used was statistix version 8.0 (Analytical Software, 2003).

3. Results and discussion

3.1 Soil organic carbon

Soil organic carbon (SOC) contents at the end of 13 years were significantly higher in soils amended with residues than the control (no addition) (Table 2). Similarly, Samahadthai et al. (2010) found that SOC increased after annual application of plant residues for 10 years. Long-term application of tamarind had highest SOC (8.41 Mg ha^{-1}) followed by provision of groundnut, and dipterocarp. This resulted from both the different amounts of residue C added and chemical composition of the residues. SOC content was positively correlated with residue C contents (r= 0.629*) but negatively correlated with C/N ratio (r= -0.616*). The higher SOC accumulation under the tamarind than the groundnut despite the higher C/N ratio of the former than the latter residue was to do with higher microbial efficiency in C utilization under the tamarind. This was indicated by the tamarind's lower metabolic quotient values than groundnut (Puttaso et al., 2010). Addition of rice straw led to lowest SOC content (5.54 Mg ha^{-1}) partly because of its lowest amount of C added. In addition, rice straw had highest cellulose content which was negatively correlated with SOC (r= -0.92**) (Puttaso et al., 2010). Cellulose is a relatively labile C compound and is readily decomposed by microorganisms. This resulted in high C loss as CO_2 (as found by

Table 1. Chemical compositions of organic residues locally available in Northeast of Thailand.

Residue chemical compositions	Groundnut stover (*Arachis hypogaea*)	Tamarind (*Tamarindus indica*)	Rice straw (*Oryza sativa*)	Dipterocarp (*Dipterocarpus tuberculatus*)
C (g kg^{-1})	388	427	367	453
N (g kg^{-1})	22.8	13.6	4.7	5.7
C/N	17	31.5	78.4	79.5
Lignin (g kg^{-1})	67.6	87.7	28.7	175.5
Polyphenol (g kg^{-1})	12.9	31.5	6.5	64.9
Cellulose (g kg^{-1})	178	143	507	306

Table 2. Soil organic C (SOC), mean weight diameter (MWD), bulk density (0-15 cm) and infiltration rate at the end of year 13 after different plant residue application.

Residue treatment	SOC (Mg ha^{-1})	MWD (mm)	Bulk density (g cm^{-3})	Infiltration rate (cm min^{-1})	
				Initial stage	Later stage
No addition	2.72d	0.21b	1.61a	0.968c	0.011
Rice straw	5.54c	0.25ab	1.57bc	2.866a	0.017
Groundnut stover	7.10b	0.28a	1.55bc	1.542bc	0.009
Dipterocarp	7.06b	0.29a	1.58ab	1.965ab	0.019
Tamarind	8.41a	0.30a	1.56bc	2.359ab	0.112
SED	0.08**	0.02*	0.02*	0.375**	0.027ns

*, **= significantly different at $p < 0.05$, 0.01, SED = standard error of the differences between means, ns = not significantly different at $p > 0.05$

Puttaso et al., 2010) and, possibly, as dissolved organic C (Katoh et al., 2005).

3.2 Changes in soil physical properties

3.2.1 Mean weight diameter

The mean weight diameter (MWD) is an indicator of soil structure. The application of plant residue increased MWD over the control (no addition) (Table 2). This was also found in Samahadthai et al. (2010) that all residues including dipterocarp, tamarind, groundnut and rice straw brought about larger MWD than the control. Among the treatments with residue application, rice straw showed the lowest MWD, but was not significantly different (p>0.05) from other residue treatments. We also found positive correlation between MWD and L (r= 0.44) and Pp (r= 0.43) but negative correlation with cellulose (r= -0.47). This indicates that residues with high L and Pp may lead to large MWD; on the other hand those with high cellulose may lead to small MWD. Martens (2000) reported that MWD was positively correlated with phenol and lignin contents of plant residues. Improvement in MWD as a consequence of an increase in SOC concentration was reflected as a positive correlation between the two properties (y= 0.18-0.03x, R^2= 0.57**). Chenu et al. (2000) also found high correlation between MWD and SOC (MWD= 0.051x+0.069, R^2=0.665). SOC is an important factor controlling aggregate formation as SOC contributes to binding of primary particles to form aggregates (Tisdall and Oades, 1982; Bhattacharaya et al., 2007). In addition, decomposing particulate organic matter fraction of SOC can act as nucleus or core upon which mineral components are adsorbed leading to aggregate formation (Golchin et al., 1994).

3.2.2 Soil bulk density

Application of different plant residues significantly decreased bulk density (Db) as compared to the control at the end of year 13 (Table 2). Samahadthai et al. (2010) in year 10 of the same experiment also found that Db significantly decreased, especially in tamarind (1.48 g cm^{-3}) treatment relative to the control treatment. It had significant positive correlation with C/N ratio (r = 0.71*) and negative correlation with N (r= -0.69*). This showed that residues with high C/N ratios have led to increases in Db (as shown by rice straw and dipterocarp), while those with high N contents have led to decreases in Db. The Db had significant negative correlation with SOC (R^2= -0.49**). The resulting significantly higher soil aggregation under groundnut and tamarind than rice straw led to lower Db in the former residues than the latter one. Other studies also showed that application of plant residues, such as maize straw, wheat straw and green manure led to increases in SOC and soil aggregates and decreases in Db (Blanco-Canqui and Lal, 2007; Zhao et al., 2009). On the contrary, under dipterocarp treatment, larger MWD (higher soil aggregation) did not translate into lower Db relative to rice straw (Table2). Dipterocarp produced the highest quantity of large macroaggregates (>2 mm), but it had significantly lowest microaggregates (0.053-0.25 mm) among residue treatments (Puttaso, unpublished). Dipterocarp's large MWD may have resulted from the contribution of the large macroaggregates. However, the reduced Db may have resulted from contributions of the microaggregates which constituted more than 60% of soil dry weight compared with <2.5% contribution of large macroaggregates (Puttaso, unpublished). Although our results generally indicated that decrease in Db was closely associated with MWD as shown by negative correlation between Db and MWD (R^2= -0.42**), our results also point out to the fact that microaggregates played a more important role at decreasing Db than larger sized aggregates.

3.2.3 Soil infiltration rate

Infiltration rates (IR) are divided into two stages, i.e. initial rapid stage and later slow stage (approaching a steady state) (Figure 1). The long-term application of residue for 13 years significantly increased initial IR over the control treatment (Table 2). The IR was 1.5-3.0 folds higher in soil with residues addition relative to the control treatment. The initial IR was highest in rice straw treatment followed by tamarind, groundnut and dipterocarp (Table 2). Initial rates of infiltration were positively correlated with SOC (R^2= 0.29*) but only showed highly significant correlation (n=12, R^2= 0.82***) when rice straw was removed. This showed that SOC in the topsoil improved soil structure through increase in MWD and decrease in Db resulting in high

IR in the soil treated with plant residues in the long term. Rice straw behaved differently than the other residue treatments because it showed high initial IR despite its low SOC. This was probably due to its highest quantity of microaggregates among all residue treatments (Puttaso, unpublished). The presence of a high quantity of microaggreagtes may have led to better pore size distribution and continuity under rice straw with a consequent higher infiltration rate. Meanwhile, infiltration rates at the later stages (steady state) were not significantly different among treatments (Table 2). At this stage, water percolation was slow because it had reached deeper soil

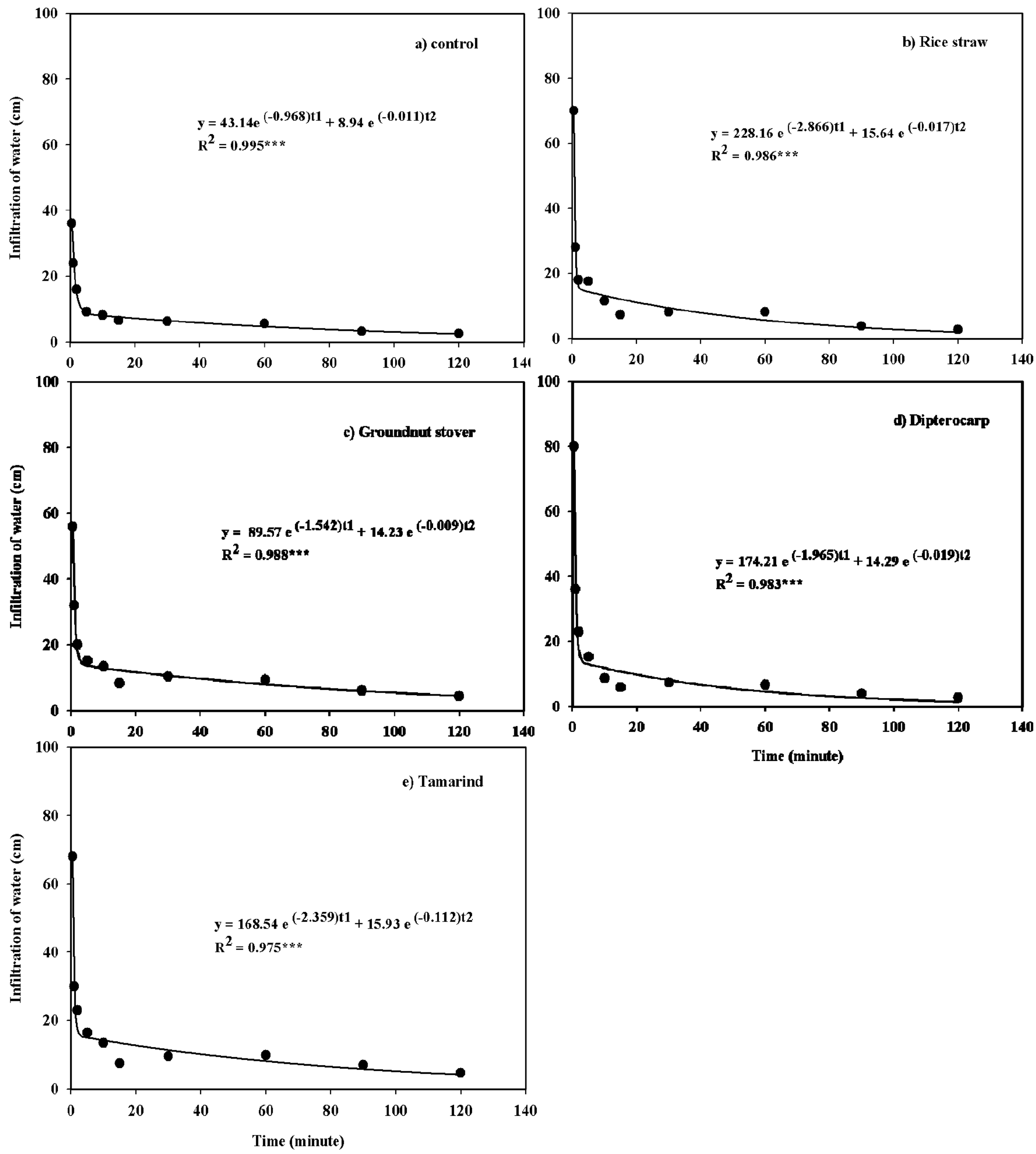

Figure 1. Infiltration rate (cm min^{-1}) in sandy soil after year 13 as affected by longterm application of different plant residues.

layers with finer texture relative to that of the topsoil which water percolated through during the initial stage.

3.3 Influence of plant residues application on effective CEC (ECEC)

The ECEC at the end of year 13 was significantly ($p< 0.001$) different in soil treated with plant residues compared to the control (1.58 cmol kg^{-1}) (Figure 2). The ECEC was increased by application of plant residues (Lathwell and Peech, 1964). The highest ECEC was found in long-term application of tamarind (8.1 cmol kg^{-1}) followed by groundnut and dipterocarp. The ECEC was lowest under rice straw (Figure 2). Chemical composition of residues played an important role in increasing ECEC. We found significant non-linear relations between ECEC and residue contents of C (R^2= 0.886**), N (R^2= 0.944***), L (R^2= 0.736**) and Pp (R^2= 0.909***) and C/N ratio (R^2= 0.878**) (Figure 3a-e). These relations show critical values (in g kg^{-1}) of C (417.3), N (14.5), L (112.4) and Pp (38.5) and C/N ratio of 46 to result in maximum ECEC in the range of 7.52-8.89 cmol kg^{-1}. Tamarind had the closest contents of C, N, L and Pp, and C/N ratio to the critical values. These results showed that residues with intermediate contents of lignin, polyphenols, N, and C/N ratio, like tamarind, led to increased ECEC. Lignin and polyphenols have been proposed as precursors of humic substances. Humic substances are a stable SOM pool, which is bound to clay colloid and results in increased reactive surface area for cation adsorption (such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, H^{+} and Al^{3+}). In addition, we also found high positive correlation between ECEC and SOC (R^2= 0.89***) (Figure 4). This confirms that increases in SOC led to increases in CEC. Our results showed that 1% increase in SOC could increase ECEC by 2.5 cmol kg^{-1}. This is lower than an increase of 7 cmol kg^{-1} per 1% SOC increase in sandy soils in Northeast Thailand reported by Vityakon (1991). Moreover, increase in ECEC may lead to increased soil aggregate

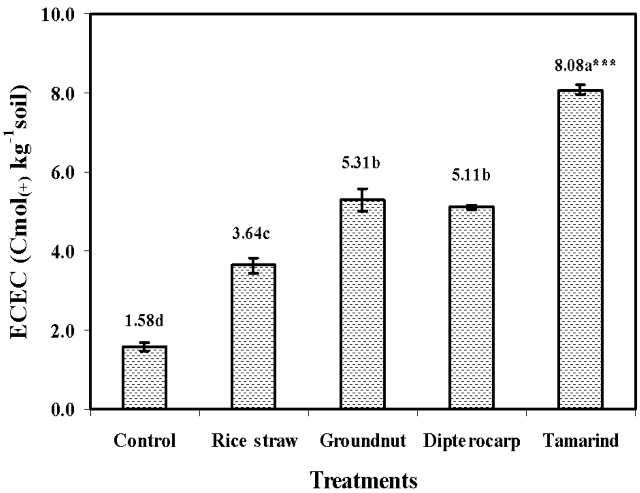

Figure 2. Effective CEC (Cmol kg^{-1}) in sandy soil as affected by different plant residue application. Vertical bars represent SE.

formation, through clay-polyvalent cations-organic matter bonding.

4. Conclusions

Physical and chemical properties of the sandy soil were significantly improved under prolonged (13 years) application of different residues as compared to treatment that did not receive the residues. The residue with intermediate quality as far as C/N ratio and contents of N, lignin and polyphenols are concerned, i.e. tamarind, brought about the greatest improvement in physical (aggregation, bulk density and to some extent infiltration rate) and chemical

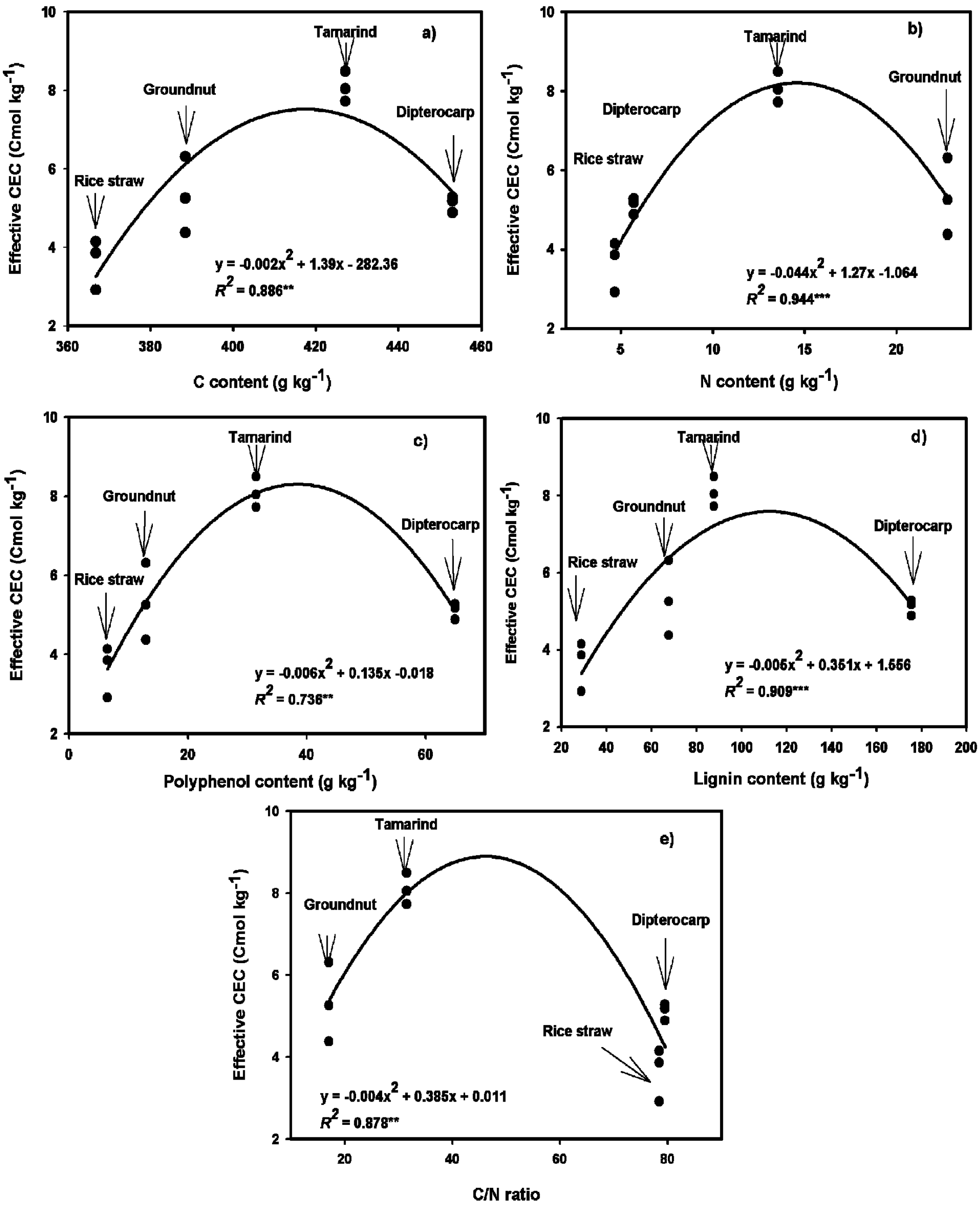

Figure 3. Relationship between ECEC and (a) C, (b) N, (c) lignin, (d) polyphenol, and (e) C/N ratio.

(effective CEC) properties of the sandy soil. Aggregation is highly desirable in sandy soils which usually do not form stable aggregate easily due to their low clay contents. In addition, increase in cation exchange capacity as indicated by ECEC, is also highly desirable as it leads to higher buffering capacity of sandy soils to retain nutrients and maintain stable soil pH. The improvement in physical and chemical properties was in parallel with the highest accumulation of SOC under the tamarind treatment. The SOC accumulation is through C stabilized in soil aggregates, as seen in the higher soil aggregation as indicated by larger MWD under the tamarind treatment. Intermediate quality organic residues (tamarind) can bring about accumulation of SOC which, in turn, leads to improved soil physical and chemical properties desirable in sandy soils. In addition, our results showed that some more refined soil quality indicators than SOC contents and MWD may be required to more thoroughly explain some changes in soil properties resulting from residue application. This is with regards to the use of microaggregate quantities in explaining fast infiltration rates under rice straw treatment despite its low SOC and the use of quantities of macro- and microaggregates in place of the average nature of MWD to explain the high bulk density under dipterocarp. Input of appropriate quality organic residues into sandy soils is a highly beneficial management option to improve and maintain soil physical and chemical fertility which leads to sustainability of production in sandy soils.

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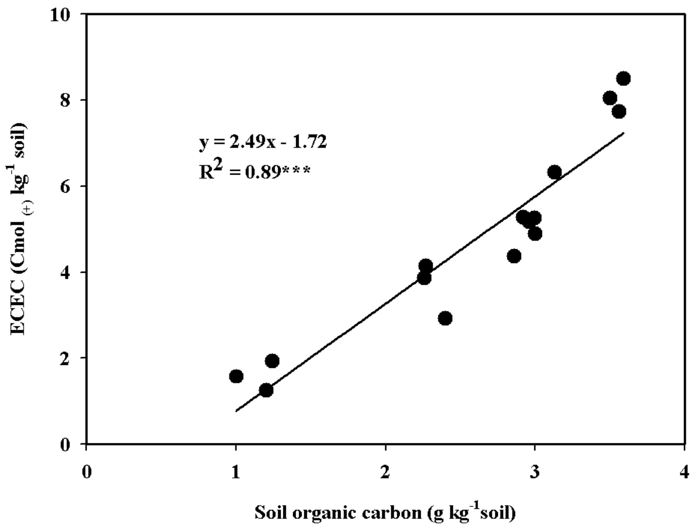

Figure 4. Relationship between soil organic carbon and ECEC.

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