

Comparative effect of deep and conventional tillage on some soil physical properties of sandstone-derived soils under cassava cultivation

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ABSTRACT: Plough pan is a major problem for cassava cultivation in upland soils of northeast Thailand. This study was undertaken with the aim of comparing the impact between deep tillage, continuously operated for ten years and conventional tillage, commonly practiced by local farmers on some physical properties of soils derived from sandstone used for cassava cultivation. There were two transects chosen, deep-tilled and conventional-tilled transects. On each transect, five mini soil profiles with the size of 1 x 1 m deep and wide were dug parallelly between two transects. Pedon analysis and field morphology were studied at the time of sampling. Soil samples were collected from genetic horizons for the analysis of particle size distribution, including sand fractions, bulk density, and hydraulic conductivity. All soils were dominated by sand particles, mainly having sand to loamy sand texture. The genetic horizon sequence of all soils was Ap-Bt. The approximate topsoil thickness of deep-tilled soils, on average, was 41.2 cm (mostly Ap1-Ap2) while the conventional-tilled soils had 25.2 cm thick topsoil (mostly Ap). The plough pans with the average bulk density of 1.85 Mg/m³ were found directly underneath the surface layer of all conventional-tilled soils. In contrast, the soils experienced deep-tilled operation showed no sign of subsoil compaction as the layer underneath the surface one had the average bulk density of only 1.55 Mg/m³ which was lower than the directly upper and lower horizons. It was also the case for hydraulic conductivity, but the values were in reverse fashion. The higher bulk density was governed by silt and clay contents while fine and very fine sand contents negatively correlated with bulk density in a significant manner. These evidently reaffirm that continuous deep tillage operation can solve the plough pan problems in these soils and should be recommended to local farmers to operate likewise.

Keywords: sandy soil; plough pan; deep tillage; soil physical property; cassava

Introduction

In northeast Thailand, cassava has been one of the major economic crops in the upland areas. In 2022, cassava growing area in this region was nearly 1 million ha, accounting for 54.2% of the total country's growing areas where Nakhon Ratchasima province had the largest growing area of 237,108 ha (Office of Agricultural Economics, 2024). The average yield per harvested area of this plant in this region in the same year was only 21.86 t/ha which was much lower than yield potential of cassava varieties commonly planted in the country. Apart from improper soil management and erratic rainfall, poor qualities of soils, physically and chemically, in the northeast are responsible for this low yield (Anusontpornperm et al., 2009; Boonrawd et al., 2021). In the context of soil physical property, compaction caused by a reduction of soil organic carbon and soil structural damage due to wheel traffic

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is one of the major problems in agricultural fields. It reduces soil pore space and increases soil strength while decreasing root growth and root elongation, resulting in reduced water and nutrients taken up by crops (Nawaz et al., 2013; Sadras et al., 2016; Colombi and Keller, 2019). Soil compaction can be referred to as topsoil and subsoil compactions. The latter is defined as a plough pan, a man-made pan caused by repeated ploughing at shallow depths under improper conditions, having high bulk density, slow hydraulic conductivity and low available water holding capacity (Hamza and Anderson, 2005). This dense layer is also commonly found directly underneath the topsoil in most upland medium- to coarse-textured soils under cassava and sugarcane cultivation (Kliaklom et al., 2010; Meewassana et al., 2010; Anusontpornperm et al., 2014). This pan not only restricts the elongation and tuberization of cassava roots but also impedes vertical movement of soil water which subsequently leads to severe soil erosion in cassava production areas. In the last decade, attempts have experimentally been made to alleviate the problems of plough pan (Anusontpornperm et al., 2014). Some reports in Thailand have demonstrated the short-term impact of loosening or breaking the pan by using ripper as a subsoiler and bigger 3-disc plough for the first plough. For instance, after one growing season ripping the plough pan in Yasothon soil series did not affect bulk density of the soil at the depth between 0–50 cm but increased hydraulic conductivity at the depth of 30–40 cm when compared to no use of ripper (Riyaphan et al., 2010). In a two-year trial on a Typic Paleustult, northeast Thailand, after ripping the plough pan prior to growing cassava in the first growing season subsoil compaction was still observed after harvesting the second crop (Kaewkamthong et al., 2014). In Warin soil series, the impact of ripper on cassava lasted only one growing season (Surin et al., 2013) because the plough pan was not completely dry at the time of the operation being performed, resulting in ripping less effective (Anusontpornperm et al., 2014). In addition, Hamza and Anderson (2002) found that deep ripping alone increased the infiltration rate in the first three years, but the effect did not last into the fourth year. Also on Warin series, continuously using deep tillage as the first plough to a depth of 40–45 cm for two years contributed to lower bulk density of the soil at a depth between 30–45 cm and stimulated more rapid saturated hydraulic conductivity at all three depths (0–15, 15–30 and 30–45 cm) when compared to conventional tillage (Pradit et al., 2017). However, the deep tillage for two consecutive years resulted only in the increase of available potassium content the topsoil (0–30 cm) of Yasothon soil series over the conventional tillage (Lunlio et al., 2017). Recent interesting meta-analysis of the impact of deep tillage illustrated that the subsoil below the regularly tilled topsoil stores large nutrient stocks and can retain water even under drought conditions and deep tillage as referred could improve the plant availability of these subsoil resources. The meta-analysis was based on 1,530 yield comparisons between deep and ordinary tillage at 67 experimental sites which were mostly conducted in temperate regions (Schneider et al., 2017). Therefore, this study was undertaken primarily to investigate some soil physical properties under conventional tillage (first plough at a depth of 0–25/30 cm) compared with that under deep tillage (first plough at a depth of 0–40/45 cm) along the same toposequence. The former was in farmer fields while the latter was in experimental areas where deep tillage had been performed consecutively for ten years. Notably, this experimental area is the only site in Thailand that deep tillage has been experimentally studied for the longest period. This studied site was initially surveyed by Meewassana et al. in 2010 for the study of plough pan characteristics under cassava cultivation. Results of this study would be beneficial for the understanding of a long-term deep-tilled operation impact on soil properties where soil properties under a

conventional tillage operation can relatively and descriptively be referenced. This will lead to having clear strategies for permanent alleviation of plough pan problems in cassava growing areas of northeast Thailand.

Materials and Methods

Site description and general settling

This descriptive field study was carried out in farmer's fields at Ban Non Somboon, Kritsana subdistrict, Sikhio district, Nakhon Ratchasima province. Two transects on the same toposequence were chosen where each transect comprised five mini soil profiles with a distance between mini soil profiles of 75 m (**Figure 1**). The coordinates of each mini soil profile and elevation/soil management practices where each mini soil profile was located were presented in **Table 1**. The first transect (Satuk soil series: Kn-1d, Kn-2d and Kn-3d soils; Warin soil series: Kn-4d and Kn-5d soils) was in the experimental area where deep tillage using 3-disc with 71.1 cm-diameter disc had continuously been operated for 10 years and a depth of the first plough was estimated to be 0–40/45 cm. As mentioned earlier that this transect were in the experimental area, ground limestone have been applied at the rate of 1.25 t/ha to the Kn-2d soil for 6 consecutive years, perlite and chicken manure have continuously been applied at the respective rates of 0.625 and 3.125 t/ha to the Kn-3d for 9 years, and chicken manure have consecutively applied at the rate of 3.125 t/ha to the Kn-4d soil for 9 years. The other transect (Satuk soil series: Kn-1c, Kn-2c and Kn-3c soils; Warin soil series: Kn-4c and Kn-5c soils) was in the area under conventional tillage where farmers have been using 3-disc plough with 55.9 cm-diameter disc or smaller to perform the first plough of which the ploughing depth was approximately 0–25/30 cm (**Table 1**). The soils in this transect has presumably been used for cassava cultivation without soil amendment addition. The mini soil profile had a size of 1 m depth x 1 m width. Field study included general information of sites chosen and soil morphological identification using profile analysis based on standard methods (Soil Survey Division Staff, 1993). Undisturbed and disturbed soil samples were collected from genetic horizons of each mini soil profile and subjected to soil analysis based on standard methods.

Soil analysis

Both disturbed and undisturbed soil samples collected from the genetic horizon of all soils in both transects were used for the analysis of some soil physical properties. A soil core was used for undisturbed soil sampling of which bulk density was analyzed following the method of Blake and Hartge (1986) while saturated hydraulic conductivity was measured through the variable head method (Klute, 1965). Soil textural classes were determined through particle size analysis by using the pipette method of Gee and Bauder (1986). Sand fractions including very coarse (1–2 mm), coarse (0.5–1 mm), medium (0.25–0.5 mm), fine (0.1–0.25 mm) and very fine (0.05–0.1 mm) sands were measured by using wet sieving (Day, 1965).

Statistical analysis

The values of soil bulk density and soil particle fractions measured were expressed as Pearson correlations (r) and the statistical significance of the correlation was examined using a two-tailed t test. The coefficient of variation was used to analyze the data (SAS Institute, 2004).

Table 1 Coordinates and land uses/soil management practices of each mini soil profiles selected in the study

Soil symbol	Coordinates	Land uses/soil management practices
Kn-1d	769409 ^E , 1671464 ^N	325 m/deep tillage/no soil amendment added
Kn-1c	769420 ^E , 1671676 ^N	325 m/conventional tillage/no soil amendment added
Kn-2d	769367 ^E , 1671623 ^N	329 m/deep tillage/ground limestone applied for 6 years
Kn-2c	769358 ^E , 1671633 ^N	329 m/conventional tillage/no soil amendment added
Kn-3d	769306 ^E , 1671578 ^N	331 m/deep tillage/perlite + chicken manure applied for 9 years
Kn-3c	769317 ^E , 1671566 ^N	332 m/conventional tillage/no soil amendment added
Kn-4d	769253 ^E , 1671522 ^N	330 m/deep tillage/chicken manure applied for 9 years
Kn-4c	769268 ^E , 1671510 ^N	331 m/conventional tillage/no soil amendment added
Kn-5d	769198 ^E , 1671464 ^N	334 m/deep tillage/no soil amendment added
Kn-5c	769215 ^E , 1671451 ^N	334 m/conventional tillage/no soil amendment added

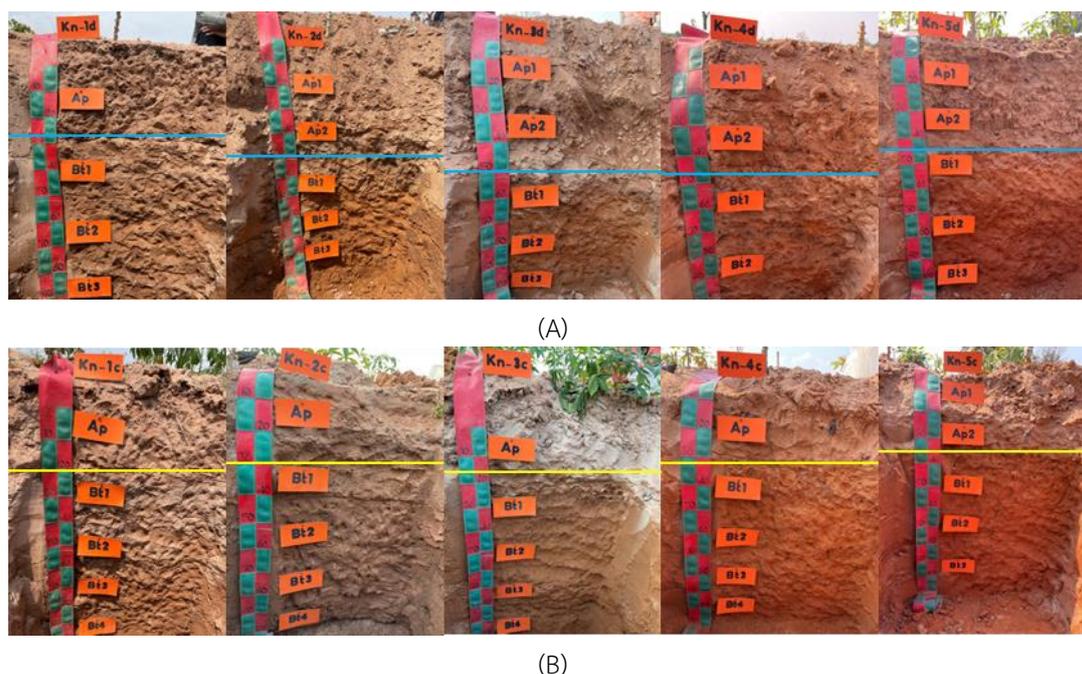
Results

General information of soils chosen

Cassava had been a major crop in both transects until this study was conducted. All soils in the area were upland soils derived from wash or local alluvium over residuum of sandstone and located on mid-slope to shoulder slope of low hill. The soils in the lower slope (Kn-1d, Kn-2d, Kn-3d, Kn-1c, Kn-2c and Kn-3c) were classified as Typic Paleustults (Uppapanpongchai et al., 2017), and those in the upper slope (Kn-4d, Kn-5d, Kn-4c and Kn-5c) were classified as Arenic Haplustults (Phuniam et al., 2012). These soils were on the sloping surface of 2–3%. All soils were characterized by the Ap-Bt genetic horizon sequence (**Figure 2**). The top layer of almost all soils in deep-tilled transect contained two sub-layers of Ap horizon, namely Ap1 and Ap2. The colors throughout the mini profile of these soils in both transects became redder with the elevation getting higher.



Figure 1 Sampling locations of soils in two transects with red-colored line indicating sampling transect studied by Meewassana et al. in 2010



Light blue and yellow lines delineate a thickness of ploughed layer in respective deep-tilled and conventional-tilled soils. Scaling tape was adjusted to the actual soil surface.

Figure 2 Mini profiles of soils in two transects: (A) deep-tilled transect and (B) conventional-tilled transect

Topsoil thickness

Topsoil thickness of each soil was estimated by moderating the average height of ridges commonly implemented for cassava cultivation in the region. The soils under deep tillage practice were composed of Ap1 and Ap2 horizons all but the Kn-1d soil with the thickness in the range of 28–51 cm. The other group of soils under conventional tillage practice all contained only an Ap horizon directly overlying Bt horizon except the Kn-5c soil that had Ap1 and Ap2 horizons with 20–35 cm of thickness range (**Figures 2 and 3**). It was notable that the approximate depth of ploughed layer, on average across each transect, was 41.2 cm for deep-tilled soils and only 25.2 cm for conventional-tilled soils.

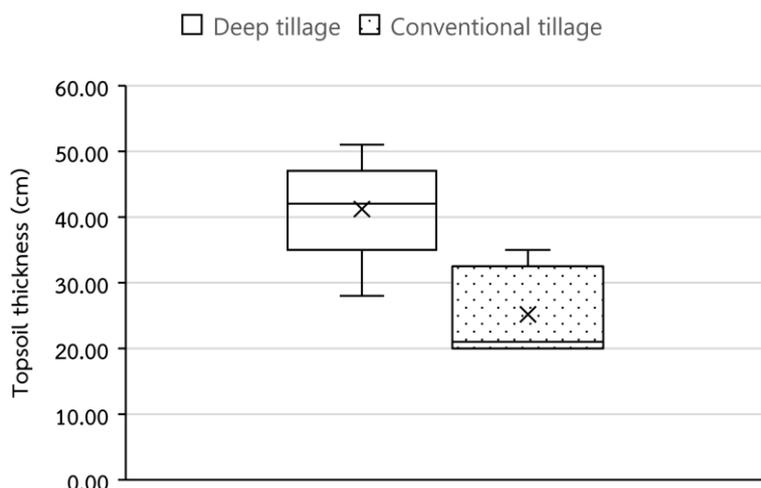


Figure 3 Approximate topsoil thickness comparison between soils under deep and conventional tillage practices where X inside each box represents means value, a horizontal line inside each box represents median value and error bars represent \pm SD

Soil particle distribution and texture

Sandy particles were dominant in all soils in both transects with a small amount of silt and clay contents slightly increasing with depth within the soil profile, resulting in the soils mostly having sand and loamy sand textural classes. It can be noticed that the amount of silt and clay particles in the second layer of soils (2-layer) in deep-tilled transect did not clearly increase over the top layer whereas these two particles in the layer directly beneath the top layer of conventional-tilled soils increased quite evidently over the surface layer (**Table 1**), particularly the Kn-2c, Kn-3c and Kn-4c soils as shown by textural class difference; sand-loamy sand for Kn-2c soil and loamy sand-sandy for Kn-3c and Kn-4c soils.

The average sand content in the top layer (Ap or Ap1) of the soils in both transects was almost identical, 876 g/kg for soils under deep tillage practice and 877 g/kg for soils under conventional tillage practice. This contrasted to the layer directly underneath the surface layer (Ap2: deep tillage and Bt1: conventional tillage) which the average amount of sand particles in the soils under deep tillage practice was far higher than that under conventional practice, 968 g/kg compared to 822 g/kg. while the 3-layer (Bt1: deep tillage and Bt2: conventional tillage) where the first plough operation was unable to reach showed the opposite trend, 831 g/kg compared to 806 g/kg (**Figure 4A**).

Table 2 Particle size distribution and textural class of soils selected in the study

Horizon	Depth (cm)	Sand (-----g/kg-----)	Silt	Clay	Texture	Horizon	Depth (cm)	Sand (-----g/kg-----)	Silt	Clay	Texture
Kn-1d						Kn-1c					
Ap	0-28	909	92	69	Sand	Ap	0-20	840	91	69	Loamy sand
Bt1	28-50	909	64	27	Sand	Bt1	20-38	889	60	51	Loamy sand
Bt2	50-75	875	89	36	Loamy sand	Bt2	38-55	803	121	76	Loamy sand
Bt3	75-100	880	86	34	Loamy Sand	Bt3	55-78	819	96	85	Loamy sand
Kn-2d						Kn-2c					
Ap1	0-30	872	82	46	Loamy sand	Ap	0-21	909	63	27	Sand
Ap2	30-51	855	98	47	Loamy sand	Bt1	21-40	796	138	64	Loamy sand
Bt1	51-72	839	123	38	Loamy Sand	Bt2	40-61	802	130	68	Loamy sand
Bt2	72-85	790	169	41	Loamy Sand	Bt3	61-80	832	94	74	Loamy sand
Kn-3d						Kn-3c					
Ap1	0-20	868	90	42	Loamy sand	Ap	0-20	875	89	36	Loamy sand
Ap2	20-42	863	90	47	Loamy sand	Bt1	20-38	795	123	82	Sandy loam
Bt1	42-65	800	133	67	Loamy Sand	Bt2	38-60	803	119	78	Loamy sand
Bt2	65-83	791	135	74	Loamy Sand	Bt3	60-80	776	150	74	Sandy loam
Kn-4d						Kn-4c					
Ap1	0-25	868	94	38	Loamy sand	Ap	0-30	881	85	34	Loamy sand
Ap2	25-43	864	92	44	Loamy sand	Bt1	30-50	776	136	88	Sandy loam
Bt1	43-69	866	83	51	Loamy sand	Bt2	50-65	805	119	76	Loamy sand
Bt2	69-100+	779	145	76	Sandy loam	Bt3	65-85	794	124	82	Loamy sand
Kn-5d						Kn-5c					
Ap1	0-22	866	94	40	Loamy sand	Ap1	0-20	879	83	38	Loamy sand
Ap2	22-42	856	102	42	Loamy sand	Ap2	20-35	854	97	49	Loamy sand
Bt1	42-65	792	126	82	Loamy Sand	Bt1	35-60	815	115	70	Loamy sand
Bt2	65-87	765	146	89	Sandy loam	Bt2	60-80	797	123	80	Sandy loam

In the case of silt content, the top three layers of soils under conventional tillage practice clearly contained greater average amounts than did the soils under deep tillage practice whereas the 4-layer showed the reverse trend (Figure 4B). It can be emphasized that the silt content in the layer directly underlying the surface layer of soils experienced conventional tillage operation had far greater amount, 111 g/kg compared to 83 g/kg. A rather similar trend was also observed, regarding clay content in each layer of which the average quantity of this soil particle in the lower three layers of conventional-tilled soils was quite higher than that of deep-tilled soils (Figure 4C) which was in contrary to the topsoil (Ap1: deep tillage and Ap: conventional tillage).

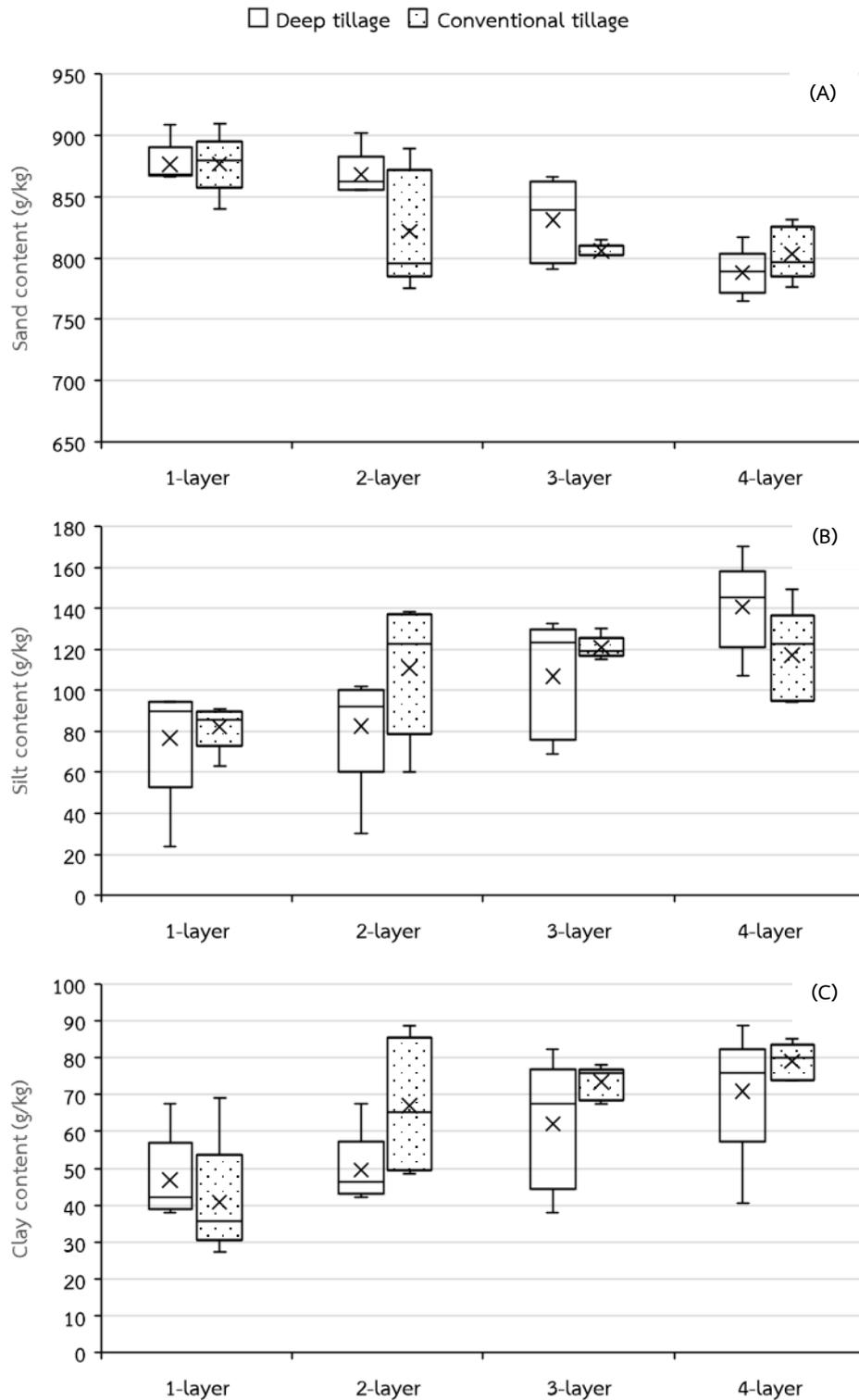


Figure 4 Average sand (A), silt (B) and clay (C) contents of relative top four layers in soils under deep and conventional tillage practices where X inside each box represents means value, a horizontal line inside each box represents median value and error bars represent \pm SD

Bulk density and hydraulic conductivity

Bulk density values of the soils on deep tillage practice transect ranged from 1.49–1.93 Mg/m³ whereas the values of soils on the other transect varied from 1.44–2.03 Mg/m³. The value tended to increase with increasing depth within the mini soil profile except for the 2-layer of the soils under deep tillage implementation. On average across 5 soils of each transect, bulk density values of the surface layer (1-layer), 3-layer and 4-layer were comparatively almost identical (**Figure 4A**). It can be noticed that the bulk density means of the horizon directly underlying the surface layer (2-layer) under deep tillage operation, which was 1.55 Mg/m³, was slightly lower than the overlying horizon (1.60 Mg/m³) and far greater than the underlying horizons (1.77 Mg/m³ similarly for both). In contrast, the horizon directly beneath the surface layer of soils under conventional tillage practice had the highest means value of 1.85 Mg/m³ which the value was much greater than that of the very top layer (1.59 Mg/m³) and the other subsoils underneath (1.77 and 1.76 Mg/m³).

Hydraulic conductivity followed the same pattern as bulk density but with a reverse trend of values. The deep-tilled soils had the hydraulic conductivity values in the range of 0.3–39.8 cm/hr while the range of 0.1–46.7 cm/hr was observed in the conventional-tilled soils. Comparatively, the surface layer of the soils in both transects, on average, had almost identical values, 25.7 and 25.0 cm/hr for respective deep tillage practice and conventional tillage practice transects. The contrast of hydraulic values in the soils between transect was clear in the layer directly underneath the surface layer and those two layers in the deeper zone. The layer directly underlying the surface layer of soils experienced deep tillage had the means hydraulic conductivity of 26.1 cm/hr which was far more rapid than the means of 4.3 cm/hr observed in the soils under conventional tillage. However, the lower two layers (3-layer and 4-layer) showed the slight opposite trend as the deep-tilled soils had the average values of 8.2 and 9.9 cm/hr while the conventional-tilled soils on average had the values of 14.7 and 11.6 cm/hr, respectively (**Figure 4B**).

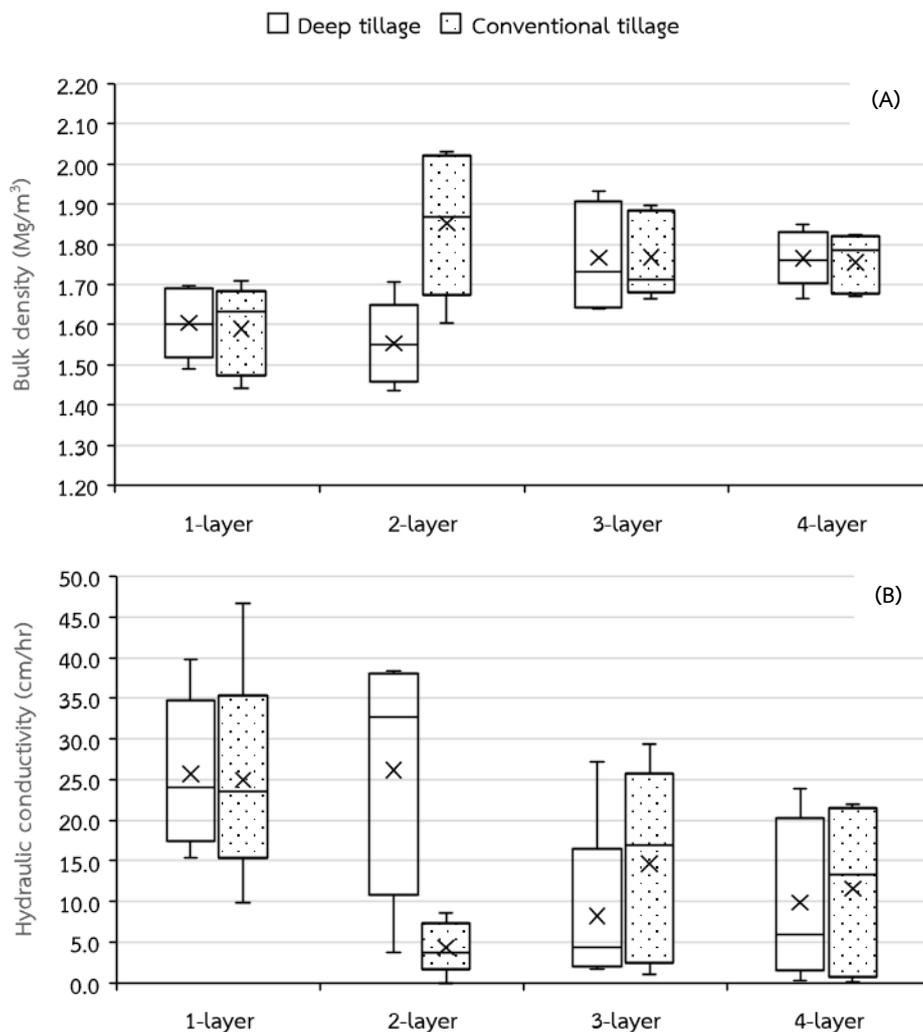


Figure 5 Average bulk density (A) and hydraulic conductivity (B) values of relative top four layers in soils under deep and conventional tillage practices where X inside each box represents means value, a horizontal line inside each box represents median value and error bars represent ± SD

Relationship between bulk density and soil particles

All sand, silt and clay particles clearly affected bulk density of the soils in this study in a highly significant manner. The sand content negatively correlated with the bulk density ($r = -0.589^{**}$) as shown in **Figure 6A** whilst increasing quantity of silt and clay particles played a part in increasing bulk density values as shown in **Figures 6B and 6C** that the silt and clay contents had a positive correlation with the bulk density ($r = 0.477^{**}$ and $r = 0.524^{**}$, respectively). Sand fractions were also separated and used for the assessment of their relationship with bulk density. All sand fractions had a correlation with bulk density except for only the coarse sand (**Figure 7A**). The coarse and medium sand contents significantly had a positive correlation with the bulk density (**Figures 7B and 7C**) but with a rather weak relationship ($r = 0.338^*$ and $r = 0.337^*$, respectively). In contrast, the fine ($r = -0.486^{**}$) and very fine sand ($r = -0.538^{**}$) contents highly significantly correlated with the bulk density in a negative manner (**Figures 7D and 7E**).

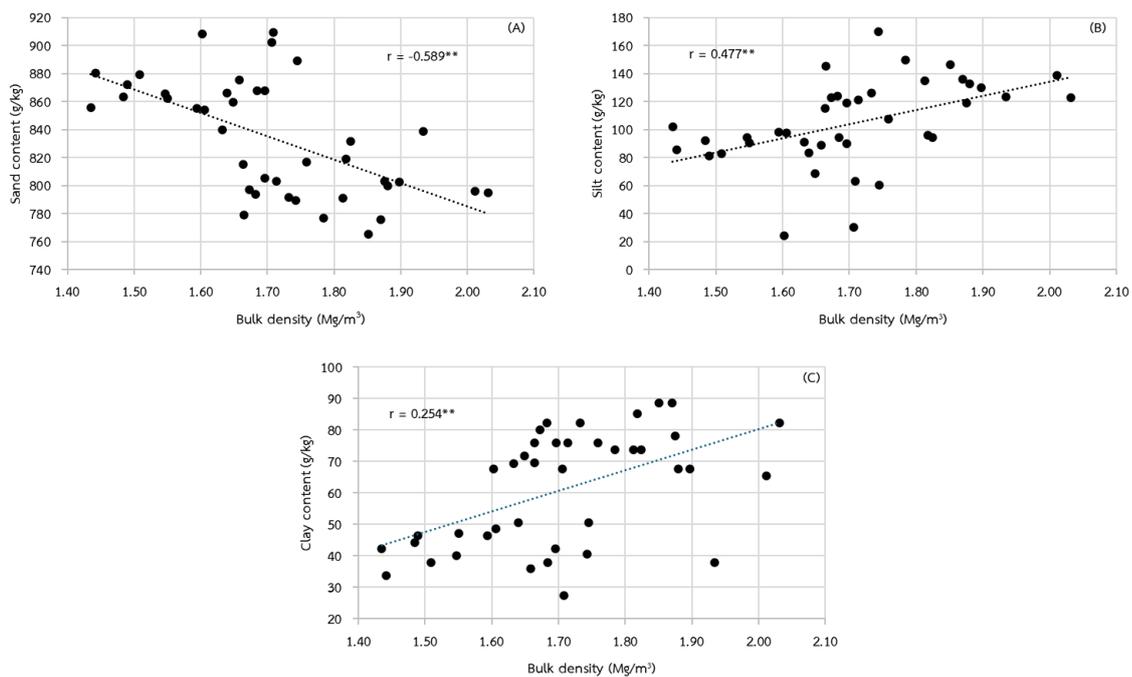


Figure 6 Correlation between bulk density and sand (A), silt (B) and clay (C) contents (n = 40)

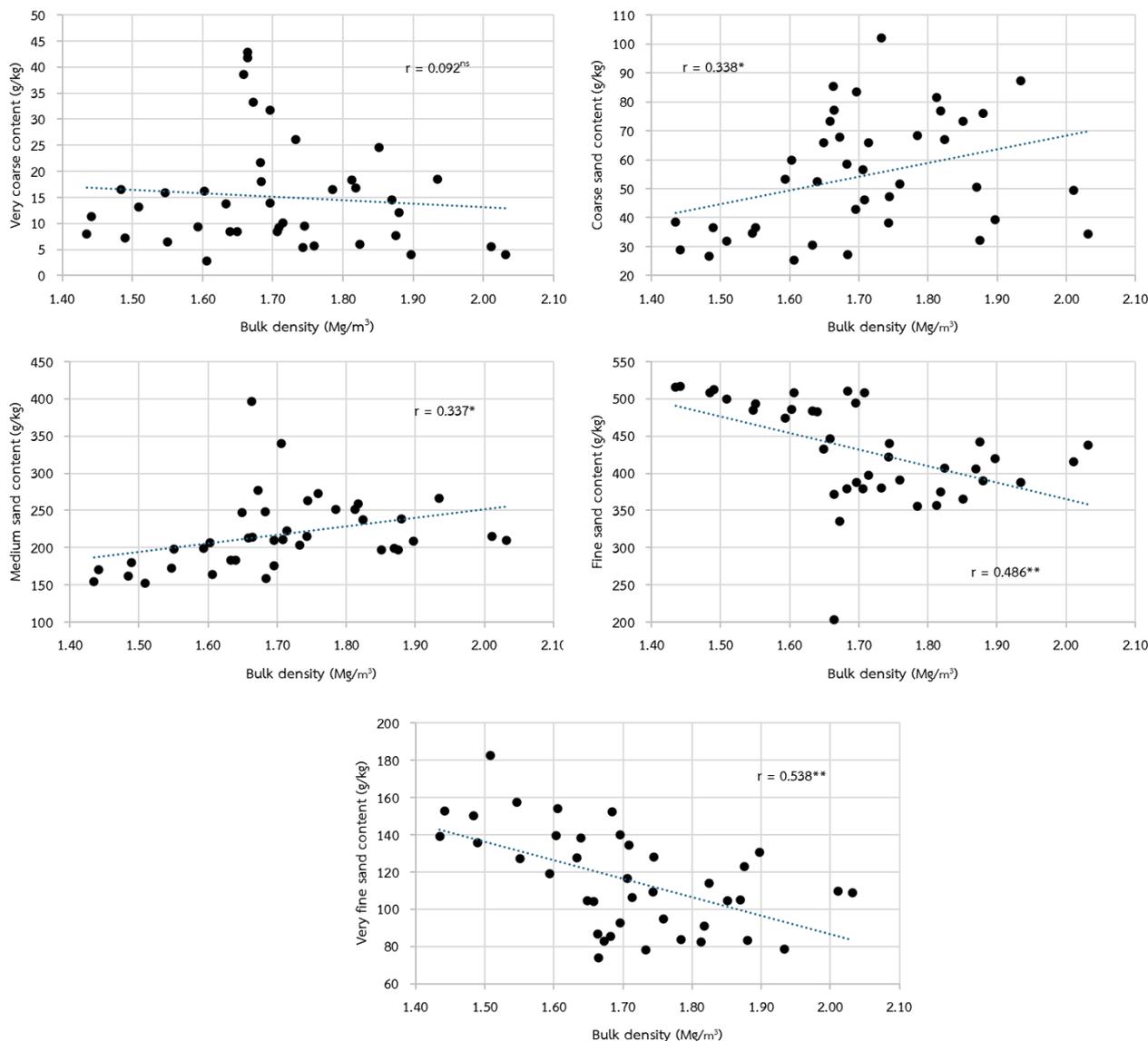


Figure 7 Correlation between bulk density and very coarse sand (A), coarse sand (B), medium sand (C), fine sand (D) and very fine sand (E) contents (n = 40)

Discussion

Impact of deep tillage on topsoil thickness and soil particle size distribution

Mechanical modifications of soil profiles, commonly referred to as deep tillage, could alleviate high subsoil strength, facilitating deeper rooting and thus the plant-availability of subsoil resources. In this current study, a 108-horsepower tractor equipped with 3-disc plough with 71.1 cm-disc diameter was used and had been operated for 10-consecutive years on the deep-tilled transect (Kn-1d, Kn-2d, Kn-3d, Kn-4d and Kn-5d) until this study was carried out. This deep tillage is a deep ploughing that turns soil horizons and results in complete or semi-complete inversion of the soil profile, with subsoil horizons ending up at the soil surface and the topsoil buried in the deeper layer. In

the case of this study, soil amendments were added to some soils, for instance, Kn-2d, Kn-3d and Kn-4d soils (**Table 1**), these can alternatively be referred to the term 'deep mixing' (Schneider et al., 2017). The deep tillage consequently resulted in thicker ploughed layers as shown in **Figure 3** with on average the approximate topsoil thickness being 41.2 cm compared to 25.2 cm in the soils under conventional tillage. This was because deep tillage mixed subsoil and topsoil together, leading to complete destruction of soil horizons, Ap and Bt1 horizons in this case, and subsequently the Bt horizon became Ap horizon of which these thick Ap horizon was subsequently divided into Ap1 and Ap2 horizon as in the case of Kn-2d, Kn-3d, Kn-4d and Kn-5d soils (**Figure 2A**). This inversion of soil horizons was also indicated by the content of sand, silt and clay particles in the 1-layer and 2-layer of soils under deep tillage that the amount of each particle size was almost identical (**Figures 4A, 4B and 4C**). In contrast, silt and clay particles were increasingly accumulated in the 2-layer of the soils under conventional tillage (**Figures 4B and 4c**) due likely to a vertical movement caused by leaching and not being disturbed by ploughing activity. This thicker topsoil in combination with soil amendments incorporated into a deeper zone clearly benefits cassava performance as shown by a study of Chuensombat et al. (2021) where all plots were located on deep-tilled transect, 46.94–56.88 t/ha of fresh tuber were observed when perlite, chicken manure and perlite + chicken manure had been applied for 7 years. Moreover, even without soil amendment addition a rather high fresh tuber yield of cassava (46.44 t/ha), much higher than the average yield of cassava (23.56 t/ha) in the region (Office of Agricultural Economic, 2020), was detected. This positive impact on cassava yield was observed because the mechanical modification of the subsoil as achieved by deep tillage can disrupt root-restricting soil layers, so-called plough pan, and enhance water storage, improving soil fertility in the long-term (Schröder and Schulte-Karring, 1984; Baumhardt et al., 2008), the latter was with the addition of proper type and amount of soil amendments (Anusontpornperm et al., 2014; Lunlio et al., 2017; Pradit et al., 2017). The positive influence of deep tillage was clearly much greater than subsoiling, sometimes referred to as deep ripping or deep chiseling, that the latter proved more costly due to the additional cost of two ripping operations in a perpendicular direction with the first plough of common land preparation for cassava cultivation still being required, and the positiveness lasted only one year (Riyaphan et al., 2010; Surin et al., 2013; Kaewkamthong et al., 2014; Anusontpornperm et al., 2014). The short-term effect of ripping may additionally be, under a little moistened plough pan, due to ripper only vertically cutting through the pan but not completely breaking it, and subsequently some small particles seeping to fill up pore spaces and make this pan packed once again after one rainy season. By all means, deep ripping in sandstone-derived soils in the northeast and possibly some other soils in the region and also other regions are impractical.

Impact of deep tillage on soil bulk density and hydraulic conductivity

Plough pan is common in cassava-cultivated upland soils (Kliaklom et al., 2010; Meewassana et al., 2010) and has become a major problem for cassava cultivation in the northeast Thailand (Anusontpornperm et al., 2009; Anusontpornperm et al., 2014). In this study area, the occurrence of plough pan was previously studied by Meewassana et al. (2010) who showed that in all 5 soils on the same toposequence (**Figure 1**) the layers below the regularly tilled topsoil had bulk density values in the range of 1.60–1.79 Mg/m³. This was still consistent with the result of the soils on conventional-tilled transect (Kn-1c, Kn-2c, Kn-3c, Kn-4c and Kn-5c) obtained in this current study. The bulk density values were almost identical in the same range or even greater in some soils (1.61–2.03 Mg/m³) as presented in **Figure 5A**. This illustrates that the plough pan still persistently and commonly occurs in

upland sandy soils used for cassava production and might be the case in other upland crops areas such as sugarcane (Kliaklom et al., 2010) and maize. This is because local farmers traditionally use small tractors, 75 horsepower or less, equipped with 3-disc plough with 55.9 cm-diameter disc or even smaller to perform the first plough. A ploughed layer hardly exceeds 30 cm depth in general. As a result, particularly ploughing during the period that the soil still contains quite a plethora of moisture, the weight of machineries, the above soil column and internal frictional forces (Gao et al., 2016) have gradually compacted the layer directly underlying the ploughed surface layer. The dense layers in this study started from 21–35 cm which was in agreement with previous study in the northeast (Anusontpornperm et al., 2009), Nakhon Ratchasima (Meewassana et al., 2010) and Khon Kaen (Kliaklom et al., 2010).

The high bulk density of the plough pan always results in slow saturated hydraulic conductivity as shown in this study. The plough pan had the values of hydraulic conductivity in the range of 0.1–8.6 cm/hr which was far slower than the ploughed layer (9.8–46.7 cm/hr) as presented in **Figure 5A**. Hence, this dense layer can impede vertical movement of water to the deeper part of soil profile which, in turn, would cause the accumulation of runoff and subsequent water erosion during high intensity period of rainfall, particularly on the land with some slope albeit long slope length. As a consequence, apart from the adverse impact of soil erosion on the loss of organic matter and plant nutrient stored in the topsoil, during dry season moisture in the subsoils, which normally can retain water under drought condition (Kirkgaard et al., 2007), also cannot rise through the dense layer, leaving annual crops, cassava in this case, to experience moisture deficiency to some degree. In addition, the subsoils directly underneath the ploughed layer reportedly, in many cases, store quite a large amount of total nitrogen (Wiesmeier et al., 2013) and total phosphorus (Kautz et al., 2013) but this compacted layer can often limit root propagation to reach plant nutrients in the subsoil (Bengough et al., 2011). Also, cassava root tuberization might also adversely be affected. Furthermore, during wet season at the time when cassava tubers have already contained starch, the plough pan can induce perch water in the rooting zone, resulting in cassava tuber rot which is common in many cassava fields (Anusontpornperm et al., 2014).

Relationship between soil bulk density and particle size distribution

The correlation between bulk density and different soil particles was purposely investigated in this study in order to provide a relationship that gives a better understanding of the conditions that favor plough pan formation in this type of soil. In this current study in the soils dominated by sand particles with sand and loamy sand as major textural classes (**Table 2**), the small amounts of silt and clay showed a negative correlation with bulk density (**Figures 6B and 6C**) which was in agreement with some reported linear correlations between bulk density and silt and clay particles (Akpa et al., 2016; de Souza et al., 2016; Beutler et al., 2017). The critical value of bulk density for restricting root growth varies with soil type (Hunt and Gilkes, 1992); however, in general bulk densities greater than 1.6 Mg/m³ tend to restrict root growth (McKenzie et al., 2004), particularly in sandy-textured soils (Arshad et al., 1996). The findings in this study were that the amounts of silt and clay particles of approximately over 100 and 65 g/kg, respectively, generated the bulk density value above the threshold suitable for roots elongation whilst with these two soil particles reaching nearly 120 and 70 g/kg, respectively the bulk density would be up to 1.80 Mg/m³ or greater which is considered to almost completely restrict root growth. In addition to silt and clay effects on soil bulk density, it was discovered in this study that the coarse and medium sand particles had a positive correlation and the fine and very fine sand particles had a negative correlation with bulk density but with much weaker

coefficient of determination than sand, silt and clay particles. This means the fraction of sand may not necessarily be used for prediction of the plough pan formation in this group of soils.

Conclusions

Deep tillage might be a tool to make crops more resilient to climate change and mitigate yield losses caused by droughts. The soils studied were dominated by sandy particles, falling into sand and loamy sand textural classes almost throughout soil mini profiles. The long-term operation of deep tillage rid of plough pan permanently as indicated by lower bulk density and more rapid hydraulic conductivity of the layer directly underneath the topsoil which, in turn, expanded the topsoil thickness to a greater extent compared to that under the conventional tillage. A thinner topsoil was observed in the soils under conventional tillage with a persistent presence of plough pan directly underlying the ploughed layer of which this dense layer had evidently higher bulk density and slower hydraulic conductivity. The bulk density in these plough pan-bearing soils was above critical level for plant root penetration. Despite these soils containing small amounts of silt and clay particles, these particles positively correlated with the bulk density, as especially demonstrated by the plough pan that had very high bulk density along with higher silt and clay contents than the loosened ones under continuous deep tillage operation. Deep ploughing short- to long-term trials should be conducted in some other soils differing in particle size distribution that have a plough pan presence. Soil amendments should be incorporated along to investigate whether they can be beneficial to soil physical viewpoints and soil fertility attributes.

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