Two Pan Soils of the Lower Volta Basin: Proposals for improving their Classification according to Soil Taxonomy and the World Reference Base

V.K. Avornyo[1], J.K. Amatekpor[2] and T.A. Adjadeh[2*]

[1] *Department of Agronomy, University for Development Studies, P.O. Box TL 1882, Tamale*

[2] *Department of Soil Science, University of Ghana, P.O. Box LG245, Legon, Accra*

*Corresponding author: *tadjadeh@ug.edu.gh*

Abstract

Kpejeglo series and *Agawtaw series* are two closely related pan soils in the Lower Volta Basin of Ghana. They have previously been classified variously according to Soil Taxonomy and the FAO/World Reference Base (WRB) systems without positively identifying the subsurface hardpan horizons. The hardpans have generally been described as compact clay loam or claypan horizons. This study was designed to 1) identify the hardpan horizons and 2) classify the soils according to the latest Soil Taxonomy and the WRB classification systems. Both soils had argillic and natric horizons. Bulk density of the pan horizons was higher than that of the horizons above them. Air-dried peds of the pan did not slake in water and 1M HCl or 40% NaOH. Up to 50% reduction in the size of the peds was only observed after alternating acid and alkali soaking for more than 5 hours. Peds from the lower limits of the hardpan of *Kpejeglo* Pedon 2, however, slaked in 1M HCl. The slaking characteristics show that the hardpan horizon could be a duripan, which possibly occurred with a petrocalcic horizon. Both soils were classified under Soil Taxonomy as Typic Duraqualfs. Natric horizon did not reflect in the classification because it is not presently provided at the subgroup level of Duraqualfs. We propose that due to the agronomic importance of natric horizon, Natric Duraqualfs would be more appropriate classification of the soils. The soils were also classified as Gleyic Solonetz (Duric) under the WRB system. Although Gleyic Solonetz places more emphasis on natric horizon than on petroduric horizon, the latter could be more limiting to plant growth. It would therefore be important if petroduric horizon reflects in the classification of the soils. Presently, under Solonetz, duric is only recognized as a supplementary qualifier so we propose that duric be elevated to a principal qualifier and should key out before gleyic so that the soils could be appropriately classified as Duric Solonetz.

Introduction

Pans, whether genetic (i.e. natural) or induced (i.e. artificial), are subsurface soil horizons or layers with very low hydraulic conductivity and very restrictive to root-growth. They are strongly compacted or indurated and have higher bulk density and lower total porosity than the layer immediately above or below them. Induced pans occur as a result of tillage operations or other human activities which may adversely affect root growth and crop development (Gomez et al., 2002; Chan et al., 2006; Trükmann et al., 2008). There are various types of pans including duripan, fragipan, claypan, ironpan and plough pan. The presence or absence of these diagnostic layers is used as differentiating characteristics at the great group level of Soil Taxonomy (Soil Survey Staff, 2014). *Kpejeglo* series and *Agawtaw* series are two major pan soils in the Accra Plains of Ghana (Brammer, 1962; Kaiser Engineers and Constructors, 1965; Obeng, 1970; Obeng et al., 1973; Agyili and Tei, 1979; Dowuona, 1985; Agyili and Amatekpor, 1993; Avornyo et al., 2013). *Agawtaw* series and associated soils cover more than 150,000 ha (Obeng, 1975) and constitute the largest single soil association in the Accra Plains (Kaiser Engineers and Constructors, 1965). They also occupy about 330 km^2 in the Ho-Keta Plains (Brammer, 1962). The presence of hardpans reduces effective soil volume available for moisture and nutrient storage, thus reducing the quality of these soils for agriculture purposes (Brammer, 1962; Kaiser Engineers and Constructors, 1965; Obeng, 1978; Avornyo et al., 2013). Furthermore, the soils easily get flooded even with moderate precipitation due to the presence of subsurface hardpan horizons and are thus highly susceptible to erosion and run-off (Brammer, 1962; Kaiser Engineers and Constructors, 1965). According to Agyili and Tei (1979), water percolation in *Agawtaw* series is impeded by the impervious hardpan which, results in loss of water through lateral seepage. Consequently, vast expanses of land in the Lower Volta Basin dominated by *Agawtaw* series and *Kpejeglo* series remain uncultivated and are mainly used as grazing fields for livestock (Brammer, 1962; Obeng, 1978). For example, a large-scale cultivation of maize on *Agawtaw* series by Glamour Farms failed as a result of excessive water logging (Agyili and Amatekpor, 1993).

Different soils in Ghana have been reported to have pans in their subsurface horizons. Eswaran et al. (1990) estimated that a total land area of 9,692 ha in Ghana is occupied by soils with plinthite and related forms. The phenomenon of ironpan has been studied extensively in Ghana (Obeng, 1970; Obeng et al., 1973). However, studies on other pan types have been very limited. Various researchers have reported the existence of hard pans in *Agawtaw* series and *Kpejeglo* series. For example, Brammer (1967) reported that the uppermost 22 – 30 cm of the subsoil of *Agawtaw* series was very compact and referred to the horizon as a hardpan. Dowuona (1985) corroborated this finding when he reported the presence of a hardpan layer consisting of about 30 cm layer of compact clay loam. Asiamah (1995) also described *Kpejeglo* series as having a compact sandy claypan underlying a 30 cm dark grey humus surface horizon. Furthermore, Amatekpor and Dowuona (2003) reported the existence of a massive and compact sandy clay loam horizon in *Agawtaw* series at a depth of about 30 cm that extended to about 60 cm from the surface. From these reports, it was obvious that the pan horizons in both soils (*Agawtaw* series and *Kpejeglo* series) were located at a similar depth from the surface. What was not clear, however, was whether these hardpan horizons were the same since there has been no previous attempt to characterize them according to any of the classification systems. *Agawtaw* series was classified by Dowuona (1985) as a Stratic Natraqualf and a Solodic Planosol according to the USDA (1975) and FAO-UNESCO (1974) systems, respectively and by Agyili and Amatekpor (1993) as a Natraqualf. Although these two classifications indicated the presence of a natric horizon, they did not bring out the characteristics of the pan in the soil. Thus, no satisfactory classification of these two soils that reflects their pan characteristics and high Na content is available. A major merit of the USDA and WRB soil classification systems is the use of unique nomenclature that gives a definite connotation of the major characteristics of the soils being classified. However, the two classification systems currently do not adequately bring out the pan and natric horizon characteristics of *Agawtaw* series and *Kpejeglo* series. This paper therefore proposes how the deficiencies in the USDA (Soil Taxonomy) and WRB classification systems could be addressed so that *Kpejeglo* series and *Agawtaw* series could be more appropriately classified.

Materials and methods

Two pedons of *Kpejeglo* series (KP1 and KP2) and two of *Agawtaw* series (AG1 and AG2) were studied. The two *Kpejeglo* pedons

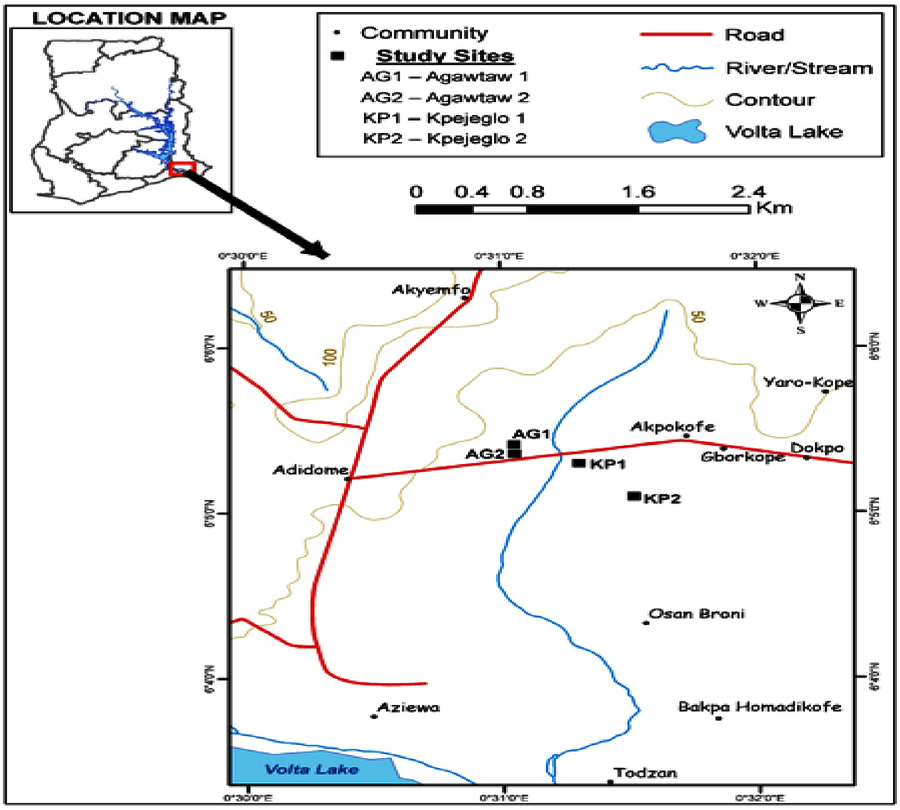

Fig. 1 Map of Ghana showing locations under investigation

were located at latitudes 6° 05'17.9" N and 6° 05' 05.8" N and longitudes 0° 31'17.8" E and 0° 31' 30.6" E respectively (Fig. 1). The two pedons of *Agawtaw* series were located on latitudes 6° 05' 22.7" N and 6° 05' 21.7" N and longitudes 0° 31' 02.8" E and 0° 31' 02.9" E, respectively. The elevation of the sites was about 21 m a.s.l. The four pedons were dug through the hardpan to a depth of 2.0 m or to the bedrock. Core samples were taken from each horizon of the pedons with a hammer-driven core sampler for bulk density determination. Disturbed samples were also collected for laboratory analyses. The climatic and physiographic characteristics of the Lower Volta Basin have been previously reported by Avornyo et al. (2013).

Chemical and physical analyses

Soil reaction, pH (H_2O and KCl)

For each horizon, pH was determined with a glass electrode in water and potassium chloride (KCl) solution using a 1:1 air-dried soil-water/1 mol L^{-1} KCl ratio after the samples had been stirred and allowed to stand for 1 h.

Soil organic carbon

Organic carbon content of the soils was determined according to the Walkley Black (1934) procedure which involved wet combustion of organic matter with a mixture of 10 ml of 1M potassium dichromate and 20 ml concentrated sulphuric acid at about 125 °C. The residual dichromate was titrated against 1M ferrous sulphate.

Cation Exchange Capacity and Extractable bases

The cation exchange capacity (CEC) of the soils and their exchangeable bases were determined according to the ammonium acetate (NH_4OAc) method using neutral 1M NH_4OAc pH 7 solution. Calcium and magnesium contents were determined by EDTA titration while sodium and potassium were determined with the flame photometer. Percentage base saturation (PBS) was derived by expressing total extractable bases as a percentage of CEC while exchangeable sodium percentage (ESP) was determined by expressing extractable sodium as a percentage of the CEC.

Electrical Conductivity

The electrical conductivity (EC) of the soils was determined by weighing 5 g of < 2 mm air-dried soil into 25 ml beakers after which 10 ml of distilled water was added, swirled to mix thoroughly and allowed to stand overnight. Conductance of the supernatant solution was read using a conductivity meter.

Particle size distribution

Particle size distribution was determined according to the Bouyoucous hydrometer method as modified by Day (1965) using sodium hexametaphosphate (calgon) as dispersing agent.

Bulk density

Undisturbed core samples oven-dried at 105 ^{o}C for 24 h, were used to determine the bulk density of the soils.

Slaking test

The pan horizons of the two soils were subjected to slaking test to determine whether they would meet the requirements of a duripan (Soil Survey Staff, 2014). Peds from the hardpan layers, 5 cm in diameter, were air dried and then submerged in water, 1M HCl and 40% NaOH for at least one hour. Peds that collapsed or became disaggregated in any of these solutions were considered to have slaked and this was used in classifying the pan layer. Ten peds per solution were used. The peds were observed after being submerged for 6, 10, 20, 30 and 60 minutes. The peds that did not slake after 60 minutes were submerged alternately in 1M HCl and 40% NaOH for prolonged periods (>5 hours).

Results and discussion

Slaking and classification of the hardpan horizons

The slaking test revealed that the horizons were not uniformly indurated. Air-dried peds of the pan horizons of KP1, AG1 and AG2 did not slake in water after more than an hour of being submerged, but prolonged soaking resulted in spalling of very thin films from KP2 (Table 1). In 1M HCl, KP1, AG1 and AG2 did

TABLE 1
Slaking test of the hard pan horizons

	Peds from pan horizons of the four pedons			
Solution	**Agawtaw Pedon 1**	**Agawtaw Pedon 2**	**Kpejeglo Pedon 1**	**Kpejeglo Pedon 2**
Water	No slaking observed	No slaking observed	No slaking observed	No slaking observed
HCl	No slaking observed	No slaking observed	No slaking observed	Peds from upper part of the horizon did not slake.
				Peds from lower parts slaked
NaOH	No slaking observed	No slaking observed	No slaking observed	----
Alternating HCl & NaOH	>50% reduction in size	>50% reduction in size	>50% reduction in size	----

not slake even after prolonged soaking, but a strong effervescence was observed with peds from the lower parts of the pan horizon of KP2 after 6 minutes prior to their complete collapse after about 40 minutes. Soaking in 40% NaOH produced similar results as in 1M HCl. More than 50% of air-dried peds of the two *Agawtaw* pans slaked only after alternately soaking in 1M HCl and 40% NaOH. For KP 1, alternating acid and alkali soaking was done for a long period (> 5 hours) before 50% reduction in the ped was observed.

Generally, peds from KP1 appeared to be more stable than those from KP2 as was revealed by the greater spalling of the latter. The slaking characteristics exhibited by the pan horizons were similar to those associated with duripans (Soil Survey Staff, 2014). Peds from KP2 appeared to be weakly cemented and thus exhibited characteristics transitional to those of a fragipan. Some duripans, which were weakly cemented, had characteristics transitional to a fragipan (Soil Survey Staff, 2014).

All the pedons were enriched with calcium carbonate nodules in the subsoil horizons (see Appendix). Stability of the air-dried peds from KP1, AG1 and AG2 and the upper part of the pan layer of KP2 in 1M HCl indicates that cementation of the pan layers was not likely to have been due to calcium carbonate. However, effervescence of the air-dried peds from the lower part of the hardpan of KP2 shows that calcium carbonate could have been an accessory cementing agent of the hardpan layer of this soil. Soil Survey Staff (2014) reported that a duripan and a petrocalcic horizon can occur together in the same horizon. Similarly, petroduric horizons can also co-occur with petrocalcic horizons (IUSS Working Group WRB, 2015).

The hardpan horizons could not be fragipans because their air-dried peds did not slake in water (Soil Survey Staff, 2014). The hardpan horizons of all the four pedons, however, slaked after prolonged alternate soaking in 40% NaOH and HCl which is a typical characteristic of a duripan (Soil Survey Staff, 2014). The hardpan layers also exhibited redoximorphic features of gray and strong brown, a characteristic reported for duripans (Soil Survey Staff, 2014). The aquic conditions of the lower Volta basin during the rainy season, especially in the areas dominated by *Kpejeglo* series and *Agawtaw* series and the very dry conditions experienced during the dry season may explain why the duripans exhibited redoximorphic features.

Hardpan horizons mentioned under the WRB classification system include: petrocalcic, petroduric, petrogypsic, petroplinthic and petrosalic horizons. The slaking characteristics of the hardpan layers of the two soils qualified them as petroduric horizons (IUSS Working Group WRB, 2015). These horizons were all more than 10 cm thick which is the minimum thickness required for a horizon to be petroduric. According to the WRB classification system (IUSS Working Group, 2015), a petroduric horizon shows reddish or reddish brown colour which fits the description of the pan horizons reported by Avornyo et al. (2013).

Classification of Kpejeglo Series and Agawtaw Series under Soil Taxonomy

The properties of *Kpejeglo* series and *Agawtaw* series did not satisfy the requirements of the soil orders which key out before Alfisols. The two soils had an argillic (Bt) horizon which was > 15% sodium saturated (i.e. natric horizon; Tables 2a to 2d). The natric horizon was not under a spodic or an oxic horizon so the two soils were neither Spodosols nor Oxisols. The two soils had neither mollic nor histic epipedons and so were neither Mollisols nor Histosols. Gelisols are soils with permanently frozen horizons which do not occur in the tropics. Furthermore, the two soils could not be classified as Vertisols because they did not satisfy the requirements of the order. Andisols are soils derived from volcanic ash or other parent materials enriched with short-range ordered minerals (allophane, imogolite and ferrihydrite) or aluminium-humus complexes while Aridisols are soils enriched with $CaCO_3$ found in arid environments (Soil Survey Staff, 2014). The environment where the two soils occur has no history of volcanic activity, neither is it arid; hence the two soils were neither Andisols nor Aridisols. The high base status of the soils also disqualifies them as Ultisols. *Agawtaw* series and *Kpejeglo* series therefore keyed out as Alfisols because they contained high amounts of extractable bases in addition to the natric horizon.

Moisture regimes are used as the differentiating criteria at the suborder level of Alfisols. The two soils (i.e. *Kpejeglo* and *Agawtaw*) had an aquic moisture regime and thus qualified as Aqualfs. Field observations indicate that these soils remained saturated for a number of days even after moderate rainfall. Buol et al., (1980), reported that the presence of mottles and also Fe and Mn concretions 2 mm in diameter are evidence of a seasonally saturated soil. All the pedons showed the presence of Fe and Mn concretions (Tables 2a to 2d; Appendix A and B). The soils had previously also been classified as Aqualfs by Dowuona (1985) and Agyili and Amatekpor (1993).

The key out order of the great groups of Aqualfs are: Cryaqualfs, Plinthaqualfs, Duraqualfs, Natraqualfs, Fragiaqualfs, Kandiaqualfs, Vermaqualfs, Albaqualfs, Glossaqualfs, Epiaqualfs and Endoaqualfs. At the great group level, the two soils were classified as Duraqualfs (i.e. Aqualfs that have a duripan). They could not be classified as Natraqualfs (i.e. Aqualfs that have a natric horizon) because Duraqualfs key out before Natraqualfs (Soil Survey Staff, 2014). Dowuona (1985) and Agyili and Amatekpor (1993) had classified *Agawtaw* series as a Natraqualf probably because they could not positively identify the indurated horizon. The hardpan horizon was previously described as sandy claypan by Asiamah (1995) or a massive and compact sandy clay loam (Amatekpor and Dowuona, 2003).

Currently under Soil Taxonomy, all Duraqualfs are provisionally classified at the subgroup level as Typic Duraqualfs (Soil Survey Staff, 2014). At the family level, soil temperature, mineralogy, cation exchange capacity, particle size, soil depth, soil reaction and rupture resistance are used to classify soils (Soil Survey Staff, 2014). Soil temperature of the area of study is isohyperthermic (i.e. the mean annual soil temperature is 22 ^{o}C or higher and the difference between mean summer and mean winter temperature does not exceed 6 ^{o}C). The soil was described as non-acidic in reaction since pH values generally ranged from 6 to 8, with an average of about 7. *Agawtaw* series contained more than 35% clay in the B horizon so qualified as fine clayey while *Kpejeglo* series which contained about 32% clay in the B horizon qualified as fine loamy. It could be inferred from the CEC values that the soils contained 1:1 clay minerals in the upper part of the solum and 2:1 clay minerals in the argillic (Bt) horizon. Thus, the soils could be classified as having mixed mineralogy which agrees with the classifications of Dowuona (1985) and Agyili and Amatekpor (1993). *Kpejeglo* series was therefore classified as *fine-loamy*, *mixed, non-acid isohyperthermic*, *Typic Duraqualf* and *Agawtaw* series as *fine clayey*, *mixed*, *non-acid, isohyperthermic*, *Typic Duraqualf* (Soil Survey Staff, 2014).

Classification of Kpejeglo series and Agawtaw series according to the World Reference Base for Soil Resources (WRB) System

Field and laboratory results obtained from this study showed the presence of two important diagnostic horizons namely natric and petroduric in the two soils. The two diagnostic horizons occurred within 100 cm from the soil surface. The soils could therefore be classified as either Solonetz or Durisols. However, Solonetz key out before Durisols hence the soils were classified as Solonetz. Under Solonetz, the principal and the supplementary qualifiers that best described the two soils were *Gleyic* and *Duric*. The two soils were thus classified as *Gleyic Solonetz* (*Duric*) (IUSS Working Group WRB, 2015). This classification agrees with that of Agyili and Amatekpor (1993) but contrasts with that of Dowuona (1985) who had classified *Agawtaw* series as a Solodic Planosol.

Proposals for improving the classification of Kpejeglo series and Agawtaw series at lower categorical levels

The *natric* horizon is of agronomic importance. Thus, it is important that its presence in a profile is reflected in the nomenclature of the soil being classified. These soils were classified as Typic Duraqualfs (Soil Survey Staff, 2014). They were not classified as Natric Duraqualfs, in spite of the presence of a *natric* horizon, because a *natric* subgroup is not recognized at present for Duraqualfs. A natric subgroup reflecting the *natric* properties of the soils would be a more appropriate classification for *Kpejeglo* series and *Agawtaw* series. Thus, we propose that a natric subgroup be recognized for Duraqualfs to appropriately classify soils such as *Kpejeglo* series and *Agawtaw* series. Similarly, classifying the soils as Gleyic Solonetz (IUSS Working Group WRB, 2015) puts more emphasis on the *natric* horizon even though the *petroduric* horizon would be more limiting to plant growth and development. We therefore propose that *duric* be elevated from a supplementary qualifier to a principal qualifier and should key out before gleyic. If these are done, the two soils would appropriately classify as Duric Solonetz with a relevant supplementary qualifier (probably *loamic*). Furthermore, establishment of a *natric* subgroup for Duraqualfs and elevation of *duric* to a principal qualifier under Solonetz, would enhance correlation between Soil Taxonomy and the WRB classification systems.

Conclusion

The hardpan horizons found in *Kpejeglo* series and *Agawtaw* series were identified to be a duripan (Soil Taxonomy) or a Petroduric horizon (WRB) using the slaking method. Although the cementing processes were not fully understood, silica and other accessory elements like $CaCO_3$ were the likely cementing agents. Under Soil Taxonomy (Soil Survey Staff, 2014) *Kpejeglo* series was classified as *fine-loamy, mixed*, *non-acid isohyperthermic*, *Typic Duraqualf* and *Agawtaw* series as *fine clayey*, *mixed, non-acid*, *isohyperthermic, Typic Duraqualf*. Both soils were classified under the WRB system (IUSS Working Group, WRB 2015) as *Gleyic Solonetz* (*Duric*). We propose the establishment of a *natric* subgroup for Duraqualfs under Soil Taxonomy so that the two soils could be appropriately classified as *Natric Duraqualfs*. Similarly, we propose that under the WRB system, *duric* be elevated from a supplementary qualifier to a principal qualifier and should key out before gleyic so that the soils could be appropriately classified as *Duric Solonetz*.

References

Agyili, P. and Tei, I.M. (1979). *Soils of the Kpong Irrigation Project Area near Akuse-Asutuare, Eastern Region. Technical Report* No. 127. S.R.I. C.S.I.R, Kumasi, Ghana.

Agyili, P. and Amatekpor, J.K. (1993). *Field-Tour- Accra Plains. In (ed) Ahenkorah, Y., Owusu-Bennoah, E. and Dowuona, G.N.N. Sustaining soil productivity in intense African agriculture*. Technical Center for Agriculture and Rural Cooperation ACP-EU (CTA).

Amatekpor, J.K. and Dowuona, G.N. (2003). *Field-Tour Guide. International conference on managing soils for food security, human health, and the environment: emerging strategies for poverty alleviation.* Soil Science Society of Ghana. 18th Annual General Meeting, 27th July – 2nd August 2003, GIMPA, Accra, Ghana.

Asiamah, R.D. (1995). *Soils of the Ho-Keta plains, Volta region, Ghana.* Soil Research Institute, Council for Scientific and Industrial research. Kwadaso – Kumasi, Ghana. pp. 115-116.

Avornyo, V.K. Adjadeh, T.A. and Amatekpor, J.K. 2013. Morphological, Chemical and Physical properties of two pan soils in the Lower Volta Basin of Ghana. *West African Journal of Applied Ecology*. **21** **(2)** 63-77.

Brammer, H. (1962). Soils. In *Agriculture and land use in Ghana*. In (ed) Wills, J.B. Oxford Univ. Press, Ghana Ministry of Food and Agriculture, Accra.

Brammer, H. (1967). Soils of the Accra Plains. Mem. No. 3. Soil Research institute, Ghana. Academy of Sciences, State Publishing Corporation, Accra – Tema.

Buol, S.W., Hole, F.D. and McCraken, R.J. (1980). *Soil Genesis and Classification*. Iowa State University Press, Ames.

Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S. and Peoples, M.B. (2006). Agronomic consequences of tractor wheel compaction on a clay soil. *Soil and Tillage Research*, **89:** 13-21.

Dowuona, G.N. (1985). *Correlation of the Ghanaian System of Soil Classification with other International Systems*. MPhil. Thesis. Department of Soil Science. Univ. of Ghana.

Eswaran, H., De Coninck, F. and Varghese, T. (1990). *Role of Plinthite and related forms. In (ed) Lal, R. and Stewart, B. A. Soil degradation*. Advances in Soil Science. Volume II. Springer –Verlag, New York. Inc.

Gomez, A., Powers, R.F., Singer, M.J. and Horwath, W.R. (2002). Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Science Society of America Journal*, **66**: 1334-1343.

IUSS Working Group WRB. (2015). *World reference base for soil resources 2014, update 2015, International soil classification system for naming soils and creating legends for soil maps*. World Soil Resources Reports No. 106. FAO, Rome.

Kaiser Engineers and Constructors Inc. (1965). *Accra plains irrigation feasibility study for Volta River Authority*, Vol. II, Report No. KEI-64-I-RE, New York

Obeng, H.B. (1970). *Characterization and classification of some ironpan soils of Ghana*. Ph.D. Thesis. Iowa State University. Ames. Iowa

Obeng, H.B., Acquaye, D.K and Bampoe-Addo, A. (1973). Ironpan geomorphic surfaces and associated soils of Ghana. *Journal of the Association for the Advancement of Agricultural Science in Africa*, **1**: 66-77.

Obeng H.B. (1978). Major soils of West Africa and their general suitability for crop and livestock production. *African Journal of Agricultural Science* **5 (1):**71–83.

Soil Survey Staff. (2014). *Keys to soil taxonomy*: 12th edition. United States Department of Agriculture, Natural Resources Conservation Service. Washington, D.C.

Trükmann, K., Reintam, E., Kuht, J., Nugis, E. and Edesi, L. (2008). Effect of soil compaction on growth of narrow-leafed lupine, oilseed rape and spring barley on sandy loam soil. *Agronomy Research*, **6:** 101-108.

APPENDIX A

Detail morphological description

Kpejeglo Pedon 1

Horizon	Depth	Description
Ap 1	0 - 10	Gray (5 YR 5/1) dry, dark grayish brown (10 YR 4/2) moist; loamy sand; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; many fine roots; clear smooth boundary; pH 6.4.
Ap 2	10 – 20	Brown (10 YR 5/3) dry, dark brown (10 YR 3/3) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; common fine roots; clear smooth boundary; pH 6.1
Btcm	20 – 45	Dark grayish brown (10 YR 4/2) dry; very dark grayish brown (10 YR 3/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; few very fine roots; common rounded soft and hard iron and manganese concretions; clear smooth boundary; pH 6.3.
Btncm	45 – 80	Gray (5Y 5/1) dry, dark gray (5 Y 4/1) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; few $CaCO_3$ nodules clear smooth boundary; pH 7.9.
Btnck 1	80 – 130	Olive gray (5 Y 5/2) dry, olive gray (5 Y 5/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 8.0.
Btnck 2	130- 150	Olive (5 Y 5/3) dry, olive gray (5 Y 5/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; many $CaCO_3$ nodules; clear smooth boundary; pH 8.1.
Cnk	150- 200	Pale olive (5 Y 6/3) dry, pale olive (5 Y 6/3) moist; sandy loam; angular blocky; slightly sticky, slightly plastic; firm; common fine irregular pores; few rounded rounded soft and hard iron and manganese concretions; many $CaCO_3$ nodules; decomposing acid gneiss; pH 8.3.

Kpejeglo Pedon 2

Horizon	Depth	Description
Ap 1	0 - 10	Dark gray (10 YR 4/1) dry, very dark grayish brown (10 YR 3/2) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; many fine roots; clear smooth boundary; pH 6.7.
Ap 2	10 – 20	Dark gray (10 YR 4/1) dry, very dark grayish brown (10 YR 3/2) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; common fine roots; clear smooth boundary; pH 6.5.
Btcm	20 – 40	Very dark gray (10 YR 3/1) dry; very dark brown (10 YR 2/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; very few, very fine roots; few rounded soft and hard iron and manganese concretions; clear smooth boundary; pH 6.9.
Btncm	40 – 65	Dark gray (10 YR 4/1) dry, gray (10 YR 5/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; very few, very fine roots; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 7.2.
Btnck 1	65–130	Light brownish gray (2. 5 Y 6/2) dry, gray (10 YR 6/1) moist; sandy clay loam; moderate, coarse, angular and sub angular blocky; slightly sticky, slightly plastic; firm; common fine tubular pores; few rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 8.2.
Btnck 2	130–150	Light gray (2.5 Y 7/2) dry, light gray (2.5 Y 7/2) moist; sandy clay loam; angular blocky; slightly sticky, slightly plastic; firm; common fine irregular pores; many $CaCO_3$ nodules; decomposing acid gneiss; pH 8.0.

APPENDIX B

Detail morphological description

Agawtaw Pedon 1

Horizon	Depth (cm)	Description
Ap 1	0 – 12	Dark grayish brown (10 YR 4/2) dry, very dark grayish brown (10 YR 3/2) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; many fine roots; clear smooth boundary; pH 6.4.
Ap 2	12 – 35	Very dark grayish brown (10 YR 3/2) dry, very dark brown (10 YR 2/2) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; common fine roots; clear smooth boundary; pH 6.4.
Btcm	35 – 60	Olive brown (2.5 Y 4/4) dry, very dark grayish brown (2.5 Y 3/2) moist; sandy clay; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; very few, very fine roots; common rounded soft and hard iron and manganese concretions; clear smooth boundary; pH 7.1.
Btnck 1	60 – 90	Light olive brown (2.5 Y 5/4) dry, olive brown (2.5 Y 4/4) moist; sandy clay; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 8.0.
Btnck 2	90 – 150	Light yellowish brown (2.5 Y 6/4) dry, grayish brown (2.5 Y 5/2) moist, sandy clay; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 8.4.
Cnk	150 - 200	Olive gray (5 Y 5/2) dry, pale olive (5 Y 6/2) moist; sandy clay loam; moderate, coarse angular and sub angular blocky; slightly sticky; slightly plastic; common $CaCO_3$ nodules; decomposing acid gneiss; pH 8.2

Agawtaw Pedon 2

Horizon	Depth	Description
Ap 1	0 -12	Dark grayish brown (10 YR 4/2) dry, very dark grayish brown (10 YR 3/1) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; many fine roots; clear smooth boundary; pH 6.7.
Ap 2	12 - 36	Dark grayish brown (10 YR 4/2) dry, very dark grayish brown (10 YR 3/2) moist; sandy loam; weak fine granular; non-sticky, non-plastic, friable; many fine tubular pores; common fine roots; clear smooth boundary; pH 6.5.
Btcm	36 - 60	Dark brown (10 YR 3/3) dry, very dark grayish brown (10 YR 3/2) moist; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; slightly sticky, slightly plastic; very firm; common fine tubular pores; very few, very fine roots; common rounded soft and hard iron and manganese concretions; clear smooth boundary; pH 6.8.
Btnck 1	60- 110	Brownish yellow (10 YR 6/6 dry), light yellowish brown (2.5 Y 6/4) dry; sandy clay loam; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 7.7.
Btnck 2	110- 132	Light yellowish brown (2.5 Y 6/4) dry, grayish brown (2.5 Y 5/2) moist; sandy clay; moderate, coarse, columnar breaking into strong, coarse angular blocky; very sticky, very plastic; firm; common fine tubular pores; common rounded soft and hard iron and manganese concretions; common $CaCO_3$ nodules; clear smooth boundary; pH 8.2.
Cnk	132- 200	Olive gray (5 Y 5/2) dry, pale olive (5 Y 6/2) moist; sandy clay loam; weak, coarse, angular blocky; slightly sticky, slightly plastic; firm; common fine irregular pores; many $CaCO_3$ nodules; decomposing acid gneiss; pH 8.4.