# Amounts and distribution of some forms of phosphorus in ferruginous soils of the interior savanna zone of Ghana

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SUMMARY

The forms and distribution of phosphorus in three well-drained and two poorly drained, widely cultivated Lixisols on two landscapes in the interior savanna zone of Ghana were studied. Total phosphorus (TP) and dithionite-citrate-bicarbonate extractable P (DCB-P) concentrations increase with depth in all the soils and are related to profile maturity in the well-drained soils. In the low-lying soils, however, the concentration is governed by drainage. The greatest amounts of TP occur in the topsoils of the Tingoli series on Catena 1, which were 132, 92, 744, and 700 mg/kg in the fine earth, silt, clay, and nodule fractions, respectively. The Kpelesawgu series on Catena 2, however, has the least TP accumulation of 78, 159, and 50 mg/kg in the fine earth, silt, and clay fractions, respectively. The large concentration of TP and DCB-P in the nodules and clays is due to their greater sesquioxide contents. The available P concentration is extremely low because of the low content of P-bearing parent material. The amounts of clay, silt, and DCB-P may be used to estimate the accumulation of TP concentration in the soils. Variations in TP saturation correspond with changes in clay accumulation in the soils on Catena 1 and in silt content in the Catena 2 soils.

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RÉSUMÉ

NARTEY, E., DOWUONA, G. N., AHENKORAH, Y., MERMUT, A. R. & TIESSEN, H.: *Les quantités et la distribution de quelques formes de phosphore dans les sols ferrugineux de l'intérieur de la zone savane du Ghana.* Les formes et la distribution de phosphore en trois bien-asséchés et deux malasséchés Lixisols largement-cultivés sur deux paysages à l'intérieur de la zone savane du Ghana étaient étudiés. Les concentrations de phosphore totale (PT) et de dithionite-citrate-bicarbonate P extractible (DCB-P) augmentent à profondeur dans tous les sols et se sont liés à la maturité du profil dans les sols bien-asséchés. Dans les sols s'étendants-bas, cependant, la concentration est gouvernée par l'assèchement. Les plus grandes quantités de PT se produisent dans les couches arables des séries de Tingoli sur catena 1 qui étaient 132, 92, 744 et 700 mg/kg dans la terre fine, le limon, l'argile et respectivement dans les fractions de nodule. Les séries de Kpelesawgu sur catena 2, toutefois, ont la moindre accumulation de PT de 78, 159 et 50 mg/kg dans la terre fine, le limon et respectivement dans les fractions d' argile. La grande concentration de PT et DCB-P dans les nodules et les argiles est dû à ses plus grands contenus de ses quioxide. La concentration de P disponible est extrémement basse à cause de faible contenu de matériel, parental contenant le P. Les quantités d' argile de limon et de DCB-P peuvent être utilisées pour estimer l'accumulation de la concentration de PT dans les sols.

## Introduction

Greatęr attention has been paid by researchers defining the areas where phosphorus (P) deficiency is most acute in soils and the ways of overcoming the short-term effects of this limitation through application of fertilizers. Most studies on P in Ghana have focused on sorption and desorption of nutrient in surface soils (Ahenkorah, 1968; Kanabo, Halm & Obeng, 1978; Owusu-Bennoah & Acquaye, 1989; Abekoe, 1989; Tiessen, Hauffe & Mermut, 1991). However, any attempt to evaluate the P status of soils cannot be complete without an understanding of the forms and distribution of P in the landscape.

Although P is considered to be immobile in soils, considering the long time spans involved in soil profile development, the element can undergo significant changes in form and location. Nevertheless, movement of soil P may occur in three ways, namely: the action of soil organisms, mass flow, and diffusion. For each process, the magnitude of the movement will depend on the fraction of soil P that is involved and the rate of movement of that fraction.

The movement of P in soils along the landscape often produces differences in P status of pedons of the same soil series or associations (Smeck & Runge, 1971). Distribution of P within soil profiles at low elevations is markedly different from those in upland positions (Smeck, 1973; Day, Collins & Washer, 1987). Total P tends to increase downslope. On the contrary, Agbenin (1992) observed that total P contents of soils in north eastern Brazil decreased down the slope.

The nature and distribution of forms of phosphorus in soils have provided useful information for assessing the available P status and estimating the degree of weathering of soils. In Ghana, however, investigations into the amounts and distribution of P in soils have received very little attention. Even in the few studies, the emphasis has been on the plough layer and not the whole profile.

This study, therefore, provides information on the amounts and distribution of some forms of soil P in modal profiles on two different catenas in the interior savanna zone of Ghana.

## Materials and methods

### *Site characteristics and soil sampling*

The study site is at 6° 25' N and 1° 00' W in the interior savanna zone of Ghana near the Savanna Agricultural Research Institute, Nyankpala. This zone is semi-arid with total annual rainfall of 1000 mm and mean daily temperature of 28 °C. The vegetation is dominantly grassland-woodland. The local geology comprises clay-shale with lenses of sandstone, siltstone, and mudstone (Adu, 1957) of the Lower Voltaian formations.

The soils studied are among the dominant and widely cultivated groups of soils in the zone. They include the Tingoli and Tolon (Plinthic Lixisols according to FAO-UNESCO, 1990) as well as Kumayili series (Ferric Lixisol) which are well drained and occupy the summit, upper slope and midslope positions, respectively, on a toposequence (Catena 1). They occur at approximate respective elevations of 186, 178, and 171 m above sea level on the catena. The Tingoli and Tolon series have developed from ironstone gravel and ferruginized brash and contain varying amounts of ironstone nodules, whereas the Kumayili series have formed from local alluvium/hill-wash with very few amounts of ironstone concretions. Two other soils, Kpelesawgu and Changnalili series (Plinthic Lixisols), occur on a toposequence (Catena 2) at elevations of 170 and 167 m above sea level, respectively. The Kpelesawgu series has formed from local alluvium and is imperfectly drained, whereas the Changnalili series, which is shallow and poorly drained, has developed from massive ironstone that is deepened by soil wash.

Soil samples were collected from each genetic horizon of all the modal profiles (pedons) for laboratory analyses. The samples were air-dried and later passed through a 2-mm sieve to obtain the fine earth fraction. The nodules (less than 2 mm in diameter) in these samples were isolated by hand-picking after sieving with an 0.5-mm sieve, washed, oven-dried and used for analysis. A portion of the fine earth fraction from each horizon was fractionated into silt and clay (Jackson, 1974) and used for chemical analyses.

### *Laboratory analyses*

Particle size distribution was determined by the conventional hydrometer method (Day, 1965). The TP concentration in the fine earth, silt, clay, and nodules was determined by a modified method of Thomas, Sheard & Moyer (1967). Available P in the fine earth and nodules was determined by the method of Olsen *et al.* (1954).

Dithionite-citrate-bicarbonate extractable phosphorus was determined by a modified method of McLeod & Clarke (1973).

**Results and discussion**

*General soil characteristics*

Nartey (1994) observed that the sola of all the soils are generally sandy loam in texture while the subsoils are clayey. The reaction of the soils and their respective associated nodules is slightly acidic with *p*H values ranging from 5.7 to 6.3. Organic carbon contents are very low, ranging from 2.8 to 7.0 g/kg while the cation exchange capacity was found to be less than 14 cmol (+)/kg.

The clay mineralogy of all the soils is dominated by kaolinite which is consistent with the low cation exchange capacity. The imperfectly and poorly drained pedons on Catena 2 also contain some amounts of mica (illite) with relatively larger amounts of K (Nartey, 1994). Profile maturity is in the order of Tingoli series > Tolon series >Kumayili series on Catena 1 whereas it is Kpelesawgu series > Changnalili series on Catena 2. Maturity among the different particle size fractions within each profile is in the order of nodule > clay > fine earth > silt.

*Forms and distribution of phosphorus*

*Total phosphorus.* Table 1 shows the TP saturation and distribution in the various size fractions. The TP concentration of the fine earth in all the soils is very low, ranging from 78 to 282 mg/kg. The Tingoli and Tolon series at upland sites have higher TP contents in the fine earth than their associated mid-slope Kumayili member on Catena 1 and the low-lying Kpelesawgu and Changnalili series on Catena 2. The TP concentration tends to increase gradually with depth in all the five profiles (Fig. 1). For Catena 1, therefore, the order of decreasing TP amounts in the soils is Tingoli series > Tolon series > Kumayili series. The most highly developed soils in a landscape tend to accumulate more total P (Godfrey & Riecken, 1954). This may explain the highest TP concentrations in the Tingoli series, which is the most matured soii in the two landscapes. The amounts of kaolinite and sesquioxides, which are larger in this soil (Nartey, 1994), can influence the P saturation because these minerals play an active role in P sorption (Juo & Fox, 1977; Fageria & Filho, 1987).

For soils on low-lying landscapes, the distribution of total P does not normally follow the sequence of profile maturity. The TP contents in the imperfectly and poorly drained soils on Catena 2, on the contrary, decrease with increasing profile maturity. A similar observation was reported by Walker & Syers (1976) in other poorly drained soils elsewhere. The higher P accumulation in the Changnalili series may be the result of translocation of material from upslope (Smeck & Runge, 1971). According to Syers *et al.* (1969), where TP is mainly concentrated in the silt fraction, soil development is often at its early stages, as in the Changnalili series. Nevertheless, in all the soils on the two catenas, TP accumulation in the silt fraction is less than in the clay fraction. This is a further evidence that the soils, especially those on Catena 1, are pedogenically more matured.

*Total phosphorus and particle size.* In all the soil profiles, TP contents in the various fractions follow the general trend of nodule≈ clay > fine earth > silt. The TP concentrations in the nodule and clay fractions decrease with depth and, therefore, weathering intensity. The silt fraction accumulates smaller amounts of TP, suggesting that the clay and the nodules are more effective in controlling the TP accumulation in all the soils (Dowuona *et al.*, 1994). Greater concentration of sesquioxides and kaolinite in the nodules and clay are responsible for the accumulation of phosphorus in these fractions (Nartey, 1994).

The greater TP accumulation in the clay fraction compared to the silt fraction agrees with reports on soils elsewhere (Lekwa & Whiteside, 1986; Day, Collins & Washer, 1987). Hanley & Murphy (1970) suggested that a meaningful way to determine the role of particle size on TP saturation is by comparing the contribution by silt

TABLE 1

*Concentration and Distribution of Some Forms of Phosphorus in the Soil Separates of the Different Profiles†*

| *Depth* | *Fine earth* | | | *Clay* | | *Silt* | | *Nodule (<2 mm)* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *(cm)* | *TP* | *Available P* | *DCB-P* | *TP* | *DCB-P* | *TP* | *DCB-P* | *TP* | *Available P* | *DCB-P* |
| | *mg/kg* | | | | | | | | | |
| | | | | | ***Catena 1*** | | | | | |
| | | | | | **Tingoli series** | | | | | |
| 0-16 | 132.2 | 2.8 | 68.6 | 744.6 | 302.8 | 91.9 | 85.3 | 700.3 | 3.1 | 253.9 |
| 16-32 | 276.2 | 2.2 | 115.9 | 588.8 | 316.7 | 95.5 | 67.5 | 777.6 | 2.7 | 259.8 |
| 32-48 | 252.0 | 1.8 | 108.1 | 491.4 | 195.2 | 66.7 | 40.7 | 675.6 | 2.8 | 234.0 |
| 48-67 | 282.1 | 1.3 | 73.3 | 588.2 | 186.7 | 203.5 | 118.8 | 425.2 | 2.5 | 120.5 |
| 67-98 | 228.3 | 1.6 | 58.7 | 332.3 | 137.8 | 163.1 | 78.1 | 281.8 | 1.5 | 70.7 |
| 98+ | 216.0 | 1.7 | 79.6 | 398.5 | 139.8 | 131.4 | 77.8 | 286.6 | 3.6 | 101.0 |
| | | | | | **Tolon series** | | | | | |
| 0-14 | 105.2 | 2.9 | 44.4 | 457.0 | 185.2 | 66.0 | 28.3 | 510.4 | 2.9 | 124.7 |
| 14-30 | 114.1 | 2.4 | 44.1 | 469.1 | 177.0 | 58.6 | 26.2 | 419.0 | 2.1 | 143.3 |
| 30-54 | 198.3 | 2.9 | 74.2 | 454.2 | 198.2 | 92.5 | 44.2 | 482.5 | 1.9 | 146.0 |
| 54-76 | 231.1 | 1.4 | 66.2 | 431.0 | 191.9 | 107.9 | 41.2 | 268.2 | 4.1 | 108.8 |
| 76-100 | 204.4 | 2.1 | 55.8 | 373.5 | 149.0 | 139.3 | 53.7 | 257.2 | 4.3 | 86.4 |
| | | | | | **Kumayili series** | | | | | |
| 0-18 | 84.2 | 2.4 | 45.9 | 380.9 | 180.5 | 61.9 | 29.7 | nd | nd | nd |
| 18-36 | 81.3 | 2.5 | 35.9 | 363.0 | 154.5 | 53.0 | 24.5 | nd | nd | nd |
| 36-57 | 96.1 | 1.6 | 36.5 | 315.9 | 118.5 | 53.9 | 22.0 | nd | nd | nd |
| 57-90 | 126.0 | 2.1 | 43.2 | 323.5 | 117.9 | 58.0 | 18.3 | 392.1 | 4.1 | 173.5 |
| 90+ | 156.2 | 2.1 | 51.6 | 264.0 | 87.7 | 100.2 | 48.2 | 314.0 | 4.6 | 122.9 |
| | | | | | ***Catena 2*** | | | | | |
| | | | | | **Kpelesawgu series** | | | | | |
| 0-15 | 78.2 | 2.3 | 31.0 | 259.2 | 123.0 | 50.4 | 18.2 | nd | nd | nd |
| 15-34 | 96.1 | 2.1 | 27.4 | 287.2 | 54.2 | 46.9 | 21.3 | nd | nd | nd |
| 34-64 | 99.3 | 1.7 | 23.5 | 268.5 | 88.0 | 52.9 | 18.3 | nd | nd | nd |
| 64-100 | 138.2 | 1.6 | 33.0 | 268.1 | 80.7 | 74.4 | 80.73 | 359.4 | 3.9 | 118.1 |
| | | | | | **Changnalili series** | | | | | |
| 0-12 | 102.2 | 3.8 | 42.8 | 432.5 | 146.2 | 58.2 | 31.0 | nd | nd | nd |
| 12-24 | 102.2 | 3.8 | 33.1 | 348.5 | 122.5 | 64.5 | 36.6 | nd | nd | nd |
| 24-37 | 114.3 | 2.4 | 32.8 | 344.0 | 46.4 | 101.8 | 37.4 | 374.1 | 5.0 | 161.6 |
| 37-57 | 180.1 | 2.3 | 46.1 | 371.7 | 105.0 | 87.2 | 43.9 | 290.7 | 4.4 | 105.0 |
| 57-100 | 90.4 | 1.9 | 45.0 | 198.2 | 47.1 | 63.7 | 24.3 | 136.8 | 3.4 | 30.6 |

† nd = not determined (due to very low amounts of nodules).

and clay size separates to the TP status of soils. In this study, clay is found to be a more important contributor than silt to the soil TP pool (Table 2). The clay fraction contributes over 90 per cent of the TP in all the well-drained soils on Catena 1. In the imperfectly drained and poorly drained soils on Catena 2, the contribution by clay is still high (about 88 per cent, on the average). This is because the Fe and Al oxides, which act as sites for phosphorus sorption, are concentrated more in the clay fraction in these soils (Nartey, 1994). The contribution by silt to the TP pool is very small (<20 per cent). Generally, in the Changnalili series, the silt fraction gives the highest contribution to TP. This relatively large contribution is the result of greater accumulation of silt in this soil and agrees with similar observation in other low-lying tropical soils elsewhere (Syers *et al.*, 1969). TheTP amounts in soils increase with increasing clay content (William

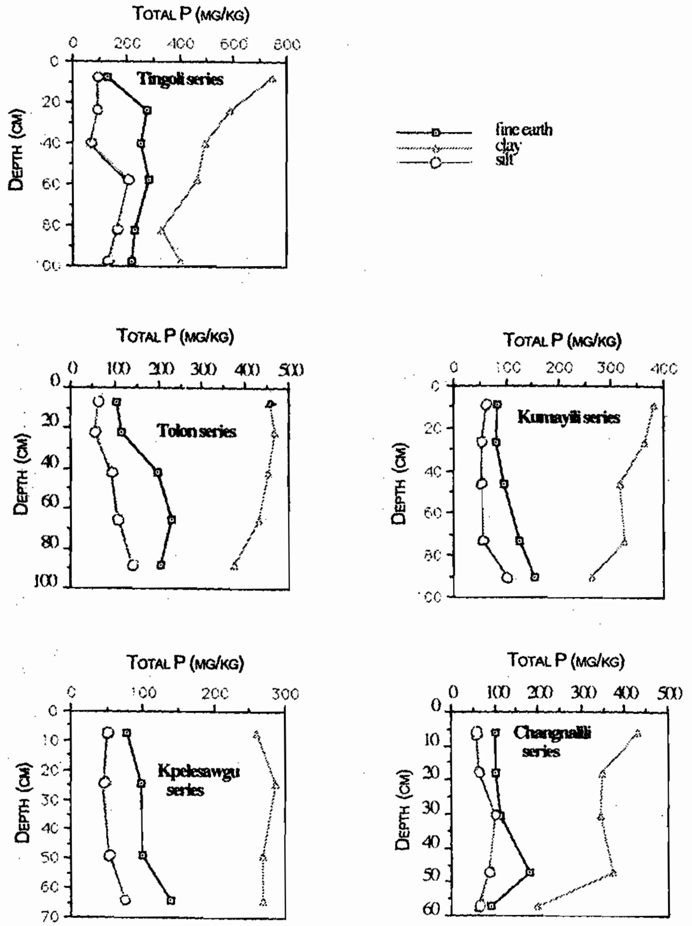


Fig. 1. Total P distribution in the silt, fine earth and clay fractions in the profiles.

from routine particle size distribution data. Consequently, accumulation of clay may be used to predict TP levels in well-drained soils whilst silt content can be used in poorly drained, low-lying soils.

The role of nodules in P saturation is noteworthy. The nodules in the sola of the Tingoli and Tolon series on Catena 1 show marked differences in TP saturation compared to those in the subsoils in each profile. In the solum, the nodules may immobilize more P (through fertilizer application or ash inputs) added to the soils because of their greater sesquioxide contents. These nodules which represent a more matured state of soil development have broken external surfaces and may serve as reservoirs to release immobilized P into the labile pool. The immobilization and release may have agronomic implications, considering that the nodule-rich Tingoli and Tolon series are widely cultivated and also subjected to annual dry season burning; factors which contribute to the low levels of P. The management of these soils must consider this behaviour to satisfy the P requirements of crops.

& Saunders, 1956; Acquaye & Oteng, 1972) which suggests co-migration of clay with phosphorus. There is a significant correlation between clay and TP in the fine earth of the Tolon ($r = 0.92^{**}$) and Kumayili series ($r = 0.98^{**}$) (Fig. 2), and also a significant correlation between silt and TP in the Kpelesawgu series ($r = 0.92^{*}$) (Fig. 3). This indicates that clay and silt translocation can be used to assess the relative accumulation of TP in soils on different landscape positions. The significance of this relation may lie in the ease with which the TP saturation of soils can be predicted

*Total phosphorus and drainage.* The generally smaller TP concentration in the soils on Catena 2 compared to Catena 1 can be attributed to drainage. The imperfectly and poorly drained soils on Catena 2, which occur in low-lying areas, become waterlogged especially during the wet

TABLE 2

*Relative Contribution to Total P by the Silt and Clay Fractions*

| *Depth (cm)* | *Particle size distribution* *Silt* | *Clay* | *Proportion of total P** *Silt* | *Clay* |
|---|---|---|---|---|
| | ........% | ........ | ........ | ........ |
| | | ***Catena 1*** | | |
| | | **Tingoli series** | | |
| 0-16 | 8.1 | 21.9 | 4.4 | 95.6 |
| 16-32 | 7.9 | 32.2 | 3.9 | 96.1 |
| 32-48 | 7.7 | 49.1 | 2.1 | 97.9 |
| 48-67 | 10.6 | 36.7 | 11.2 | 88.8 |
| 67-98 | 8.9 | 44.9 | 8.9 | 91.1 |
| 98+ | 8.8 | 50.6 | 5.4 | 94.6 |
| | | **Tolon series** | | |
| 0-14 | 7.9 | 21.5 | 5.1 | 94.9 |
| 14-30 | 12.4 | 25.2 | 5.8 | 94.2 |
| 30-54 | 15.4 | 36.3 | 8.0 | 92.0 |
| 54-76 | 6.3 | 47.2 | 3.3 | 96.7 |
| 76-100 | 7.3 | 31.9 | 7.8 | 92.2 |
| | | **Kumayili series** | | |
| 0-18 | 8.0 | 19.2 | 6.4 | 93.6 |
| 18-36 | 11.8 | 23.9 | 6.7 | 93.3 |
| 36-57 | 15.9 | 29.5 | 8.4 | 91.6 |
| 57-90 | 15.5 | 39.0 | 6.6 | 93.4 |
| 90+ | 13.8 | 49.3 | 9.6 | 90.4 |
| | | ***Catena 2*** | | |
| | | **Kpelesawgu series** | | |
| 0-15 | 15.0 | 21.5 | 12.0 | 88.0 |
| 15-34 | 18.5 | 30.3 | 9.1 | 90.9 |
| 34-64 | 22.6 | 42.9 | 9.4 | 90.6 |
| 64-100+ | 25.9 | 32.1 | 18.3 | 81.7 |
| | | **Changnalili series** | | |
| 0-12 | 22.7 | 20.3 | 13.1 | 86.9 |
| 12-24 | 20.9 | 28.2 | 12.0 | 88.0 |
| 24-37 | 22.0 | 33.4 | 16.3 | 83.7 |
| 37-57 | 24.6 | 40.5 | 12.5 | 87.5 |
| 57-100+ | 12.6 | 61.0 | 6.2 | 93.8 |

*calculated as: $\frac{\text{total P in silt or clay} \times \%\ \text{silt or clay}}{(\text{total P in silt} \times \%\ \text{silt}) + (\text{total P in clay} \times \%\ \text{clay})} \times 100\ \%$

season. This, therefore, predisposes the Catena 2 soils to leaching losses of phosphorus especially, inorganic P and tallies with the evidence on leaching of P from soils associated with redox conditions caused by a fluctuating water table (Glenworth, 1947).

The differences in P saturation in the three soils on Catena 1 can be explained by differences in

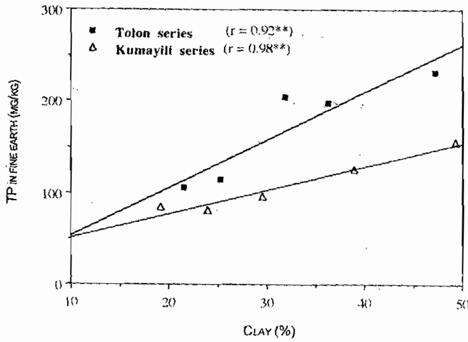


Fig. 2. Relationship between total P concentration in the fine earth fraction and clay content (**$P$<0.01).

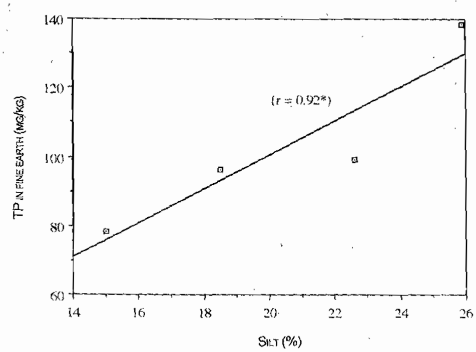


Fig. 3. Relationship between total P concentration in the fine earth fraction and silt content.

drainage. As slope or relief increases, drainage improves which leads to a decrease in calcium phosphate concentrations. This subsequently results in an increase in both occluded and non-occluded P and, therefore, TP (Hsu & Jackson, 1960). Consequently, the midslope Kumayili series on Catena 1 has the least amount of TP compared to the upland end member, Tingoli series, which has the greatest TP saturation.

*Available phosphorus*

The available P (AP) concentration in the fine earth and associated nodules is extremely low (< 6 mg/kg) compared to the TP (Table 1), probably because of the very low TP contents of the parent material (Adu, 1957). Moreover, the addition of P to the soil through vegetative cycling in the savanna zone is very small; therefore, organic phosphate which contributes to AP levels is low (Halm & Bampoe-Addo, 1972).

The AP saturation is generally greater in the solum of each profile. This is consistent with the small concentrations of DCB and oxalate extractable Fe and Al in the upper portions of the soils (Nartey, 1994). The Tingoli series, which has the highest TP content, recorded the lowest mean available P concentration in the profile because of its high iron oxide content. The Changnalili series, on the other hand, has the highest AP content, probably due to its smaller sesquioxide content and relatively greater organic carbon accumulation (Nartey, 1994).

*Dithionite-citrate-bicarbonate extractable phosphorus (DCB-P)*

The dithionite-citrate-bicarbonate extractable phosphorus (DCB-P) is the P attached to Fe and Al and extracted by DCB. The DCB-P is higher in the soils on Catena 1 than in the soils on Catena 2 (Table 1). This agrees with the observation by Schwertmann & Fanning (1976) that DCB-P concentration decreases with increasing soil wetness. Considering that the nodules have larger amounts of sesquioxides (Nartey, 1994), one would expect them to contain the highest amount of DCB-P. On the contrary, the clay fraction rather has the greatest concentration of DCB-P, especially in the two upland soils on Catena 1. It is, therefore, likely that the attachment of P to the DCB extractable Fe and Al is dependent on some factors other than sesquioxide content alone. The nature, amounts, and surface of clay minerals (e.g. kaolinite) probably also have some interactive roles to play.

The decrease in the DCB-P concentrations of the clay and nodule fractions with depth agrees with the observation by Schwertmann & Fanning (1976), notwithstanding the increase in sesquioxide contents with depth (Nartey, 1994). This trend may be attributed to a more readily available P supply in the zone of bio-accumulation in the solum. In the Catena 1 soils, the DCB-P concentration is greatest in the Tingoli series, followed by the Tolon and Kumayili series in that order. The gradient in DCB-P concentration, therefore, follows the stage of decreasing maturity and crystallinity in these soils. Furthermore, this gradation in maturity which is consistent with the variations in TP saturation, implies that the DCB-P concentration may be a more reliable estimate of TP saturation in soils. The significant correlation between the DCB-P and the TP concentrations in the Tolon series on Catena 1 soils ($r$ = 0.80*) supports this observation. In the Catena 2 soils, DCB-P concentration is higher in the Changnalili series than in the Kpelesawgu series which also corresponds with the trend in TP concentrations in the two soils. The higher DCB-P in the relatively low-lying Changnalili series could also be due to translocation of material from upslope.

**Conclusion**

The TP contents in the soils follow a profile concentration gradient of Tingoli series > Tolon series > Kumayili series on Catena 1 and Changnalili series > Kpelesawgu series on Catena 2. In each profile, TP saturation in the various fractions follows the decreasing order of nodule ≈ clay > fine earth > silt. The clay fraction is a better contributor to the soil TP pool so that the nature and amounts of clay as well as the DCB-P concentration may be used to predict the TP saturation in the soils studied, especially in the well-drained soils on Catena 1. In the poorly drained soils, however, the silt content can be used to predict the TP levels. The TP and DCB-P concentrations in the Tingoli, Tolon and Kumayili series are related to profile maturity. However, for the Kpelesawgu and Changnalili series on Catena 2, TP and DCB-P concentrations are related to drainage. The AP content is highest in the Changnalili series because of its relatively low sesquioxide and high organic carbon contents. Agronomically, the two upland soils on Catena 1 may either require lower P input or be more useful in meeting the phosphorus requirements of crops than the soils on Catena 2.

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