PHOSPHORUS IN IOWA SOILS
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Introduction

Phosphorus is a key element in all living things. It is also a major fertilizer element and a major component of manure. Excess phosphorus in bodies of water causes growth of algae and other aquatic plants and thus is of environmental concern. Phosphorus is also a dynamic element in soil genesis. The amount, distribution, and chemical composition of phosphorus in soils are closely related to the classic factors of soil formation-climate, organisms, parent material, topography, and time. Also, in the past 150 years in Iowa, human influence on soils and landscapes is an additional variable that contributes to changes in soil profile characteristics and properties. These changes include but are not limited to the properties associated with accelerated erosion and related deposition, fertilization, cultivation and resulting decrease in organic matter, and changes in the water regimes of the whole soil due to artificial drainage.

In 1940, Pearson, Spry, and Pierre published a paper entitled “The Vertical Distribution of Total and Dilute Acid-soluble Phosphorus in Twelve Iowa Soil Profiles”. Since that time there has been an interest in understanding and predicting the phosphorus regimes of Iowa soils. The paper cited and other subsequent research formed the basis for the refinement of soil test recommendations that recognize low and high subsoil P categories. This distinction results in the range of soil test categories being modified to acknowledge the difference in available subsoil P. For example, the very low soil test category for P for corn production is 0-8 ppm for soils with low subsoil P but 0-5 for soils with high subsoil P. The differences in subsoil P are directly related to the composition of the P compounds in soils which in turn is related to the factors of soil formation. Therefore, it is important to understand the transformations and dynamics of P that occur in soil ecosystems.

Phosphorus Forms in Soil

Terminology used to describe various forms of P in the soil is diverse but most researchers use terminology related to the extractant used. Smeeck (1985) used the terms soluble, labile, primary minerals, secondary minerals, organic and occluded to describe P forms. Soluble P is extractable with water or a dilute salt. Labile P is isotopically exchangeable or anion resin extractable phosphorus which is in equilibrium with P in the soil solution. Primary minerals are apatites which are acid-extractable. Secondary P minerals include minerals with P chemisorbed to their surfaces (commonly Fe and Al oxides and carbonates) as well as minerals formed by low temperature crystallization which contain P as a structural component. Secondary P minerals can be viewed as dictating long-term sluggish movement toward equilibria. Organic P is that P associated with organic matter. Occluded P is used to describe P that is physically encapsulated by minerals which have no P in their structure.

Transformations

A version of the P cycle is shown in Figure 1. The initial source of all P in soils is the primary minerals present in the parent material. Apatite is the most common primary mineral to serve as a source for P. Its solubility is increased under acid conditions and soluble P is released. The soluble P may be leached, taken up by plants or microorganisms, enter the labile pool, or be transformed into secondary minerals. Soil properties which determine the anion exchange capacity control the size of the potential labile P pool. However, the actual quantity of the labile P is related to the solubility product and dissolution of kinetics of secondary P minerals. Some secondary P forms (dicalcium phosphate dihydrate or octocalcium phosphate rapidly equilibrate with labile and soluble P but other such as hydroxyapatite equilibrate so slowly that equilibrium is seldom attained (Murrman and Peech, 1969). While it is generally thought that P is relatively immobile in soils, this is not true over the longer term. Phosphorus profiles are interpreted in term of eluvial and illuvial horizons (Runge and Riecken, 1966; Fenton et al., 1967)

Soil Test Phosphorus (STP)
Soil test data reported in this paper unless otherwise specified were determined by the Bray 1 method. This method uses a weakly acid extractant and solubilized P in two ways: 1) the acid extractant (pH 3) solubilizes mostly acid-soluble Ca-phosphates and some Al- and Fe-phosphates that become soluble at low pH values and 2) the addition of NH$_4$F ions complexes the Fe and Al in the soil solution. Other methods will solubilize different amounts of P. However, the importance of any method is the ability to extract a representative portion of the P available to the plant that in turn can be used to predict the availability of soil P to the plant under a variety of conditions. Figure 2 shows the relationship between pH and phosphorus solubility in the soil. The dashed line shows the upper limit of available P in solution and illustrates the reason that for soils with 2:1 type clay minerals the optimum pH for P availability is in the pH range of 6.5 to 7.0. The dominant P form at this pH is H$_2$PO$_4^-$ and HPO$_4^{2-}$.

Birchett (1974) studied the relationship of the Bray, Olsen, and Resin extractable P for soils of southwest Iowa. Data for three southwestern Iowa soils and a comparison with a Tama soil from eastern Iowa are shown in Figure 3. In all the soils studied, less P was extracted by the Olsen extractant than by the Bray or Resin extractant. However, the slopes of the STP depth-distribution curves are similar. Two major exceptions were the Rathbun and Weller profiles in which certain horizons had greater amounts of extractable P by the Resin method than by the Bray. Similar but smaller differences were reported for the Kniffin profile. These difference were attributed to the possibility that the Resin method prevented the readsorption of dissolved P by the clay surfaces. The ratio of the amount of STP extracted varied with horizon. The Olsen method extracted relatively more P with increasing depth in the profiles suggesting that this method extracts a larger portion of the Ca-P. The Olsen method had a higher correlation with plant-available P in the C horizon than the Bray method. For the subsoils, the simple correlations between Bray P and Olsen P decreased with horizon depth and was associated with the decreasing correlations with depth with slight increases in average soil pH.

As the soil depth and soil pH increased, the ratio of Ca-phosphates to the Fe-and Al-phosphates increased, the relative effectiveness of the Bray to the Olsen method decreased. Addition of the soil pH variable increased the correlation between the two but horizon depth was not included in the regression and may also have been a factor. Miller (1974) studied Tama profiles in eastern Iowa on different landscape positions. He compared the Bray 1 and Bray 2 extraction methods. The Bray 2 method uses 1N HCL as compared to .025 N HCL for the Bray 1. He reported that the Bray 2 method extracted 1.4 to 1.7 times more STP than the Bray 1 method in the sola of the well and somewhat poorly soils studied. Below forty inches, the Bray 2 method extracted 2.4 to 2.7 times more STP than Bray 1. When pH values increased to near neutral the Bray 1 decreased by 50% and the Bray 2 STP increased by several hundred percent. At the increase in Ca-P with depth is several times greater in the near neutral range than in acidic soil environments.

Effect of Profile differentiation on STP

The soil forming factors important in profile differentiation are climate and time. Climatic factors of temperature and precipitation are especially important in chemical reactions in the soil. Precipitation provides the soil water necessary for chemical reactions and leaching. Temperature is an important factor in the speed of reactions. Time is an important factor in the stage of weathering, usually described in terms of youth, maturity and old age. Birchett described the depth-distribution of STP for soils formed in loess parent material under prairie vegetation. Three zones, designated as zones 1, 2, and 3 are shown in Figure 4 for a Marshall soil with STP values determined by the Bray 1 method. He also studied transition and forested soils from southern Iowa. Soils formed under forest vegetation have the same general depth curve for STP but have greater amounts of STP. Zone 1 was described as the surface or A1 horizon for virgin soils or the Ap horizon for cultivated soils. It is the part of the soil where cropping, return of plant residues, and the additional of fertilizers and manure can cause large variation in STP. However, there are also other factors that affect P availability to plants. Availability is a function not only of the amount in solution but also the amount of water present in the soil and the distance the P must move to reach the root.

Zone 2 is the part of the STP depth curve with the lowest amount of P. It is generally in those horizons immediately beneath the Ap or A1 horizons and includes either parts or all of the E, A2..., and upper part of the B horizon. This depth is often between 6 and 24 inches for most of the profiles studied by Birchett.

Below the minimum STP levels, the amount of STP increases to a zone of maximum solubility that is usually in the lower B horizon or the upper B horizon. In many of the profiles studied, this zone was at a depth of 36 to 48 inches. If free
carbonates were encountered, above this depth very low levels of STP were present. In these cases, the maximum solubility occurred in less alkaline or more acid horizons closer to the soil surface.

Ida, Monona, Marshall, and Sharpsburg comprise a developmental sequence of loess-derived soils formed under prairie vegetation. Ida soils have free carbonates throughout their profile. Ida soils are low in available P. Birchett reported that for the Monona soils studied there was a wide range of Bray-extractable P that were apparently related to the degree of weathering. The Monona profiles with high pH and shallower depth to carbonates had low amounts of extractable P and were close to the Ida soils in their characteristics. As the soil properties of Monona came closer to Marshall soils, extractable P increased. These relationships result in range of extractable P in Monona soils. The same trends were reported for Marshall soils (Figure 5A). Those profiles sampled in the Monona-Marshall transitional area had P distributions similar to the Monona profiles while those in the Marshall-Sharpsburg transition area had P distributions similar to those in the modal Sharpsburg area. The differences in amounts of extractable P were apparently related to soil pH. Those profiles with high amounts of extractable P had pH values ranging from 5.67-6.06 in the 24 to 48 inch horizons while those profiles with lower amounts of extractable P had pH values ranging from 6.31 to 6.87. It appeared that the lower pH values increased the solubility of Ca-phosphates in these soils. The largest amount of extractable P was in the C1 horizon, at the base of the solum, where weathering had removed the free carbonates and the pH was slightly below neutrality.

Soil Test P and Vegetation

The early work of Pearson et al., 1940 demonstrated the effect of different native vegetation on the STP content of soils. However, while native vegetation may be the most obvious variable present, soil genesis theory uses the term organisms which is a more holistic approach and sets soil as a part of the ecosystem. STP is responsive to the total ecosystem and it is difficult to separate the variables but the soil, as influenced by the dominant vegetative type and associated environment, is the component tied most closely to the STP. Within a biosequence (a sequence of soil alike in all soil forming factors except vegetation) the forested member has the highest content of STP, the transitional member (both grass and forest) is intermediate and the prairie soil has the least. This comparison is true in relative amounts as shown in Figure 5B. However, note that the STP content of Tama, a loess-derived prairie soil, is higher than that of Kniffin, a loess-derived forested soil. However, the Kniffin soils are more highly weathered than the Tama soils.

Kazemi (1983) summarized soil test data from 251 profiles located in the eastern part of Iowa. Counties included were Bremer, Howard Fayette, Linn, Muscatine, and Keokuk. The major objective of this study was to study the effect of soil property differences, including native vegetation, on the amount and depth-distribution of STP. Multiple regression techniques were used to develop prediction equations for STP. The native vegetation had a dominant effect on STP and decreased from forest to prairie (Figure 6 & 7). Eroded soils had lower subsoil STP levels than uneroded soils. The STP decreased from well to poorly drained soils (Figure 8). Runge and Riecken (1966) also reported higher amounts of available P in somewhat poor and moderately well drained soils as compared to poorly drained soils. This trend was related to higher pH values in the poorly drained soils in both studies. Kazemi also found that loess parent material had higher subsoil STP than any other group of parent materials, till parent material had the lowest STP and STP values decreased linearly from convex to concave slopes.

Soil Test P and Parent Material

In general, soil formed in loess have higher contents of STP when all other soil forming factors are constant. The differences between Tama (loess-derived), Kenyon (till-derived) and Clarion (till-derived) are shown in Figure 9. Figure 10 presents a summary of the analyses by Kazemi (1983) relating STP depth distribution to major parent materials in Iowa. Eolian deposits (excluding loess) were lowest in STP. Loess was highest. Alluvium, till, and loess over till were intermediate in STP content.

Total Phosphorus

Major environmental concern for soil phosphorus involve phosphorus leaving a soil surface in the form of dissolved P in
runoff or with the soil particle in erosional processes. Therefore, a knowledge of the total phosphorus content of soils and the depth distribution of total phosphorus in different soils are important parameters to understand. While it is generally thought that P is relatively immobile in soils, this is not true over the longer term. Total phosphorus profiles, such as the ones shown in Figure 11, are interpreted in terms of eluvial and illuvial horizons. Two deep profiles, one beneath Marshall and the other beneath Tama show the depth trends expected in well-drained soils formed in thick loess, one in western Iowa (Potawattamie County) and the other in eastern Iowa (Tama County).

Vegetation (Biotic Factor)

Biosequence effects on the genesis and resulting differences in soil phosphorus have long been recognized (Pearson et al., 1940; Fenton et al., 1967; Mausbach, 1969; Tembhare, 1973; Collins, 1977; Miller, 1974. Fenton et al., 1967 arrayed soil profile data by biosequences to test the effect of native vegetation on the phosphorus characteristics of soils. Total phosphorus was high in the surface horizon, decreases to a minimum and then increased with depth within all members of the biosequences. The general trend of the distribution is similar whether the parent material is loess or glacial till. The depth distributions of the well and moderately drained loess-derived soils are shown in Figure 12 and the well-drained till-derived soils are shown in Figure 13. Depth to the TP minimum is most shallow in the forested member of the biosequence (Table 1). The TP minimum within a biosequence is always less in the transitional or forested member as compared to the prairie member.

Within a biosequence the forested soil also has the lowest content of less than 2 micron clay in the minimum TP horizon. The TP minima in the prairie soil profiles are more closely associated with the maximum clay content within the profile. This trend is illustrated by the data in Table 2. The average clay content in the horizon of minimum TP decreases from 37.2% for the prairie soils to 20.1% for the forest soils. The range in the mean maximum clay within the profiles varies within a narrow range of 38 to 40.6%. The trend is shown in Table 2. In the forested soils and the transitional Grundy soils the TP minima coincides with the part of the zone described as the E horizon. In all other soils, except for the transitional Grundy soil, the TP minimum is in the B horizon and it is most closely associated with the zone of maximum clay in the prairie soils (Table 2). The data relating minimum TP values to layer of maximum clay content in prairie soils is in agreement with the observations of Runge and Riecken (1966). In the transition and forested members the minimum TP value are more closely associated with the upper B or E horizon and not the zone of maximum clay.

Figure 12 shows the depth distribution of total P for a number of well to moderately well-drained loess-derived biosequences. There are differences in the depth distributions related to the native vegetation. Forested soils have the greatest amount of total P to a depth of 40 inches as shown in Table 1. In general, for well-drained soils, where we expect the net vector of water movement to be downward, the P distributions are more predictable. Figure 14 shows the loess-derived somewhat poorly drained Muscatine and Mahaske biosequences and Figure 15 shows the poorly drained landscape associates of these soils. Figure 13 shows the total P distribution in two till-derived biosequences. The Clarion and Kenyon biosequence members are well-drained and have similar depth distributions of total P as the well-drained loess-derived soils but lower amounts. The till-derived somewhat poorly drained Nicollet and the poorly drained Webster biosequence are also shown in Figure 13. These soils have higher fluctuating water tables and thus the depth distribution of total P in these soils is less predictable that for the better drained soils.

As soil horizon differentiation increases, the P minerals change in form and distribution. With respect to phosphorus, native vegetation differences are related to forms of phosphorus. Mausbach (1969) reported that the levels of Ca-phosphates decreased and the Fe and Al-phosphates increased progressively from the prairie soils to the transitions and to the forested soils (Figure 16). This increase in Fe and Al phosphates was associated with decreasing pH from the prairie to the forest soils. This relationship is illustrated in Figure 17 which shows the relationship between pH and the ratio of Fe-P + Al-P divided by Ca-P for a number of Iowa soils. Hsu and Jackson (1960) found that Fe and Al-phosphates are stable at pH values lower than the pH values at which Ca-phosphates are stable. The lower pH under forest vegetation contributes to increased weathering rates. Smeck and Runge (1971) showed increasing aluminum, iron and reductant soluble P and decreasing calcium P along a traverse from a Haplaquoll to an Albaqualf at the end of the transect. They also found a progressive increase in STP along the same traverse. P availability increased as horizon differentiation increased.

Westin and Buntley (1966a, 1967) reported that the cooler drier Borolls had less Fe-P and reductant P and more Ca-P than the Ustolls in South Dakota.
Parent Material

Loess generally has higher contents of TP than till (see Figures 12 & 13). Pearson et al., 1940, reported that the glacial till they studied contained about 300 ppm of TP while the loess averaged about 700 ppm. These differences related to parent material have also been reported in subsequent research in Iowa. However, the actual difference in the amount of total phosphorus present is less if bulk density is considered. An acre foot of till (assuming a bulk density of 1.5) and using the 300 ppm content has 122,316 pounds of P while an acre foot of loess has 247,350 pounds. Corrected on this basis the loess has approximately twice as much TP rather than 2.3 when expressed in ppm. However, the TP content of the loess ranges from the value cited above to lower values where the loess sections have been weathered. For example, Seymour soils in southeastern Iowa formed in loess but the TP content of the least altered loess is 540 ppm while in western Iowa beneath the Marshall soil TP contents of 850 ppm are present. TP content of alluvium has a wide range. TP contents are low in more weathered alluvium and highest in calcareous alluvium.

Time and Topography

The plot shown in Figure 18 shows the effect of time and topography on TP. Clarinda is a paleosol derived from pre-Illinoian till. Note the low content of TP in this soil. The low TP content is attributed to the advanced stage of weathering of this soil. The Sperry soil is a loess-derived very poorly drained soil in eastern Iowa. It occurs in closed depressions and has the highest TP contents that I found in the Iowa data. Smeck, 1973; Walker and Syers, 1976; Smeck and Runge, 1971 showed that phosphorus is translocated within the soil profile and landscape within a pedologic time-frame. Smeck (1985) reported that of the soils studied in Illinois, in each toposequence the TP content was highest in soils on the low end of the hydrologic gradient. The content of TP in Sperry supports that interpretation. Theoretical changes in P over time are shown in Figure 19. Note that eventually all the primary P minerals will weather. Walker and Syers (1976) suggested that for the soil conditions they studied, this process would take about 22,000 years. Occluded P continues to increase at the expense of secondary P until eventually only occluded P and organic P remain.

Organic P

Kosse (1966) studied organic carbon/organic phosphorus ratios in selected Iowa soils. Values for surface horizons of the poorly drained soils studied ranged from 90 to 152 and were markedly higher than for the somewhat poorly, moderately well and well drained soils. It has been well established that the driving force for conversion of primary to secondary and occluded forms is decreasing pH due to weathering and leaching of the soil. However, the driving force for organic P has not been as well documented. Early work suggested a direct relationship between organic matter and organic P content of a soil. However, Smeck and Runge (1972) determined that organic matter production may be limited by factors other than P availability. Low levels of organic matter content occur in some soils with high levels of available P. Organic P is more stable at low pH rather than high pH. Liming tends to allow breakdown and mineralization of org P. Both N and org P decline with cultivation. Organic P is held by covalent bonds and does not ionize. Decomposition breaks down O2 bonds and the P can mineralize. The adsorption of P is stronger than that for cations. Figure 19 shows an idealized diagram of soil development related to organic P and organic C.

Summary—Soil Test Phosphorus and Total Phosphorus

Figure 20 shows a plot of TP and STP for a Tama soil in Iowa. As might be expected, there is no direct relationship between TP and STP. However, TP is a key element in soil genesis. As soils develop, the TP undergoes changes that are related to the weathering environment. We expect the amount and forms of TP to change with soil-forming processes. It was demonstrated that the driving force for conversion of primary to secondary and occluded forms is decreasing pH due to weathering and leaching of the soil. STP was shown to be highest in soils formed under forest vegetation and this in large part is due to the forms of phosphorus which in turn is related to pH and the weathering process. Forest soils are more acid and the weathering of clay minerals release Fe and Al which in turn react with the phosphorus. The amount of STP extracted for a given soil is related to the combination of P forms and pH (Figure 2).

P and Environmental Problems
As discussed by Voss and Griffith, agriculture has been designated as the primary source of phosphorus entering inland streams, lakes, and water impoundments. Phosphorus leaves agricultural fields as dissolved phosphorus and particulate phosphorus attached to soil sediment. Crop production cultural practices were cited as major factors in the concentration and amount of P in the runoff. Thus far, I have used primarily soil series names in this paper. However, on a landscape basis, the soil unit that provides the most information is the soil map unit, a combination of the soil series and phases including surface texture, erosion phase and slope class. It is at this level that nutrient management plans should be based. Soil map units within one soil series exhibit wide ranges in organic matter content, clay content, slope gradient, length, and configuration all of which are factors that contribute to the amount of dissolved and particulate phosphorus moved in runoff. For example most of the well and moderately well drained soil series have several slope and erosion phases. The differences described in the soil series description state the following: “The thickness of the A horizon, depth to subhorizon highest in clay, maximum percent clay, thickness of Bt horizon, depth to carbonates, depth to mottling and solum thickness usually decrease as gradient increases on convex slopes”. These factors indicate that each soil map unit has a distinct set of characteristics that will interact with the type of cultural practices used for any field. These are all important properties that should be a part of any soil management decision-making process.

**Soil Survey**

Soil survey involves the mapping, classification, correlation, and interpretation of soils. The first soil survey in Iowa was in the Dubuque County area but did not include the entire county. The field work was done in 1902 and the report was published in 1903. Since that time, most Iowa counties have had at least two soil surveys completed and some have had three. The basic factors of soil formation have not changed but the use of the soils for intensive agriculture has resulted in changes in some soil properties, especially of the surface horizons. However, generally factors other than soil differences have been responsible for multiple soil surveys over one area. Over time, our concept of soil has changed. Early soil scientists with a background in geology considered the soil to be primarily that part of the earth’s surface that had been darkened by the addition of organic matter. Our concept of soil has evolved so that soil now is considered a natural body made up of several horizons or layers that are genetically related to the soil forming factors under which the soil has developed. Total analyses of soils for phosphorus and potassium was a common practice during the early 1900's. Later, it was learned that it was not the total amount of a nutrient that was important for plant growth but the amount that was available to the plant. Other major factors in resurveys were the scale and the base map used.

The early soil maps were generally made at a scale of 1 inch per mile on a plane-table base map. In the late 1930's the use of aerial photographs as base maps for soil survey was implemented. Most of the surveys were made at a scale of 4 inches per mile and most of the modern surveys we have in Iowa were made at that scale. Beginning in the 1990's, orthophotographs were used as base maps and the field mapping is presently being done at a scale of 1:12,000 or 5.28 inches per mile.

**Availability of Soil Information**

Soil surveys are available for all Iowa counties in published reports and presently 95 of the 99 counties also have the same information available in digital format. Many digital soil maps of Iowa are available on the internet at http://www.ia.nrcs.usda.gov/

To access the soil information select Soils, Soils Information, and Digital Soil Survey Data From Iowa Cooperative Soil Survey on successive screens. Data bases giving soil properties and interpretations are available at the same site. The Iowa State University Extension home page also contains soil information as well as a link to the digital soil maps and databases. The home page address is:
http://extension.agron.iastate.edu/soils/soilsurv.html

Descriptions for all soil series in the U.S. are located at: http://www.statlab.iastate.edu/cgi-bin/osd/osdname.cgi

For those who do not have access to the internet, the digital soil information and associated data bases are available on CD-ROM or diskettes. The digital soil information is available in several different formats and is suitable for use in most Geographic Information Systems (GIS). For those users not interested in using a GIS the digital information may be used with the ISOIL program which is our software package for handling soil maps and data. Contact me at the above address if you have questions on the availability of soil information in Iowa.
Figure 1. Phosphorus transformations in natural soil ecosystems. From Smeck (1985)
Figure 2. Relative proportion of phosphate ions in solution at different pH levels in a Ca-H₃PO₄ system. From Troesh, 1993.

Figure 3. Comparison of three phosphorus extraction methods. From Birchett, 1974.
Figure 4. Zones in STP depth-distribution for deep loess. From Birchet, 1974.
Figure 5. STP depth distribution for selected loess-derived soils. From Birchett, 1974.

Figure 6. Predicted STP depth distribution for loess-derived biosequences. From Kazemi, 1983.
Figure 7. STP depth distribution for Tama and Otley biosequences.
Figure 8. Predicted STP depth distribution for well drained (30) and poorly (70) drained loess and till-derived soils. From Kazemi, 1983.

Figure 9. STP depth distributions for Tama, Kenyon, and Clarion soils.
Figure 10. Predicted STP depth distribution for Iowa soil parent materials. From Kazemi, 1983.

Figure 11. Total phosphorus depth distribution in Marshall and Tama soils.
Figure 12. Depth distribution of TP for loess-derived moderately well and well drained soils.

Figure 13. Depth distribution of TP for till-derived moderately well, well drained soils, somewhat poorly and poorly drained soils.
Figure 14. Depth distribution of TP for loess-derived somewhat poorly drained soils.

Figure 15. Depth distribution of TP for loess-derived poorly drained soils.
Figure 16. Phosphorus fractions in the Tama and Garwin biosequences. From Mausbach, 1969.
Figure 17. Phosphorus fraction ratios and pH for selected Iowa soils.

Figure 18. Total P content of Sperry and Clarinda.
Figure 19. Changes in forms and amount of phosphorus with time. From Walker and Syers, 1976.

Figure 20. Depth distribution of Total P and STP for Tama soil.
Table 1. AVERAGE TOTAL P PER 2.54 CM, TOTAL P MINIMUM, AND DEPTH TO TOTAL P MINIMUM

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<tr>
<td></td>
<td>P</td>
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<tr>
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<td>P DRAINED&quot;</td>
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*CLARION, NICOLLET, AND WEBSTER BIOSEQUENCE DATA BASED ON A TOTAL DEPTH OF 101.6 CM.
Table 2. DEPTH TO (TP) MIN. AND CLAY CONTENT AT THAT DEPTH

<table>
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<td>M TO MW DRAINED</td>
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<td>P T F</td>
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SELECTED BIBLIOGRAPHY ON SOIL PHOSPHORUS


Smith, F. W., B. G. Ellis, and J. Grava. 1957. Use of acid fluoride solutions for the extraction of available phosphorus in calcareous soils and in soils to which rock phosphate has been added. Soil Sci. Soc. Amer. Proc. 21: 400-404.


