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A Routine Laboratory Method to Determine Phosphorus Availability, Capacity, and Release Characteristics for Soils

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Introduction

Phosphorus (P) is an essential nutrient for plant growth and is often applied to agricultural land to increase crop production. Many chemical solutions have been proposed to extract available forms of P in soils and use the information to assess soil P for crop production and as bases for making recommendation. Water probably was the first extract that scientists applied to measure P in soils. The small amounts of soil P extracted by water and difficulties related to chemical analysis limited the use of water as a soil test.

Actually, soil P testing for crop production did not become common until the mid-20th century. Bray and Kurtz (1945) suggested a soil P test (Bray-1), which is a combination of hydrochloric acid (HCl) and ammonium fluoride (NH_4F) to remove available forms of P from soils. In 1953, Mehlich introduced a combination of HCl and sulfuric acid (H_2SO_4) (Mehlich-1) to extract available P from soils. Both Bray-1 and Mehlich-1 solutions can dissolve calcium-, aluminum- and iron-phosphate minerals as well as P adsorbed on colloidal surfaces in soils. In 1984, Mehlich modified his initial soil test and developed a multi-element extractant (Mehlich-3) which is suitable for removing P and other elements in acid and neutral soils (Mehlich, 1984). The Mehlich-3 solution is a combination of acids (acetic [HOAc] and nitric [HNO_3]), salts (ammonium fluoride [NH_4F] and ammonium nitrate [NH_4NO_3]), and the chelating agent ethylenediaminetetraacetic acid (EDTA).

Olsen et al. (1954) introduced sodium bicarbonate (0.5 M $NaHCO_3$) solution adjusted at a pH of 8.5 to extract P from neutral, alkaline, and calcareous soils. The high pH (8.5) can precipitate calcium carbonate which decreases calcium (Ca^{2+}) ion concentration in solution and enhances the dissolution of Ca-phosphate minerals ($Ca[H_2PO_4]_2$, $CaHPO_4$, and $Ca_3[PO_4]_2$). Further, the Olsen test solution can remove both dissolved and adsorbed P forms from soils.

The concept of P-sink was applied to measure the amount of available soil P which can be released in response to such sink. An anion exchange resin (AER) was used in water as a P-sink to determine available P in a wide range of soils. An AER has an advantage over chemical extractants because it uses water and can measure both soil P capacity and rate of P release in addition to available P in soil (Amer et al., 1955; Vaidyanathan and Talibudeen, 1970; Sibbesen, 1978; Uusitalo and Yli-Halla 1999). The objective of this study was to develop a technique implementing the AER P-sink concept to determine P availability, capacity, and release characteristics for a wide range of soils that differ greatly in chemical properties.

Materials and Methods

For this study, 26 samples were collected from the surface horizon of 15 U.S. soil series and one soil sample (Albia series) from Denmark. The samples were selected to represent a wide range of properties and climatic factors. Two or more samples were collected from seven benchmark soils. For these seven soils, the number in parentheses next to the soil name represents the sample number. Soil analyses were performed by methods described in the Soil Survey Investigations Report (SSIR) No. 42 (USDA/NRCS, 2014). Alphanumeric codes in parentheses next to each method represent specific standard operating procedures. Analyses were conducted on air-dried, 0,2-mm soil samples. Particle-size analysis was performed by sieve and pipette method (3A1). Total carbon (C) content was determined by dry combustion (6A2f). Soil pH (water) was measured in a 1:1 soil/water extract (8C1f) while pH (0.01M CaCl2) was determined in a 1:2 soil/solution suspension (8C1f). Cation exchange capacity (CEC) was conducted by NH_4OAc buffered at pH 7.0 (5A8b), and $CaCO_3$ equivalent was estimated by the manometer method (6E1g). The water soluble P (6S7c), Bray-1 P (6S3e), and Olsen P (6S9a) were measured for soils. The classification and properties for soils are given in Table 1.

Development of the AER Method

We measured soil P by using AER bags similar to those used by Sibbesen (1978) and Uusitalo and Yli-Halla (1999). Spherical resin beads were placed in a perforated nylon bag which was immersed in soil suspension and shaken for a specific period to release soil P. Phosphorus retained by resin was removed by using a sodium chloride (NaCl) solution and measured by colorimetric method (Olsen and Sommers, 1982) or Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), (Perkin Elmer 3300 DV) (1B2b) as described in USDA/NRCS (2014).

Dowex Marathon A2 AER, strong base, type II, 510 to 610 µm spherical beads (DOW Chemical Company) was used for all laboratory experiments. The resin is chloromethylated copolymer of styrene and divinyl benzene which is provided in chloride form. Nitex nylon fabric with 300-µm pores (Sefar Inc., [America]) was used to make the resin bags. Four grams of air-dry AER was confined in each bag. The resin was converted to bicarbonate form before use by soaking bags over-night in 1.0 M $NaHCO_3$ solution and washing out excess salt with distilled water.

Three laboratory experiments 1) efficiency of chloride solutions; 2) errors associated with using HCl; and 3) soil:solution ratio were performed to develop the AER method to determine phosphorus release characteristics (PRC) for soils as follows:

Efficiency of Chloride Solutions

The objective of this experiment was to investigate the efficiency of three chloride solutions (0.5 M HCl, 0.5 M NaCl, and 1.0 M NaCl) in removing P adsorbed by the AER.

A 100-ml of KH_2PO_4 solution and a resin bag were placed in a 250-ml polyethylene bottle. The bottle was mounted horizontally on a reciprocating shaker (displacement = 4.0 cm, and speed = 100 rpm) and shaken for 24 hours at room temperature (20 ± 2°C). At the end of shaking period, the resin bag was rinsed with distilled water and placed in a 125-ml polyethylene bottle containing 50-ml solution of 0.5 M HCl, 0.5 M NaCl, or 1.0 M NaCl. All treatments were replicated four times.

The bottle was shaken horizontally in a reciprocating shaker for 1 hour at room temperature. The 1st hour solution was transferred into a 60-ml polyethylene bottle. The resin bag was shaken for 1 hour with another 50-ml of the respective solution. The 2nd hour solution was transferred into a separate 60-ml bottle. Phosphorus concentration in solutions was determined by an appropriate method.

The results indicated that the 1st hour of shaking the resin bag with either 1.0 M NaCl or 0.5 M HCl solution removed > 96 percent of P retained by resin. Most of P removed by the 2nd hour of shaking was associated with solution entrapped in the resin bag. When P in this solution (about 3.0-ml/resin bag) was considered, almost all retained P could be accounted for. Only 93 percent of retained P was removed by 0.5 M NaCl solution after the 1st hour of shaking. It appeared that the 2nd hour was necessary for 0.5 M NaCl to remove all P from resin.

Errors Associated with Using Hydrochloric Acid (HCl)

The previous experiment indicated that either 0.5 M HCl or 1.0 M NaCl could be used to remove P adsorbed by AER. The objective of this experiment was to investigate why using HCl to remove P adsorbed by AER (from soil suspension) produced higher P values than NaCl.

The experiment was performed on Caribou (1) (acidic soil), and Windthorst (4) (alkaline soil). Two g of air-dry soil (<2mm) along with 100-ml of distilled water, and a resin bag were placed in a 250-ml polyethylene bottle, four replicates were used for each treatment. The bottle was mounted horizontally on a reciprocating shaker (displacement = 4.0 cm, and speed = 100 rpm) and shaken for 24 hours at room temperature (20 ± 2°C). At the end of shaking period, the resin bag was taken out of the soil suspension, and rinsed with distilled water Phosphorus retained by resin was removed either by 0.5 M HCl or 1.0 M NaCl solution as described above. Phosphorus concentration in both 0.5 M HCl and 1.0 M NaCl solutions was determined.

The results indicated that the 0.5 M HCl solution resulted in higher P values (162.6±6.5 and 227±5.2 mg/kg) than the 1.0 M NaCl solution (142.9±6.9 and 207.5±10.4) for both the acidic and alkaline soils, respectively. A drawback of using a nylon resin bag to extract P from soil suspension is the adherence of fine soil particles to the nylon fabric. The amount of adhering particles is usually related to clay and organic matter content of soil. In a preliminary experiment, we found only a few milligrams of adhering particles for most soils investigated and that it was independent of the amount of soil used. However, most soil P is associated with fine soil particles.

The 0.5 M HCl solution appeared to dissolve more P from the adhering soil particles, but we could avoid this problem by using the mild NaCl solution to remove P from resin. Cooperband and Logan (1994) and Uusitalo and Yli-Halla (1999) reported that using NaCl to remove P from resin could avoid dissolution of P from adhering soil particles.

Soil:Solution Ratio

The objective was to investigate the optimal soil:water ratio for soils. The experiment was performed on Caribou (2) (acidic), and Genola (2) (alkaline calcareous). Three soil:solution ratios were implemented where 1, 2, or 4 g of air-dry soil sample (<2mm) along with 100-ml of distilled water and a resin bag were placed in a 250-ml polyethylene bottle. The method was conducted as explained above to determine the amount of P released for 1 and 24 hours of shaking, however, only 1.0 M NaCl solution was applied to remove P from resin.

The effect of soil:solution ratio on P released from the acidic and alkaline calcareous soil is presented in Table 2. For both 1-h and 24-h extraction periods, P released (mg/kg soil) increased with decreasing the ratio. In the presence of P-sink (AER) in the soil:water system during extraction, the dynamic equilibrium for both precipitation/dissolution and adsorption/desorption reactions are no longer valid. Under these conditions, dissolution and desorption reactions are dominant in the system and enhanced by decreasing soil:solution ratio. Both water soluble and adsorbed forms of P are finite sources and their release during the 1st hour should be complete and independent of the soil:solution ratio. The data for the 1-h extraction suggested P was released from sparingly soluble minerals in addition to water soluble and adsorbed P sources in both soils. In light of the results obtained, using high soil:solution ratio might be preferred for light-textured soils usually low in organic matter (OM) and P content. However, the low soil:solution ratio would be more suitable for heavy soils with high OM and P content. We have adopted the medium soil:solution ratio (2:100), which should be suitable for most soils.

The Routine Laboratory Method

Based on data derived from the three above experiments, the AER method was designed to measure amounts of P released from soil at 0.25, 0.5, 1, 2, 4, 8, 24, and 48 hours of extraction periods. The method has been performed on soils varying greatly in their properties. Classification and properties of soils are given in Table 1. The method is outlined in three sections (soil extraction, Phosphorus removal from resin, and Phosphorus measurement) as follows:

Soil Extraction

Step 1: Add 2.0 g of air-dry soil sample (< 2 mm) and 100-ml of distilled water in a wide-mouth, 250-ml polyethylene bottle. Use at least two replicates for each soil sample in addition to a control treatment where all steps of the extraction process are performed in the absence of soil.

Step 2: Place a resin bag (containing 4.0 g of air-dry AER-HCO3) in each bottle. The bottle is mounted horizontally on a reciprocating shaker (displacement = 4.0 cm, and speed = 100 rpm) and shaken for a specific period at room temperature (20 ± 2°C). After shaking, remove retained P from resin as described below (b).

Step 3: Run step 2 above for all shaking periods. The length of individual shaking period is determined in reference to the beginning of first shaking period at time=0.

Phosphorus Removal from Resin

Step 1: Lift the resin bag out of the soil suspension and wait for 2 minutes to drain free water. Rinse the bag with a known volume of distilled water (i.e., 5.0-ml) to remove attached soil particles. Add rinsing water to the soil suspension, and keep the soil suspension (when it is necessary) for next extraction.

Step 2: Place the resin bag in a wide-mouth, 125-ml polyethylene bottle containing 50-ml of 1.0 M NaCl solution and shake the bottle horizontally in a reciprocating shaker (displacement = 4.0 cm, and speed = 100 rpm) for 1 hour at room temperature.

Step 3: Transfer the NaCl solution to a 60-ml polyethylene bottle and add 2.0-ml of concentrated HCl to each bottle.

Phosphorus Measurement

Determine P concentration (µg/ml) in the acidified 1.0 M NaCl solution by the modified phospho-molybdate/ascorbic acid method (Olsen and Sommers, 1982) or Inductively Coupled Plasma-Optical Emission Spectrometry (Perkin Elmer 3300 DV) (1B2b) as described in USDA/NRCS (2014).

Results and Discussions

Soil P Tests and Extracted Forms

Soil P adsorbed on surfaces of colloidal $CaCO_3$ and hydrated oxides of Al and Fe can be replaced by other anions such as sulfate, chloride, hydroxyl, and bicarbonate (Olsen et al., 1954; Kamprath and Watson, 1980). Water extraction may remove a small amount of adsorbed P in addition to water soluble forms in soils. On the other hand, bicarbonate solution adjusted at pH 8.5 (Olsen extraction) can remove water soluble, adsorbed P and some amounts of Ca-, Al-, and Fe-phosphate minerals. Olsen and Sommers (1982) reported that in alkaline, calcareous, and near neutral soils, Olsen extraction decreases the concentration of Ca in solution which dissolves Ca-phosphate minerals. In acid and near neutral soils, the high pH dissolves Al- and Fe-phosphates (Lindsay and Moreno, 1960).

Bray and Kurtz (1945) developed the Bray-1 test (0.03 M NH_4F and 0.025 M HCl). The test is an aggressive extraction for acid and near neutral soils where it can remove large amounts of Ca-, Al-, and Fe-phosphates in addition to water soluble and adsorbed P forms (Elrashidi et al., 2001). The Bray-1 extraction dissolves Ca, Al-, and Fe-phosphates by the solvent action of HCl (Thomas and Peaslee, 1973), and by the ability of fluoride ion (NH_4F) to complex Al and Fe which releases P from Al- and Fe-phosphates (Chang and Jackson, 1957; Elrashidi and Lindsay, 1986). Chloride ion (HCl) can also replace P adsorbed on colloidal surfaces (Kamprath and Watson, 1980).

Both Olsen and Bray-1 extractions can remove water soluble and adsorbed forms of P and portions of Ca-, Al-, Fe-phosphate minerals for soils. In general, Bray-1 extraction can remove larger amounts of P minerals than those removed by Olsen extraction (Burt et al., 2002). As mentioned, mechanisms responsible for dissolving P minerals are more aggressive in Bray-1 than in Olsen extraction. This indicates that Olsen extraction removes P from relatively soluble P minerals compared to Bray-1 which can attack minerals of lower solubility.

The data for the 24 soils investigated (Table 3) show that AER-1h extractable P is always higher than water-P, but it is much lower than Bray-1-P. Meanwhile, AER-1h and Olsen removed similar P concentration for most soils investigated. A significant correlation was observed between AER-1h extractable P and each of water-P (0.89**), Olsen-P (0.46*), and Bray-1-P (0.49*). These data suggested that the AER-1h extractable P was mainly driven from water soluble, adsorbed forms, and relatively soluble P minerals. The data for most soils also suggested that 24- and 48-h AER extraction could remove all P forms dissolved by Bray-1 and Olsen solution. For 24-h AER extractable P, a significant correlation of 0.84** was observed with Bray-1, and 0.77** with Olsen. Significant correlation was also found for 48-h AER extractable P. Similar results were obtained for 21 benchmark soils of the U.S. (Burt et al., 2002). Olsen and Khasawneh (1980) reported that resin-extractable P was related to labile P and to Olsen's bicarbonate extraction. They concluded that resin P was a valid measure of the quantity factor for soils.

Phosphorus Release Characteristics (PRC) for Soils

Figure 1 illustrates the relationship between different extraction periods (hour) and P released (mg/kg soil) for four acidic (Figure 1a), and four alkaline soils (Figure 1b). Similar relationship was observed for other soils (not shown). For the 24 soils, an average of 39 percent of P was released during the 1st hour while the remaining 61 percent released by the following 47 hours of extraction. The corresponding values were 33 percent and 67 percent for 15 acidic soils compared to 49 percent and 51 percent for 9 alkaline soils. The results reflected, to some extent, the solubility of different P minerals and its adherence to the solid phase in these two groups of soils. The data also suggested a difference in P release behavior between the 1st hour and the following 47 hours of extraction. Accordingly, the two regions would be addressed separately in this study.

Plotting Log of the extraction period (hour) against the amount of P released (mg/kg soil) for the 1-48h region gave a linear relationship for all soils investigated. The equation could be written as follows:

$$P = I + S2 \times \text{Log } h \qquad (1)$$

Where: P = P released (mg/kg soil), I = intercept, S2 = slope, and h = extraction period (hour).

When Log h > 0.0, this relationship could be used to predict P released from soil for any extraction period between 1 and 48 hours. The linear relationship is shown for four acidic (Figure 2a), and four alkaline soils (Figure 2b).

A different relationship was expected for the 1st hour of extraction where water soluble and adsorbed P forms were major contributors for released P. We had to assume the amount of P released = 0.0 at the beginning of extraction time to develop the linear relationship (Log h x P) for the 1st hour region, however, this time should be > 0.0 h because of using the log function. To select the boundary for the 1st hour region, we assumed a beginning time at 0.1, 0.5, or 1.0 minute which produced a slope (S1) = I/2.78, I/2.08, and I/1.78, respectively. The 1.0 minute was selected because the 1-60min slope (I/1.78) gave better P prediction for the 24 soils investigated. The linear relationship for the 1-60min region could be written as follows:

$$P = I + (I \div 1.78) \times \text{Log } h \qquad (2)$$

The linear equations to predict P released (mg/kg soil) for both 1-60min and 1-48h regions are given in Table 4 for the 24 soils. The intercept (I) at 1h extraction period reflects mainly water soluble and adsorbed forms of P in soil. For the 24 soils, it varied widely between 12.6 and 147 mg/kg soil. The slope (S2) for 1-48h region is related to the rate of P release from sparingly soluble P minerals in soil. However, S2 values showed no apparent difference between acidic and alkaline soils investigated. This might reflect a disturbance in P dynamic equilibrium caused mainly by management practices.

An agricultural soil usually contains numerous numbers of P minerals in different physical forms (i.e., amorphous and crystallized) and solubility. Al-, Fe-, and Mn-phosphates dominate in acidic environment, while Ca- and Mg-phosphates are major minerals in alkaline and calcareous soils (Lindsay, 1979). Both acidic and alkaline phosphates could co-exist in near neutral soils. Additions of P fertilizer or manure to soil could generate adsorption/desorption or precipitation/dissolution reactions and disturb the dynamic equilibrium, which would change P solubility and release (Elrashidi et al., 1999a; 1999b). High P and OM values for some of the soils investigated suggested additions of P fertilizer and/or manure. This might also explain the wide range of intercept (I) and slope (S2) values observed within the acidic and alkaline soils investigated.

We applied the two linear models (equations 1 and 2) to predict P released at different extraction periods (PRC) for the 24 soils. A good agreement was found between predicted and experimental P release values for the two extraction regions (1-60min and 1-48h). The data for four acidic soils are shown in Figures (3 and 4), and in Figures (5 and 6) for four alkaline soils, respectively. Good agreements between predicted and experimental values were also observed for other soils investigated (not shown). Because the linear relationship (Log h x P) can be represented by a minimum of two points, for a routine laboratory AER extraction method, we proposed to use only two extraction periods (1 and 24 h) to determine PRC for soils, named the Double-Point AER Extraction (DP-AER). The DP-AER method has been published in the Soil Survey Investigation Report (SSIR No. 42) (USDA/NRCS, 2014) as a standard operating procedure (4D1a) for soil P.

Finally, in the second part of this soil survey investigations report, a case study on Phosphorus availability and release characteristics for irrigated cropland in Afghanistan, discusses implementation of the DP-AER method as proposed in this report.

CASE STUDY

Phosphorus Availability and Release Characteristics for Irrigated Cropland in Afghanistan

Abstract

The incredibly low yield for crops grown on irrigated calcareous soils in Afghanistan could be attributed to fertility problems related to the shortage of available phosphorus (P). The objective was to investigate P for soils representing irrigated cropland in Afghanistan. A total of 14 soil pedons were sampled from Farah Province and Kunar Province, Afghanistan. A total of 42 soil samples were selected from the top three horizons in these pedons. The NRCS double-point anion exchange resin extraction method (DP-AER) was applied to investigate P availability, capacity, and release characteristics in these soils. The data obtained from the DP-AER were compared with available P determined by the Olsen, Mehlich-3, and water methods. The amount of readily available P measured by the methods followed this order: water < Olsen < DP-AER < Mehlich-3 and averaged 0.14, 4.95, 9.73, and 15.2 mg/kg soil, respectively. The P capacity ranged from 1.21 to 87.3 mg/kg with an average of 22.3 mg/kg soil. Following a fast release of the readily available forms, the rate of P release from soils slowly decreased with time, indicating a dissolution process from sparingly soluble phosphate minerals. The amount of available P, capacity, and release rate were generally low for most soils. Phosphorus fertilizers and organic amendments should be recommended to improve soil fertility and secure good harvest for the irrigated cropland in Afghanistan. Either the Olsen or the DP-AER method could provide a good index for P availability in these soils. However, the DP-AER could also supply useful information on both the soil P capacity and release characteristics.

Introduction

As part of USDA’s effort to support the Afghanistan military campaign, Operation Enduring Freedom, the Natural Resources Conservation Service-Soil Survey Laboratory (NRCS-SSL), working in partnership with the USDA Foreign Agricultural Service (FAS), developed a plan to promote the development of the agricultural sector in Afghanistan because nearly 75 percent of the people of Afghanistan are directly employed in agriculture. The development of the agricultural sector is crucial to creating opportunity and hope for the people of Afghanistan.

After 30 years of war, uncontrolled timber harvesting, overgrazing, destroyed infrastructure, and a non-existent extension service, the country is desperately poor and agricultural land is unable to produce enough food to meet the needs of its population. The incredibly low yields for crops grown on irrigated land indicate a soil fertility problem. The NRCS decided to tackle the issue by proposing a soil sampling plan to survey and evaluate the fertility of agricultural land for Farah and Kunar provinces. A total of 13 pedons were sampled from both Farah and Kunar provinces, and an additional pedon was sampled from the Kabul region. We addressed the soil fertility and phosphorus (P) issue by investigating soil samples taken from the top three horizons (depth averaging 50 to 80 cm). Accordingly, a total of 42 soil samples were selected for this study.

A preliminary report indicated that the chemistry of these soils is dominated by high pH and $CaCO_3$ content (Tallyn et al., 2010). In arid regions, chemical reactions controlling P availability are mainly influenced by both pH and $CaCO_3$ content in soils. Calcium phosphate minerals (i.e., tricalcium phosphate, hydroxyl-apatite, and fluor-apatite) have extremely low solubility in alkaline calcareous soils (Lindsay, 1979). Phosphorus sorption by surfaces of clay minerals dominating in arid environments (i.e., smectites and micas) increases considerably in the presence of high calcium ions concentration and pH values in soils (Sposito, 1989). Further, organic matter content is typically very low and this may have unfavorable effects on soil properties and the availability of P in arid soils.

Conventional estimates of plant-available P have employed chemical extractants for soils. Olsen et al. (1954) introduced 0.5 M sodium bicarbonate solution at a pH of 8.5 to extract available P from calcareous soils. This solution reduces calcium ions in solution (through precipitation of calcium carbonate), and this reduction enhances the dissolution of calcium phosphate minerals. Moreover, it removes dissolved and adsorbed P on calcium carbonate and iron oxide surfaces. Mehlich developed the Mehlich-3 solution (Mehlich, 1984), which is suitable for extracting P and other elements for a wide range of soils. The multi-mechanisms for P extraction enabled Mehlich-3 to successfully measure P availability for 50 U.S. soils including acidic, neutral, and alkaline calcareous soils (Elrashidi et al., 2003).

Despite their wide use, chemical extractants are not well understood in terms of their mode of action and selectivity (Curtin et al., 1987). Further, chemical extractants are limited in their ability to accurately measure available P because they are operationally defined by the chemical extractant used and because they only measure static P pools (Abrams and Jarrell, 1992). Another disadvantage is that chemical extractants may mobilize non-labile P forms which may not be truly plant available (Logan, 1982; Fixen and Grove, 1990). On the other hand, an anion exchange resin (AER) has an advantage over chemical extractants because it uses water and functions similarly to plant-root surfaces, absorbing available P ions from the in situ P pool in the soil (Menon et al., 1989; Myers et al., 2005). Further, the AER method can measure soil P availability, capacity, and rate of release (Amer et al., 1955; Sibbesen, 1978; Uusitalo and Yli-Halla, 1999).

In this study, we applied the double-point AER (DP-AER) extraction method (USDA/NRCS, 2004) to investigate P availability, capacity, and release characteristics for irrigated cropland in Farah and Kunar provinces, Afghanistan. Moreover, we compared P data derived from the DP-AER method with P determined by two chemical extractants (Olsen and Mehlich-3), and by the water method as described by the USDA/NRCS (2004).

Materials and Methods

Study Area

Climatic conditions in Afghanistan exhibit great daily and seasonal variations, largely because of the extremes in elevation that characterize the country. During the day, variations in temperature may range from freezing conditions at dawn to almost 100º F (38º C) at noon. Summer temperatures as high as 120º F (49º C) have been recorded in the northern valleys. Midwinter temperatures as low as 15º F (-9.4º C) are common at the 6,500 feet (1,980 m) level in the Hindu Kush. Kabul, situated at an elevation of 6,000 feet (1,830 m), has cold winters and pleasant summers. Afghanistan is a relatively dry country, the annual rainfall averages about 12 inches (305 mm). Most of the rainfall occurs between October and April. Sandstorms occur frequently in the deserts and arid plains.

A total of 13 pedons were sampled from Farah and Kunar provinces and an additional pedon was sampled from the Kabul region. A map of Afghanistan showing these sampling locations is given in Figure 7. No series names have yet been assigned for Afghanistan soils. Thus, for the sake of simplicity, the pedon’s location (e.g., Gurgi, Yazdi, and Marawara) is used throughout this report to refer to the soil sample or pedon under investigation. When more than one pedon was sampled in a certain location (e.g., Gurgi, Farah City, and Sarkani), then a number (1 or 2) follows the name (e.g., Gurgi1 and Gurgi2). Further, the Asadabad pedon, sampled in the Kabul area is discussed throughout this report along with the pedons from the Kunar province. The soil sampling locations, soil classifications and the names and depths of the top three horizons for the 14 pedons in Farah and Kunar provinces are given in Table 5.

Soil Analysis

Soil samples were analyzed on air-dried soil material less than 2-mm in size by methods described in Soil Survey Investigations Report No. 42 (USDA/NRCS, 2004). Alphanumeric codes in parentheses next to each method represent specific standard operating procedures. Particle-size analysis was performed by sieve and pipette method (3A1). Cation exchange capacity (CEC) was conducted by ammonium-acetate (NH4OAc) buffered at pH 7.0 (5A8b). Total carbon (C) concentration was determined by dry combustion (6A2f), and $CaCO_3$ equivalent was estimated by electronic manometer method (6E1g). Organic C in soil was estimated from both the total-C, and $CaCO_3$-C. Soil pH was measured in 0.01 M CaCl2 for 1:2 soil/solution suspension (8C1e). Bulk density (BD) was determined by paraffin-coated clods, oven-dry (4A2a).

The amount of available P was estimated using the water extract (4D2a), Olsen (4D5a), Mehlich-3 (4D6b), and DP-AER (4D1a) methods. Extractable forms of aluminum (Al), iron (Fe), and manganese (Mn) were determined by the Mehlich-3 method (4D6b). Dithionite-Citrate extraction (4G1a1-3) was used to measure Al, Fe, and Mn associated with amorphous oxide/hydroxide minerals in soils. Extractable forms of calcium and magnesium were measured by the ammonium-acetate (NH4OAc) method (4B4c).

The properties for 42 soil samples, collected from the top three horizons of 14 pedons, are presented in Table 5. The amount of available P measured by different methods (water, Olsen, Mehlich-3, and DP-AER), as well as the concentration of elements (Al, Fe, Mn, Ca, and Mg) extracted with the Mehlich-3, Dithionite-Citrate, and NH4OAc solution methods are given in Table 6. In addition to P availability, we used the double-point anion exchange resin extraction method (4D1a) to determine P capacity, and release characteristics for soils. A brief description of the DP-AER method (4D1a) is given above. Parameters for the linear regression equations developed to describe P released for the 1 to 60-min, and 1 to 24-h or 48-h extraction regions are given in Table 7.

Results and Discussions

Soil Properties

The particle size analysis indicated that the 42 soil samples tested were generally coarse-textured ranging from sand to silty clay with the clay content fluctuating between 4.6 and 45.1 percent, and averaging 17.3 percent. However, only six samples (most of them from Yazdi and Farah City1) had a clay content > 25 percent while both sand and silt were the major fractions in most soils, ranging from 4.6 to 86.0 percent and 8.2 to 68.4 percent, respectively. The calcium carbonate ($CaCO_3$) content fluctuated widely between 0.0 and 51.0 percent with an average of 17.8 percent, indicating that most soils could be categorized as calcareous with very low organic carbon (OC) content, ranging from 0.05 to 1.58 percent with an average of 0.50 percent. The bulk density (BD) ranged from 1.2 to 1.86 g/cm^3 with an average of 1.60 g/cm^3. These relatively high BD values should not raise any concern with respect to soil compaction and its adverse effects on root growth. Coarse-textured $CaCO_3$-rich soils with large quantities of quartz sand and calcite minerals typically have high values of bulk density (BD). Under dry conditions (drought), however, a surface soil with high percentages of both clay and $CaCO_3$ could develop a hard cemented layer. These adverse conditions apply only to the Yazdi pedon, which contained 39.4 percent clay and 27 percent $CaCO_3$ in the surface Ap horizon.

The results (Table 5) also indicated a low cation exchange capacity (CEC), ranging from 1.9 to 12.9 cmol(+)/kg and averaging 6.8 cmol(+)/kg. These low CEC values could be attributed to the high content of $CaCO_3$ (low or no surface charge) and the low clay percent and OC percent in soils. As is typical for calcareous soils in dry regions, pH values were within the alkaline range (7.4 to 8.6), except for two subsurface soil samples (B horizon) collected from Watorpor and Asadabad pedons. The results of electrical conductivity (EC) implied that all soils were non-saline (< 4.0 mmhos/cm [dS/m]), except for those samples collected from the Kohe Asya pedon where exceptionally high EC values of 194 and 27 mmhos/cm (dS/m) were detected in the A horizon and B horizon, respectively. The analysis indicated that chloride and sulfate were the major anions and were associated mainly with sodium, while less association was detected with magnesium and potassium. In addition to the high concentration of both chloride and sulfate anions, a significant concentration of nitrate was observed for soil samples collected from the Kohe Asya pedon, indicating a likely addition of N fertilizers.

Available Phosphorus

For agricultural soils, most of the readily available P can be present in water-soluble forms, and as P adsorbed on surfaces of hydrated oxides of Al and Fe and clay minerals (Pierzynski et al., 2005). In arid environments, soils typically have free calcium carbonate minerals and high pH values. Calcium phosphate minerals of very low solubility (i.e., tri-calcium phosphate, hydroxyl apatite, and flour apatite) are dominant in these alkaline calcareous soils (Lindsay, 1979). Further, for soils in arid environments, organic phosphates are not expected to be present in significant concentrations because of the very low organic matter content (Pierzynski et al., 2005).

The DP-AER method was applied to measure the amount of P released from soil by AER at 1-hour (AER-1h), 24-hour (AER-24h), and 48-hour (AER-48h) extraction periods. The amount of P determined by the water, Olsen, Mehlich-3, and DP-AER methods at different extraction periods is given for the 42 soil samples collected from 14 pedons in Afghanistan (Table 6). For all soils, the amount of P extracted by various methods followed this order: water < Olsen < AER-1h < Mehlich-3 < AER-24h < AER-48h. The water extraction may remove a small amount of adsorbed P in addition to water-soluble forms, which are typically low in arid soils. The amount of P determined by the water method was extremely low, ranging between 0.01 and 0.42 mg/kg with an average of 0.14 mg/kg. These low P concentrations should not be surprising because the method applied a high water to soil ratio (10:1) and a relatively short extraction period (30 minutes).

The bicarbonate solution adjusted to pH 8.5 (Olsen extract) can remove water-soluble P, adsorbed P, and fractions of calcium phosphate minerals. Olsen and Sommers (1982) reported that in alkaline, calcareous, and near neutral soils, the Olsen extraction decreases the concentration of Ca in solution, which enhances the dissolution of Ca-phosphate minerals. In this study, the amount of P extracted by the Olsen method was generally within the low range for most soils, fluctuating between 0.46 and 19.2 mg/kg with an average of 4.95 mg/kg. However, two surface samples collected from cropped soils in Kunar Province (Sarkani2 and Watorpor) appeared to have relatively high P concentrations of 18.6 and 19.2 mg/kg, respectively. Maguire et al. (2005) reported that the Olsen P concentration of 15 mg /kg is considered the optimum agronomic threshold for agricultural soils in Colorado and Idaho.

The rate of resin P sorption depends solely on the rate of P desorption or dissolution from the soil minerals and not on the properties of the resin itself (Krause and Ramlal, 1987). In their study on 24 United States soils, Elrashidi et al. (2003) concluded that the AER-1h P was mainly drived from water-soluble and adsorbed forms in soils. The authors also found that the AER-48h could remove all P forms dissolved by the Olsen solution. Olsen and Khasawneh (1980) reported that the resin-extractable P is related to labile P and to the Olsen bicarbonate extraction. In their initial study on calcareous soils, Amer et al. (1955) concluded that the employment of AER to quantify labile soil P constituted a major methodological breakthrough. Therefore, the AER-48h could be considered a valid measure of the capacity factor for soils.

The DP-AER extraction method can be applied to quantify both the readily available P (AER-1h P) and P capacity or supplying power (AER-48h P) for soils. In this study, the readily available soil P measured by the DP-AER extraction method gave relatively higher P values than those extracted by the water and Olsen methods (above). The readily available P (AER-h1 P) ranged from 0.6 to 43.8 mg/kg with an average of 9.73 mg/kg. Meanwhile, the P capacity (AER-48 P) had a very wide range (1.21 to 87.3 mg/kg) and an average of 22.3 mg/kg for soils.

The Mehlich-3 solution is a combination of acids (0.2 M HOAc and 0.013 M HNO_3), ammonium salts (0.015 M NH_4F and 0.25 M NH_4NO_3), and 0.001 M of the chelating agent ethylenediaminetetraacetic acid (EDTA). Hydrogen, F-, and OAc- are the principal ions used in the Mehlich-3 solution to remove P from soils. In alkaline calcareous soils, the Mehlich-3 method is expected to extract both water soluble and adsorbed P forms in addition to dissolving significant amounts of Ca-phosphate minerals. A Mehlich-3 P concentration of 50 mg/kg soil is generally considered as the optimum agronomic threshold for cropped soils in the United States (Sims et al., 2002; Maguire et al., 2005).

For the 42 samples collected from the 14 soil pedons in Afghanistan, the amount of P extracted by the Mehlich-3 solution ranged between 0.0 and 55.8 mg/kg with an average of 15.2 mg/kg. For most soils tested, the P amount extracted by the Mehlich-3 method was lower than the amount of P determined by the DP-AER method for the 48-hour extraction (AER-48h P). However, the Mehlich-3 P was slightly higher than the amount of available P determined by 1-hour extraction (AER-1h P). These data suggested that the high $CaCO_3$ content in Afghanistan soils might have reduced the ability of the Mehlich-3 solution to extract P from soils. Calcium carbonate could have neutralized acidity in the Mehlich-3 solution (0.2 M HOAc and 0.013 M HNO_3).

Relationship with Soil Parameters

We used statistical correlation to investigate the relationship between P measured by different methods. A highly significant correlation with a coefficient “R” ranging from 0.955** to 0.999** was found between P measured by different extraction periods for the DP-AER method (AER-1h, AER-24h, and AER-48h). A significant correlation was observed between P determined by the water and DP-AER method (R= 0.409**, 0.385*, and 0.381* for AER-1h, AER-24h, and AER-48h, respectively), as well as Olsen (0.482**) and Mehlich-3 (0.652**) method. Similarly, P measured by the Olsen method correlated well with all other methods investigated: AER-1h (0.636**), AER-24h (724**), AER-48h (0.730**), water (0.482**), and Mehlich-3 (0.618**). Phosphorus determined by the Mehlich-3 method failed to show any relationship with P measured by the AER-1h extraction method. However, as mentioned above, the Mehlich-3-P method showed significant correlation with the four other methods. Maguire et al. (2005) reported that even though the various soil tests extract different amounts of soil P, the results tend to be well correlated. Fixen and Grove (1990) reviewed the literature for P correlation between soil test methods and showed significant correlation coefficients almost always between such soil tests as Mehlich-3, Olsen, water, and Bray-1. Moreover, Atia and Mallarino (2002) reported highly significant correlation between the Olsen, Mehlich-3, and Bray-1 soil tests.

We also investigated the relationship between P determined by different methods and soil parameters known to affect the solubility of P in soils (Table 8). A highly significant correlation was detected between P determined by the DP-AER and clay percent, CEC, Mehlich-3 Fe, Mehlich-3 Mn, and NH4OAc Mg. On the contrary, P determined by the water method failed to show any relation with all soil parameters investigated, except for a negative correlation with both the soil pH and $CaCO_3$ percent. The results suggested that the water method might not be a suitable index for the availability of P in these soils. On the other hand, P determined by the

Olsen method had a significant correlation with the organic C percent, $CaCO_3$ percent, CEC, Mehlich-3 Fe, and Mehlich-3 Mn. Similarly, P determined by the Mehlich-3 method showed significant correlation with the clay percent, $CaCO_3$ percent, and Mehlich-3 Mn. Contrary to the Mehlich-3 extraction, elements extracted with the Dithionite-Citrate solution (i.e., Al, Fe, and Mn) generally failed to show significant correlations with the amount of available P determined by different methods (these data are not shown in this report).

A multiple regression model (SAS, 2003) was applied to improve the relationship between P determined by different methods and soil parameters as well as to predict the amount of available P in soils. The best 3-variable model relating the amount of available P (as a dependent factor) to different soil parameters (independent factors) is shown in Table 9. The Mehlich-3 Fe, Mehlich-3 Mn, and clay percent offered the best model to predict P measured by the DP-AER extraction method. For P measured by the Olsen method, the Mehlich-3 Fe along with the soil pH and $CaCO_3$ percent gave the best prediction. The Mehlich-3 Al, Mehlich-3 Fe, and $CaCO_3$ percent could provide the best prediction for the amount of P determined by the Mehlich-3 method. The best model to predict P extracted by the water method included the Mehlich-3 Al, NH4OAc Ca, and $CaCO_3$ percent as independent parameters.

The data given in Table 6 show that the Dithionite-Citrate solution has dissolved considerable amounts of Fe and relatively high concentrations of both Al and Mn for most soils investigated. These data suggested the presence of amorphous oxide/hydroxide of Fe, Al, and Mn minerals in the soils (USDA/NRCS, 2004). These oxide/hydroxide minerals are known to play an important role in the sorption of P by soils (Lindsay, 1979; Sposito, 1989). Further, the importance of soil pH, clay percent, and $CaCO_3$ percent in the solubility and availability of P is well documented in the literature (Olsen and Sommers, 1982; Pierzynski et al., 2005).

Phosphorus Release Characteristics (PRC)

Figure 8 shows the relationship between the AER extraction period (hour) and the accumulating amount of P released (mg/kg soil) in the top horizon for eight pedons, Farah Province (top), and for six pedons, Kunar Province (bottom). A similar relationship was obtained for all subsurface horizons in the 14 pedons investigated (not shown). The relationship implied that the total amount of P released has somehow leveled off, approaching a maximum near the end of the extraction process. The total amount of P released from soil by AER during the 48-hour extraction could represent the soil P capacity or supplying power (Elrashidi et al., 2003). The knowledge of soil P capacity is important because the growing season for agricultural crops may extend for several months where continuous supply of P and other essential nutrients is needed to secure profitable harvest.

The results indicated that the top horizon in both Yazdi (48.4 mg/kg) and Farah City2 (46.3 mg/kg) had the highest soil P capacity of the eight pedons sampled from Farah Province. The P capacity was generally low (< 20 mg/kg soil) for the top horizon in other pedons. On the other hand, the top horizon in Sarkani2 appeared to have the highest P capacity (67.6 mg/kg soil) of the six pedons sampled from the Kunar Province. The top horizons in Yazdi, Farah City2, and Sarkani2 appeared to be the only surface soils investigated with sufficient P amounts to support crops grown on these irrigated agricultural areas in Afghanistan. Other soils, however, appeared to be in great need of P fertilizers to secure good crop production.

For all 42 samples collected from the 14 pedons in Afghanistan, an average of 46 percent of P was released from soil by AER during the first hour and the remaining 54 percent was released during the following 47 hours of extraction. No significant difference in these values was observed when the P release data were calculated for each province (Farah and Kunar). Similar values were calculated for nine calcareous U.S. soils, where an average of 49 percent of P was released during the first hour and the remaining 51 percent was released during the following 47 hours of extraction (Elrashidi et al., 2003). The authors also reported that the corresponding values for 15 acidic U.S. soils were 33 and 67 percent which reflected, to some extent, the different solubility of natural P minerals in the acidic environment (i.e., Al- and Fe-phosphates).

We investigated the distribution of released P within the top three horizons in all 14 pedons. The amount of P released from soil appeared to decrease with depth in all pedons investigated, except for the Yazdi pedon where the amount of P released increased with depth. For the Watorpor pedon, Figure 9 illustrates the predicted amount of P released from soil during the 1-48h (top) and 1-60min (bottom) extraction period for the top three horizons (Ap, Bt1, and Bt2). The amount of P released by AER during the first hour of extraction (1-60min) was 15.3 > 2.3 > 1.1 mg/kg soil for the Ap, Bt1, and Bt2 horizons, respectively. The amount of P released by AER during the 48 hours of extraction (1-48h) was 42.3 > 13.0 > 2.9 mg/kg soil, respectively. Except for Yazdi, a similar P trend (decreasing with depth) was observed for the other 12 pedons (not shown).

Figure 10 shows the predicted amount of P released for the top three horizons in the Yazdi pedon. The amount of P released from soil during the first hour of extraction (1-60min) was 23.9 < 40.5 < 43.8 mg/kg for the Ap, Bt1, and Bt2 horizons, respectively (Figure 10, bottom). The amount of P released during the 1-48h extraction period was 48.4 < 82.8 < 87.3 mg/kg for the Ap, Bt1, and Bt2 horizons, respectively (Figure 10, top). This exceptionally increasing trend with depth could be attributed to the downward movement either by irrigation water or rainfall. The fact that the amount of P released from Yazdi soils was much higher than from other pedons implied the addition of P fertilizer. Yazdi soils have relatively high clay and $CaCO_3$ content (Table 1) which could contribute to the formation of soil cracks under dry conditions. These cracks could enhance the downward movement of water and P in the soil profile.

Plotting the log of the extraction period (hour) against the amount of P released from soil by AER (mg/kg) always produced a linear relationship (Elrashidi et al., 2003). The linear relationship applied for both the 1-48h and 1-60min extraction periods. For all 42 soil samples, the linear regression equations to predict the amount of P released from soil by AER (mg/kg) for both the 1-48h and 1-60min extraction periods are given in Table 7. Figure 11 shows the linear relationship for top horizons collected from the eight pedons in Farah Province (top) and the six pedons in Kunar Province (bottom). A similar linear relationship was found for all 28 soil samples collected from subsurface horizons (not shown).

As mentioned above, the intercept (I) at the 1h extraction period mainly reflected both the water-soluble and adsorbed forms of P (readily available P) in soil (Elrashidi et al., 2003, 2005). For the top three horizons in the eight Farah pedons, the value of intercept (I) varied widely, ranging between 3.5 and 43.8 mg P/kg soil, and averaging 10.7 mg P/kg soil. On the other hand, the intercept (I) ranged from 1.1 to 23.7 mg P/kg soil with an average of 8.49 mg P/kg soil for the top three horizons in the six Kunar pedons. When we included data for all 14 pedons, the intercept (I) fluctuated widely between 1.1 and 43.8 mg P/kg and averaged 9.7 mg P/kg soil. These data were much lower than P values reported for the 24 United States soils where the readily available P (I) ranged between 12.6 and 147 mg/kg soil (Elrashidi et al., 2003). In another study, Elrashidi et al. (2008) reported higher values for the readily available P (I) ranging from 45.8 to 114.9 mg/kg for five cropped soils in West Virginia that had been amended with poultry manure. It appeared that the manure had added considerable amounts of P to these soils.

Figure 12 shows that the rate of P release from soil decreased significantly following the initial high rate of release during the first hour. After the exhaustion of easily-released P, it appeared that the release was mainly derived from the dissolution of sparingly soluble minerals. For alkaline calcareous soils, P minerals are dominated by Ca-phosphates with extremely low solubility (i.e., tricalcium phosphate, hydroxy-apatite and fluor-apatite) (Lindsay, 1979). The initial fast rate of P release from soils, followed by slower release, was consistent with the observations made by Lookman et al. (1995), Sharpley (1996), and Siddique and Robinson (2004). In their work on P release from lake sediments, Kuo and Lotse (1974) concluded that the initial fast reaction represented the desorption of more labile P, while the latter fractions are rated as less mobile.

The Watorpor pedon (Farah Province) was a good example of a soil sample with extremely low P content. In this pedon, the rate of P release was 15.3, 2.3, and 1.1 mg/h during the first hour of extraction for the Ap, Bt1, and Bt2 horizons, respectively (Figure 12, top). Then, the rate decreased with time and bottomed (0.15, 0.06, and 0.01 mg/h, respectively) during the 48th hour of the extraction period. Similar results were obtained for other soils with relatively low P content (not shown). Elrashidi et al. (2005) reported similar low rates of P release for a calcareous surface soil sample from Texas (Windthorst, Fine, mixed, thermic Udic Paleustalf). The rate was 10.8 and 0.09 mg P/h at the first and 48th hour of extraction, respectively. The authors concluded that the rate of P release could approach zero only when all P minerals in the soil were dissolved completely, which was unlikely under the experimental conditions. The dissolution process of Ca-phosphates might take several months because of the extremely low solubility of some P minerals (Lindsay, 1979).

Figure 12 (bottom) shows a relatively high rate of P release from surface soil samples collected from the Yazdi pedon which probably has received some application of P fertilizer. As opposed to the Watorpor pedon, a higher rate of P release was recorded (23.9, 40.5, and 43.8 mg/h) during the first hour of extraction for the Ap, Bt1, and Bt2 horizons, respectively. Then, the rate of P release decreased with time and leveled off (0.13, 0.23, and 0.24 mg/h, respectively) during the 48th hour of extraction. The P-rich Yazdi soil samples, however, continued to release minute amounts of P into solution near the end of the extraction process (48 hours).

Conclusions

The amount of available P was generally low for most soils tested and the application of fertilizers should be considered to sustain healthy soil fertility and improve crop production. For arid calcareous soils with high P sorption capacity, the application method should aim to minimize fertilizer-soil contact. Granulated forms are usually more effective in reducing such contact than other forms of fertilizers. At the same time, P fertilizer should be placed in a zone where a maximum number of roots can proliferate. For such soils, organic matter content is typically very low which has adverse effects on soil biochemical and physical properties as well as on soil fertility. Under these conditions, the addition of organic amendments (i.e., organic compost, animal manure, or municipal sewage) along with P fertilizer is highly recommended.

Either the Olsen sodium bicarbonate solution or the DP-AER extraction method can provide a good P availability index for the irrigated cropland in Afghanistan. The DP-AER method, however, has an advantage over chemical extractants because it uses water and the extraction mechanism simulates P absorption by plant roots. Further, the DP-AER method can quantify both the amount of readily available P and the P supplying power (capacity) and can provide a reliable measure for the rate of P release.

The water method extracted extremely low P amounts from soils and was poorly correlated with the soil properties and the amount of P extracted by other methods. This result could be attributed to the fact that the method applied a high ratio of the water to soil (10:1) and a relatively short extraction period (30 minutes). These extraction conditions might not allow all forms of the available P to be released and approach equilibrium in the soil:water system. On the other hand, the high $CaCO_3$ content appeared to neutralize the acidity in the Mehlich-3 solution and thus limited the ability of this method to extract all forms of the available P from the $CaCO_3$-rich soils.

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Tables

Table 1. Classification and properties for 27 soil samples investigated.

Soil	Classification	Clay	pH	pH	OC	$CaCO_3$	CEC	BD
		(%)	(water)	(CaCl2)	(%)	(%)	(Cmol/kg)	(g/cc)
Greenson	Fine-silty, Mixed, Superactive, Mesic Oxyaquic Calcixeroll	19.2	7.4	7.1	3.54	3.0	22.4	1.23
Genola (1)	Fine-silty, Mixed, Calcareous, Mesic Typic Calcixerept	45.1	8.1	7.8	7.59	34.0	23.5	1.23
Genola (2)	Fine-silty, Mixed, Calcareous, Mesic Typic Calcixerept	28.3	8.2	7.8	7.07	29.0	18.1	1.23
Layton (1)	Sandy, Mixed, Superactive, Mesic Oxyaquic Haploxeroll	6.0	8.2	7.9	0.81	1.0	5.7	1.66
Layton (2)	Sandy, Mixed, Superactive, Mesic Oxyaquic Haploxeroll	4.7	8.1	7.8	0.83	1.0	5.5	1.57
Layton (3)	Sandy, Mixed, Superactive, Mesic Oxyaquic Haploxeroll	4.9	8.1	7.8	0.56	1.0	5.4	1.64
Layton (4)	Sandy, Mixed, Superactive, Mesic Oxyaquic Haploxeroll	4.2	8.8	8.5	1.49	1.0	6.4	1.66
Windthorst (1)	Fine, Mixed, Thermic, Udic Paleustalf	11.2	5.4	5.0	0.57	0.0	6.7	1.51
Windthorst (2)	Fine, Mixed, Thermic, Udic Paleustalf	15.8	6.1	5.3	0.37	0.0	8.5	1.61
Windthorst (3)	Fine, Mixed, Thermic, Udic Paleustalf	12.0	5.1	4.9	0.70	0.0	4.2	1.51
Windthorst (4)	Fine, Mixed, Thermic, Udic Paleustalf	25.1	7.3	7.1	1.76	1.0	17.2	1.25
Colby	Fine-loamy, Mixed , Superactive, Mesic Aridic Ustorthent	19.9	7.8	7.6	2.01	4.0	21.6	1.35
Rosebud	Fine-loamy, Mixed, Mesic Aridic Argiustoll	22.0	7.9	7.4	1.05	1.0	22.6	1.33
Kim	Fine-loamy, Mixed, Superactive, Mesic Aridic Haplustalf	29.1	7.9	7.5	1.92	9.0	16.3	1.41
Syrupcreek	Loamy, Skeletal, Amorphic/Isotic, Frigid Alfic Udivitrand	8.6	4.9	4.4	21.82	0.0	19.6	0.82
Caribou (1)	Loamy, Skeletal, Halloysitic, Acid, Frigid Typic Udorthent	12.8	5.8	5.4	2.42	0.0	15.4	1.48
Caribou (2)	Loamy, Skeletal, Halloysitic, Acid, Frigid Typic Udorthent	12.6	5.7	5.2	2.17	0.0	14.4	1.48
Charlton	Coarse-loamy, Mixed, Mesic Typic Dystrochrept	10.1	4.1	3.9	9.86	0.0	21.2	1.14
Albia	Fine-loamy, Mixed, Mesic Aeric Fragiaqualf	16.3	6.0	5.8	1.36	0.0	3.5	1.34
Pleasant	Fine, Smectitic, Mesic Cumlic Vertic Epiaquoll	21.2	6.0	5.6	1.27	0.0	18.1	1.25
Caspiana (1)	Fine-silty, Mixed, Thermic Typic Argidoll	17.8	6.2	5.8	1.38	0.0	17.9	1.34
Caspiana (2)	Fine-silty, Mixed, Thermic Typic Argidoll	18.0	6.2	6.0	1.34	0.0	16.1	1.34
Marshall (1)	Fine-silty, Mixed, Mesic Typic Hapludoll	26.4	6.2	6.1	2.56	0.0	24.4	1.28
Marshall (2)	Fine-silty, Mixed, Mesic Typic Hapludoll	29.2	4.9	4.9	2.19	0.0	24.2	1.4
Christian (1)	Fine-silty, Mixed, Semiactive, Mesic Typic Hapludult	28.7	6.9	6.9	2.74	0.0	11.0	1.62
Christian (2)	Fine-silty, Mixed, Semiactive, Mesic Typic Hapludult	30.8	6.9	6.9	2.73	0.0	10.5	1.62
Hestehave	Fine-loamy, Mixed, Active, Frigid Typic Hapludalf	13.6	4.0	3.6	1.70	0.0	8.8	1.56

Table 2. Effect of soil:water ratio on 1h, and 24h anion exchange resin (AER)-extractable P (mg/kg soil) for Caribou (2) and Genola (2) soils.

Extraction period (h)	soil:water (1:100)		soil:water (2:100)		soil:water (4:100)	
	Mean	SD	Mean	SD	Mean	SD
	mg P/ kg soil					
Caribou loamy (2) soil						
1	39.39	2.50	31.08	2.94	25.79	4.45
24	163.69	6.09	132.80	5.50	115.43	23.59
Genola fine-silty (2) soil						
1	213.39	4.44	193.12	17.20	166.58	30.41
24	385.23	6.86	378.54	15.75	352.12	31.90

Table 3. Phosphorus measured by Bray-1, Olsen, and water method, and 1h, 24h, and 48h anion exchange resin (AER)-extratable P (mg/kg soil) for 24 soils.

Soils	Bray 1	Olsen	Water	AER-1h	AER-24h	AER-48h
	(mg P/kg soil)					
Greenson	133.05	97.60	34.92	113.07	185.67	195.96
Genola (1)	0.10	15.20	10.42	33.29	60.73	62.87
Layton (1)	19.45	9.16	4.65	19.67	36.12	39.43
Layton (2)	23.70	10.98	5.55	17.85	33.08	36.47
Layton (3)	26.70	10.71	5.52	18.83	38.91	42.51
Layton (4)	167.75	154.80	26.06	135.91	255.80	274.01
Windthorst (1)	35.00	12.58	3.15	11.95	26.00	29.98
Windthorst (2)	3.25	1.15	0.90	3.80	14.77	15.89
Windthorst (3)	41.60	32.60	3.52	16.57	42.41	48.64
Colby	0.05	28.25	3.31	33.61	64.25	70.93
Rosebud	7.85	14.03	1.14	6.47	12.25	13.51
Kim	0.05	17.98	1.51	12.57	29.23	32.93
Syrupcreek	331.85	288.00	15.29	43.95	200.07	226.49
Caribou (2)	275.80	138.00	3.57	38.56	185.37	243.06
Charlton	51.20	5.07	1.64	20.73	62.04	67.10
Albia	168.15	66.80	1.88	39.73	125.38	153.69
Pleasant	87.50	33.18	11.79	56.46	108.79	120.07
Caspiana (1)	85.55	26.56	11.36	48.47	112.13	129.26
Caspiana (2)	87.65	25.59	13.15	52.13	108.89	128.51
Marshall (1)	125.90	38.63	14.50	85.29	168.82	187.62
Marshall (2)	96.70	10.53	7.54	65.44	130.82	149.90
Christian (1)	46.40	8.28	3.74	24.44	51.86	56.45
Christian (2)	44.80	12.43	4.11	7.29	39.87	46.98
Hestehave	57.60	8.66	2.56	27.61	65.86	73.92

Table 4. Linear regression equations used to predict P released by anion exchange resin (AER) (mg/kg soil) for 1-60min, and 1-48h extraction regions in 24 soils.

Soil	Intercept (I)	Slope (S1) (1-60min)	Slope (S2) (1-48h)
Greenson	118.1	66.4	48.6
Genola (1)	35.4	19.9	17.8
Layton (1)	19.9	11.2	11.7
Layton (2)	16.9	9.5	11.4
Layton (3)	18.8	10.5	14.4
Layton (4)	147.0	82.7	79.6
Windthorst (1)	12.6	7.1	10.2
Windthorst (2)	4.3	2.4	7.3
Windthorst (3)	15.7	8.8	19.3
Colby	33.6	18.9	22.2
Rosebud	6.5	3.6	4.2
Kim	13.4	7.5	11.7
Syrupcreek	43.2	24.3	113.1
Caribou (2)	23.4	13.2	120.8
Charlton	21.2	11.9	28.5
Albia	33.2	18.7	68.2
Pleasant	54.2	30.5	38.9
Caspiana (1)	47.0	26.4	48.2
Caspiana (2)	49.1	27.6	45.0
Marshall (1)	83.5	47.0	61.4
Marshall (2)	62.4	35.1	50.4
Christian (1)	26.9	15.1	18.3
Christian (2)	7.3	4.1	23.6
Hestehave	28.4	16.0	27.6

* P = **I** + S1 x (Log h) for 1-60 min; P = **I** + S2 x (Log h) for 1-48 h extraction region

Correlation coefficient (r) between P and (Log h) for all regression equations were higher than 0.99

Table 5. Classification and properties of soil samples collected from top three horizons for 14 pedons in Farah Province and Kunar Province, Afghanistan.

Serial #	Pedon	Horizon	Depth	Classification	Clay	BD	CEC	EC	pH-CaCl2	Total C	$CaCO_3$	Organic C
			(Cm)		(%)	(g/cm3)	(cmol(+)/kg)	(dS/m)		(%)	(%)	(%)
1	**Gurgi1†**	**Ap**	**0-15**	Sandy, carbonatic, hyperthermic	8.40	1.68	4.60	0.79	7.80	4.73	36.00	0.41
2		**Bw1**	**15-31**	Typic Haplocambids	12.10	1.58	4.60	1.02	7.90	4.13	32.00	0.29
3		**Bw2**	**31-53**		9.00	1.66	2.90	0.73	8.00	5.17	37.00	0.73
4	**Gurgi2†**	**A1**	**0-11**	Loamy-skeletal, carbonic,	5.00	1.73	2.40	*0.14*	7.90	5.98	49.00	0.10
5		**A2**	**11-31**	hyperthermic Typic Haplargids	4.60	1.67	3.00	*0.11*	8.00	5.31	44.00	0.03
6		**Bw1**	**31-59**		5.80	1.74	1.90	*0.11*	8.00	6.11	51.00	0.00
7	**Mawran†**	**Ap**	**0-18**	Coarse-loamy, mixed, active,	21.10	1.43	8.80	0.94	7.90	3.74	27.00	0.50
8		**Bw**	**18-49**	hyperthermic Typic Haplocambids	24.30	1.48	7.90	2.86	8.00	3.79	29.00	0.31
9		**2Bt1**	**49-67**		21.70	1.46	6.40	5.31	8.10	3.92	32.00	0.08
10	**Farah City1†**	**Ap**	**0-12**	Fine-loamy, mixed, subactive,	22.70	1.52	7.20	1.98	7.90	3.96	29.00	0.48
11		**Bw**	**12-29**	hyperthermic Typic Calciargids	25.60	1.61	7.70	0.64	8.00	3.88	28.00	0.52
12		**Bt1**	**29-57**		35.60	1.62	9.00	0.59	8.10	3.54	27.00	0.30
13	**Yazdi†**	**Ap**	**0-14**	Fine, mixed, semiactive,	39.40	1.50	12.60	1.57	8.20	4.02	27.00	0.78
14		**Bt1**	**14-49**	hyperthermic Fluventic Aquicambids	45.10	1.61	12.90	1.40	8.20	3.83	26.00	0.71
15		**Bt2**	**49-79**		42.40	1.65	11.30	1.47	8.30	4.04	31.00	0.32
16	**Farah City2†**	**Ap**	**0-12**	Fine-loamy, mixed, semiactive,	11.30	1.46	4.80	3.41	8.10	3.90	31.00	0.18
17		**Bw1**	**12-32**	hyperthermic Sodic Haplocambids	19.40	1.57	6.10	3.82	8.00	3.17	26.00	0.05
18		**2Bw2**	**32-76**		24.30	1.48	7.10	3.35	8.10	3.65	29.00	0.17
19	**Kohe Asya†**	**Az**	**0-11**	Coarse-loamy, mixed, active,	20.70	1.40	4.80	194.00	8.60	1.63	9.00	0.55
20		**Btz**	**11-49**	hyperthermic Aquic Haplocalcids	17.30	UD	7.00	27.00	8.60	3.47	27.00	0.23
21		**Btkz**	**49-83**		11.70	UD	5.30	5.20	8.20	2.86	24.00	0.00
22	**Karez Sofa†**	**A**	**0-15**	Fine-loamy, mixed, semiactive,	19.20	ND	4.40	3.17	8.10	2.06	16.00	0.14
23		**Btk1**	**15-39**	hyperthermic Typic Calciargids	22.40	ND	6.80	2.11	8.10	2.03	17.00	0.00
24		**Btk2**	**39-86**		28.10	ND	7.10	1.51	8.40	2.17	18.00	0.01
25	**Sarkani1‡**	**Ap**	**0-20**	sandy-skeletal, mixed,	8.60	1.65	5.50	1.77	7.60	0.43	2.00	0.19
26		**Bw1**	**20-60**	thermic Xeric Calciargids	5.10	1.73	3.60	***0.18***	7.80	0.87	6.00	0.15
27		**Bw2**	**60-77**		6.90	1.86	4.40	***0.25***	7.70	0.37	3.00	0.01
28	**Sarkani2‡**	**Ap**	**0-9**	Coarse-silty, mixed, active,	15.00	UD	7.50	0.85	7.80	1.82	7.00	0.98
29		**Bt**	**9-42**	thermic Oxyaquic Haploxerolls	14.70	1.59	6.90	0.65	7.80	1.39	7.00	0.55
30		**Bw1**	**42-68**		8.60	1.45	3.70	***0.21***	7.80	1.55	10.00	0.35
31	**Marawara‡**	**Ap**	**0-11**	Coarse-loamy, mixed, active,	8.90	1.53	6.50	0.85	7.40	0.55	0.50	0.49
32		**Bk**	**11-27**	thermic Calcic Haploxeralfs	9.50	1.44	7.20	***0.19***	7.60	0.36	0.50	0.30
33		**Btk1**	**27-47**		14.00	1.50	8.40	***0.18***	7.70	0.56	3.00	0.20
34	**Mabogai‡**	**Ap**	**0-12**	Coarse-loamy, paramicaceous,	10.30	1.45	7.10	***0.22***	7.60	1.60	4.00	1.12
35		**Bk1**	**12-38**	active, thermic Aridic	6.40	1.66	4.40	***0.17***	7.60	0.67	1.00	0.55
36		**Bk2**	**38-87**	Calcixerolls	6.60	1.51	3.70	***0.12***	7.70	0.62	2.00	0.38
37	**Watorpor‡**	**Ap**	**0-7**	Fine-loamy, mixed, active,	19.90	1.59	11.80	0.72	7.40	1.64	0.50	1.58
38		**Bt1**	**7-42**	thermic Aridic Haploxerolls	19.80	1.54	11.60	***0.20***	6.90	1.43	0.00	1.43
39		**Bt2**	**42-62**		20.20	1.59	8.80	***0.09***	7.10	0.94	0.00	0.94
40	**Asadabad‡**	**Ap**	**0-15**	Fine-loamy, mixed, active,	16.80	1.20	11.50	***0.20***	7.20	1.64	0.50	1.58
41		**2Bt1**	**15-34**	thermic Aridic Argixerolls	20.50	1.50	10.20	***0.11***	7.10	0.87	0.50	0.81
42		**2Bt2**	**34-71**		17.50	1.60	7.70	***0.06***	6.90	0.49	0.00	0.49

† Pedon sampled from Farah Province, Western Afghanistan

‡ Pedon sampled from Kunar Province, Eastern Afghanistan

Table 6. Extractable phosphorus, aluminum, iron, manganese, calcium, and magnesium concentration (mg/kg soil) determined by different methods in 42 soil samples collected from top three horizons for 14 pedons in Farah Province and Kunar Provinces, Afghanistan.

Serial #	AER-1h-P (mg/kg)	AER-24h-P (mg/kg)	AER-48h-P (mg/kg)	Olsen-P (mg/kg)	Water-P (mg/kg)	Mehlich 3-P (mg/kg)	Mehlich 3-Al (mg/kg)	Mehlich 3-Fe (mg/kg)	Mehlich 3-Mn (mg/kg)	**Cit-Dith-Al (mg/kg)**	**Cit-Dith-Fe (mg/kg)**	**Cit-Dith-Mn (mg/kg)**	NH4OAc-Ca (mg/kg)	NH4OAc-Mg (mg/kg)
1	5.50	9.50	10.37	1.72	0.09	11.02	2.4	124.0	86.6	47.07	5,100	193.47	16,606	583
2	5.50	8.30	8.91	1.47	0.08	9.10	2.6	117.0	86.4	86.63	5,957	241.45	17,054	705
3	6.90	10.00	10.67	1.12	0.08	10.85	2.0	115.9	70.2	3.51	5,071	191.03	17,218	583
4	6.70	12.80	14.13	4.09	0.14	2.39	0.7	139.4	61.8	1.00	4,465	158.35	16,034	219
5	5.20	9.70	10.68	2.18	0.07	1.32	0.1	132.2	63.8	1.00	4,424	152.68	30,804	243
6	4.90	8.30	9.04	1.27	0.06	3.96	0.0	122.0	51.5	1.00	4,194	104.85	15,953	243
7	6.00	10.20	11.12	2.47	0.09	0.93	7.9	102.0	91.0	109.78	9,049	367.39	48,715	1,556
8	3.50	6.10	6.67	0.76	0.01	0.51	3.0	113.6	78.9	28.39	7,869	347.36	17,422	1,531
9	3.50	5.70	6.18	1.09	0.01	0.41	0.7	114.2	72.7	1.00	7,982	258.70	17,422	1,580
10	9.70	16.70	18.23	3.64	0.10	2.75	3.5	127.4	95.2	1.00	8,744	313.65	17,830	1,385
11	8.60	16.00	17.61	2.09	0.19	2.69	2.8	128.5	90.1	1.00	9,417	376.76	18,972	1,385
12	9.30	15.90	17.34	2.78	0.19	1.75	2.7	100.9	78.1	74.83	9,005	386.31	18,319	1,677
13	23.90	44.00	48.38	5.93	0.18	6.82	6.9	144.8	132.2	105.06	6,205	314.98	19,421	2,771
14	40.50	75.20	82.77	9.62	0.28	13.09	8.6	156.3	153.8	204.47	8,561	394.43	19,706	3,184
15	43.80	79.50	87.29	12.75	0.08	4.98	0.3	161.1	147.4	192.10	7,586	397.41	18,401	3,354
16	18.60	41.30	46.25	5.79	0.05	7.79	0.0	159.4	79.7	1.00	7,673	201.93	18,686	1,337
17	7.30	34.60	40.55	5.65	0.02	23.71	14.9	162.2	74.8	1.00	7,241	214.71	29,090	1,240
18	8.20	14.20	15.51	1.99	0.01	0.48	10.1	108.9	64.7	1.00	7,175	257.74	18,238	2,260
19	3.50	9.50	10.81	12.01	0.05	27.31	4.2	78.7	62.2	1.00	3,051	104.72	66,708	5,274
20	5.60	8.60	9.26	1.94	0.03	0.25	0.0	47.8	60.2	1.00	5,265	261.91	16,646	1,993
21	0.60	1.10	1.21	0.46	0.07	0.00	0.0	47.8	60.2	143.22	8,009	420.98	16,361	924
22	17.60	31.00	33.92	6.75	0.42	28.12	27.0	65.3	49.5	0.00	5,032	174.55	15,830	510
23	6.00	9.00	9.66	0.81	0.09	8.44	164.0	63.5	77.1	110.68	6,897	267.48	16,279	851
24	5.00	7.80	8.41	1.50	0.17	7.74	6.5	35.0	26.9	86.06	7,145	256.16	16,116	632
25	12.50	27.40	30.66	5.32	0.29	39.61	206.6	53.2	148.2	149.36	4,857	326.28	10,322	219
26	5.40	9.90	10.88	2.99	0.25	17.55	9.5	21.9	37.4	7.69	2,592	188.16	13,586	146
27	7.40	15.00	16.66	2.30	0.22	37.77	9.5	21.9	37.4	61.42	3,630	245.16	10,567	194
28	23.70	59.70	67.55	18.60	0.31	55.81	208.3	300.3	141.2	362.54	6,950	274.15	16,891	1,167
29	19.90	47.70	53.76	13.80	0.29	45.92	200.6	235.7	128.2	384.61	7,411	237.37	16,728	1,069
30	6.70	16.10	18.15	6.87	0.10	20.15	37.8	181.0	53.7	185.14	6,745	149.25	15,994	705
31	11.50	18.80	20.39	11.77	0.37	31.67	263.4	51.5	150.8	196.06	6,126	243.20	6,732	437
32	6.20	19.60	22.52	1.90	0.08	41.75	270.8	50.3	167.0	231.61	6,136	271.88	5,386	340
33	2.80	4.90	5.36	1.44	0.05	7.15	206.6	34.9	135.0	351.98	7,021	297.60	16,565	486
34	12.80	23.40	25.71	9.03	0.34	41.15	236.8	59.2	108.6	231.16	4,298	157.60	15,545	292
35	2.70	6.20	6.97	1.69	0.23	32.56	180.7	38.3	84.2	63.17	2,784	96.59	9,588	170
36	3.10	5.50	6.02	1.19	0.19	12.43	73.2	23.1	57.3	100.56	2,954	75.29	13,219	146
37	15.30	37.50	42.33	19.21	0.21	32.15	623.2	265.4	59.2	646.65	9,431	117.02	7,140	365
38	2.30	11.10	13.03	2.15	0.05	4.59	647.1	251.7	74.4	543.86	9,287	167.12	5,141	340
39	1.10	2.60	2.92	2.25	0.06	0.81	667.5	134.4	78.5	546.10	11,418	237.07	3,550	243
40	12.70	30.80	34.70	9.06	0.12	26.68	652.4	177.0	87.0	661.70	9,235	304.54	6,283	340
41	4.70	13.30	15.20	5.22	0.06	8.86	832.3	131.6	93.3	747.52	10,892	442.74	4,814	292
42	2.00	6.30	7.25	3.31	0.05	4.18	934.5	76.1	23.3	660.45	10,409	160.23	3,264	219

Table 7. Linear regression equations used to predict phosphorus released by anion exchange resin (AER) (mg/kg soil) for 1-60min and 1-48h extraction regions for 42 soil samples collected from 14 pedons in Farah Province and Kunar Provinces, Afghanistan.

Serial #	Pedon (name/province)	Horizon	Depth (Cm)	Intercept (I)	Slope (S1) (1-60 min)	Slope (S2) (1-48 h)
				(mg P/kg)		
1	Gurgi1†	Ap	0-15	5.50	3.09	2.90
2		Bw1	15-31	5.50	3.09	2.03
3		Bw2	31-53	6.90	3.88	2.25
4	Gurgi2†	A1	0-11	6.70	3.77	4.42
5		A2	11-31	5.20	2.93	3.26
6		Bw1	31-59	4.90	2.76	2.46
7	Mawran†	Ap	0-18	6.00	3.38	3.04
8		Bw	18-49	3.50	1.97	1.88
9		2Bt1	49-67	3.50	1.97	1.59
10	Farah City1†	Ap	0-12	9.70	5.46	5.07
11		Bw	12-29	8.60	4.84	5.36
12		Bt1	29-57	9.30	5.23	4.78
13	Yazdi†	Ap	0-14	23.90	13.44	14.56
14		Bt1	14-49	40.50	22.78	25.14
15		Bt2	49-79	43.80	24.63	25.87
16	Farah City2†	Ap	0-12	18.60	10.46	16.45
17		Bw1	12-32	7.30	4.11	19.78
18		2Bw2	32-76	8.20	4.61	4.35
19	Kohe Asya†	Az	0-11	3.50	1.97	4.35
20		Btz	11-49	5.60	3.15	2.17
21		Btkz	49-83	0.60	0.34	0.36
22	Karez Sofa†	A	0-15	17.60	9.90	9.71
23		Btk1	15-39	6.00	3.37	2.17
24		Btk2	39-86	5.00	2.81	2.03
25	Sarkani1‡	Ap	0-20	12.50	7.03	10.80
26		Bw1	20-60	5.40	3.04	3.26
27		Bw2	60-77	7.40	4.16	5.51
28	Sarkani2‡	Ap	0-9	23.70	13.33	26.08
29		Bt	9-42	19.90	11.19	20.14
30		Bw1	42-68	6.70	3.77	6.81
31	Marawara‡	Ap	0-11	11.50	6.47	5.29
32		Bk	11-27	6.20	3.49	9.71
33		Btk1	27-47	2.80	1.57	1.52
34	Mabogai‡	Ap	0-12	12.80	7.20	7.68
35		Bk1	12-38	2.70	1.52	2.54
36		Bk2	38-87	3.10	1.74	1.74
37	Watorpor‡	Ap	0-7	15.30	8.61	16.08
38		Bt1	7-42	2.30	1.29	6.38
39		Bt2	42-62	1.10	0.62	1.09
40	Asadabad‡	Ap	0-15	12.70	7.14	13.11
41		2Bt1	15-34	4.70	2.64	6.23
42		2Bt2	34-71	2.00	1.12	3.12

† Pedon sampled from Farah Province, Western Afghanistan

‡ Pedon sampled from Kunar Province, Eastern Afghanistan

§ P = I + S1 x (Log h) for 1-60 min extraction region; P = I + S2 x (Log h) for 1-48h extraction region;

where P = P released, I = intercept, S1 and S2 are slope, and h = extraction period (hour).

Table 8. Correlation between available soil phosphorus (mg/kg soil) determined by different methods and some properties for 42 soil samples collected from 14 pedons in Farah Province and Kunar Province, Afghanistan.

Method	Clay	CEC	EC	pH-CaCl2	Organic C	$CaCO_3$	Mehlich3-Al	Mehlich3-Fe	Mehlich3-Mn	NH4OAc-Ca	NH4OAc-Mg
	(%)	(cmol(+)/kg)	(dS/m)		(%)	(%)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
AER-1h-P	0.571	0.468	-0.110	0.243	0.203	0.102	-0.144	0.410	0.566	0.016	0.449
Water-P	-0.018	0.047	-0.089	-0.395	0.078	-0.307	-0.033	-0.046	0.279	-0.189	-0.187
Olsen-P	0.192	0.354	0.213	-0.071	0.516	-0.309	0.220	0.586	0.381	0.084	0.277
Mehlich3-P	-0.311	-0.058	0.093	-0.220	0.282	-0.579	0.149	0.131	0.366	-0.106	-0.160

† Correlation values of 0.298 and 0.385 indicate significance at 5% and 1% level, respectively.

Table 9. Best 3-variable models relating available phosphorus to different soil properties for 42 soil samples collected from 14 pedons in Farah Province and Kunar Province, Afghanistan.

Independent Variable	Best 3-Variable Model	R2
(AER-1h)-P	(AER-1h)-P = -9.32 + 0.03 (Mehlich 3-Fe) + 0.11 (Mehlich 3-Mn) + 0.38 (Clay%)	0.553**
(AER-24h)-P	(AER-24h)-P = -19.66 + 0.10 (Mehlich 3-Fe) + 0.21 (Mehlich 3-Mn) + 0.56 (Clay%)	0.590**
(AER-48h)-P	(AER-48h)-P = -21.91 + 0.12 (Mehlich 3-Fe) + 0.24 (Mehlich 3-Mn) + 0.60 (Clay%)	0.592**
Olsen-P	Olsen-P = -43.42 + 0.05 (Mehlich 3-Fe) + 5.89 (pH) - 0.21 ($CaCO_3$%)	0.608**
Water-P	Water-P = 0.30 - 0.0003 (Mehlich 3-Al) - 0.000003 (NH4OAc-Ca) - 0.005 ($CaCO_3$%)	0.301**
Mehlich3-P	Mehlich3-P = 29.16 - 0.04 (Mehlich3-Al) + 0.08 (Mehlich3-Fe) - 1.01 ($CaCO_3$%)	0.535**
** Indicates significance at 1% level.		

Figures

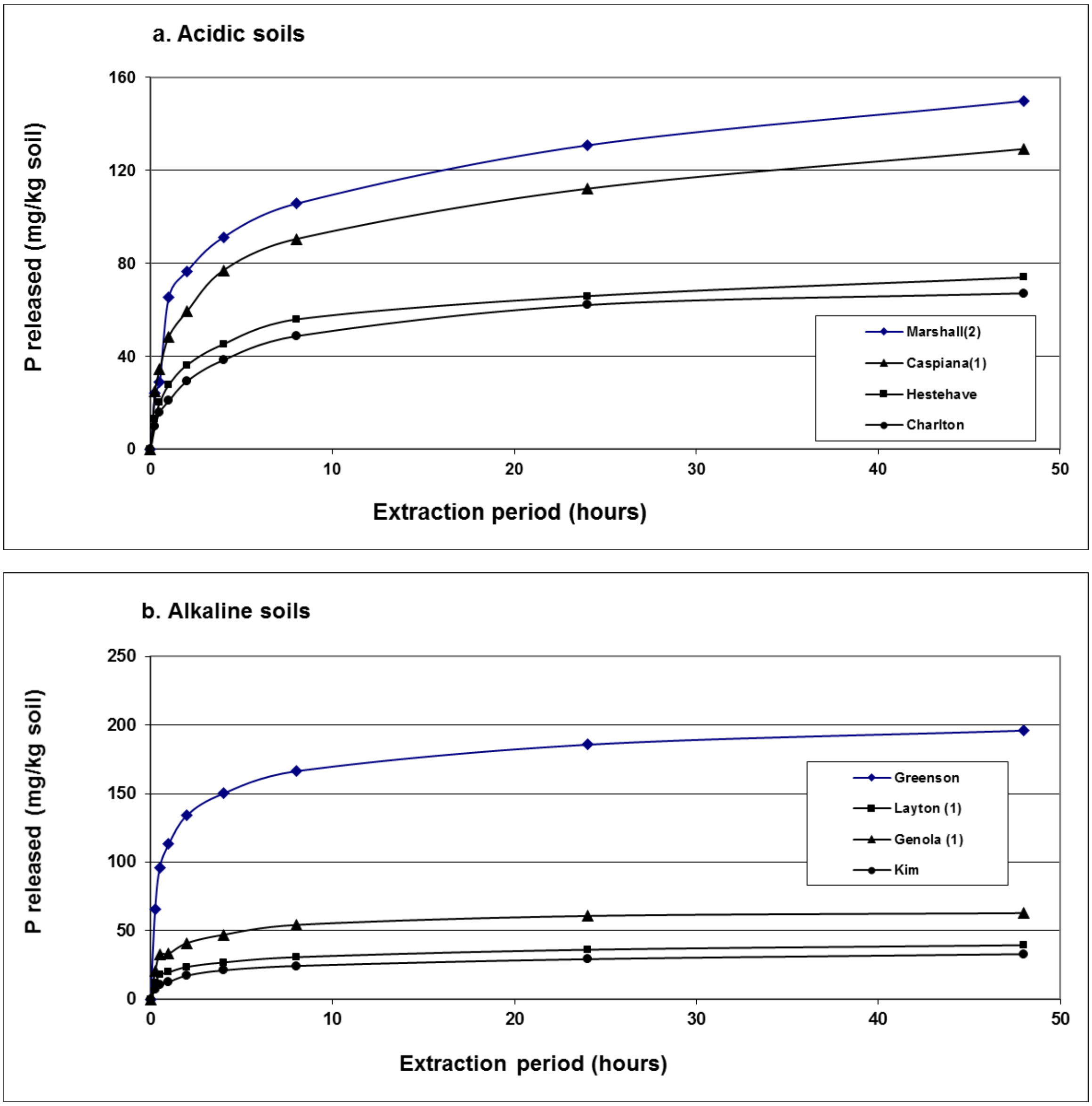


Figure 1. Relationship between extraction period (hours) and P released (mg/kg soil) for eight acidic (1a) and alkaline soils (1b).

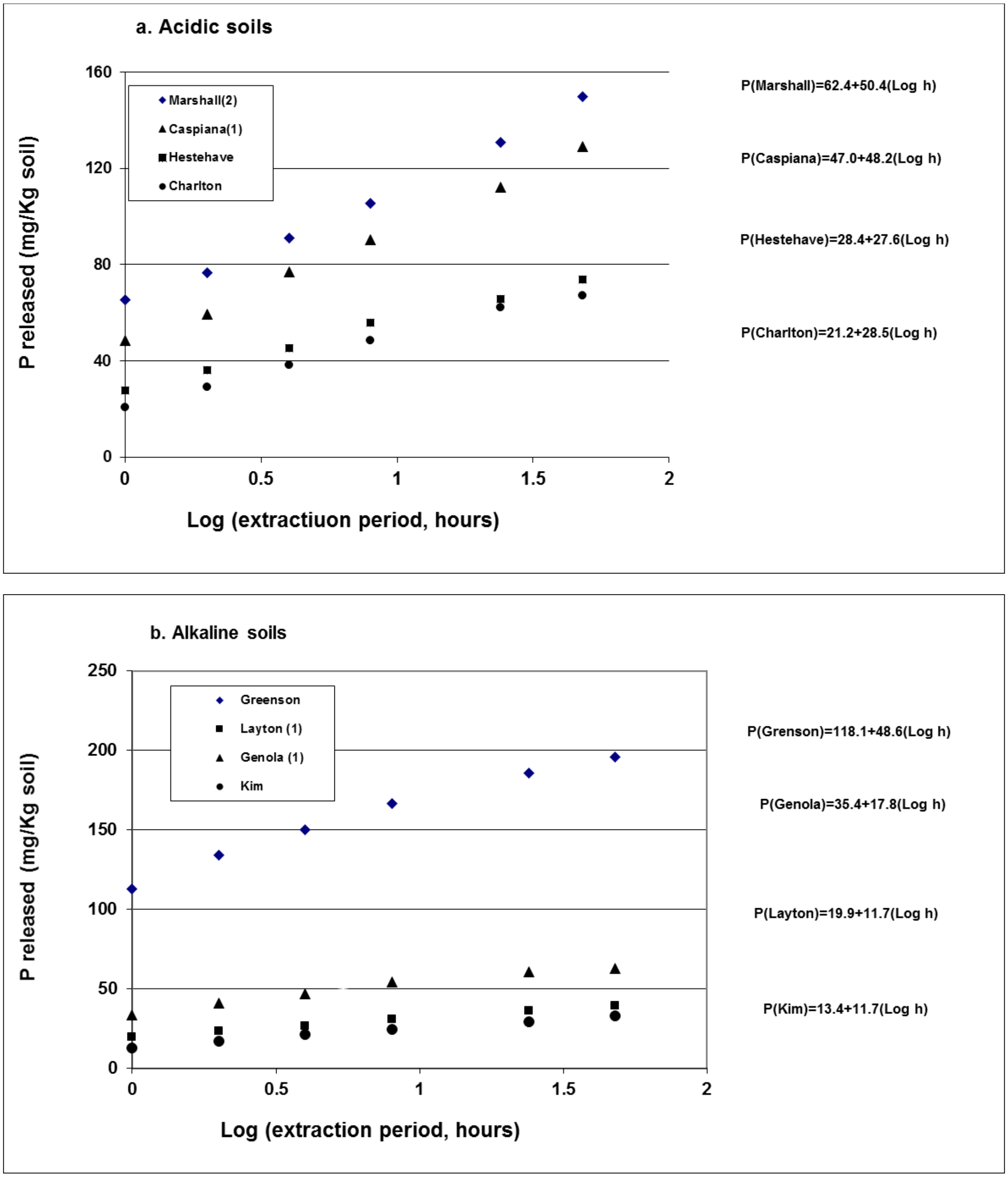


Figure 2. Relationship between Log (extraction period, hours) and P released (mg/kg soil) for eight acidic (2a) and alkaline soils (2b).

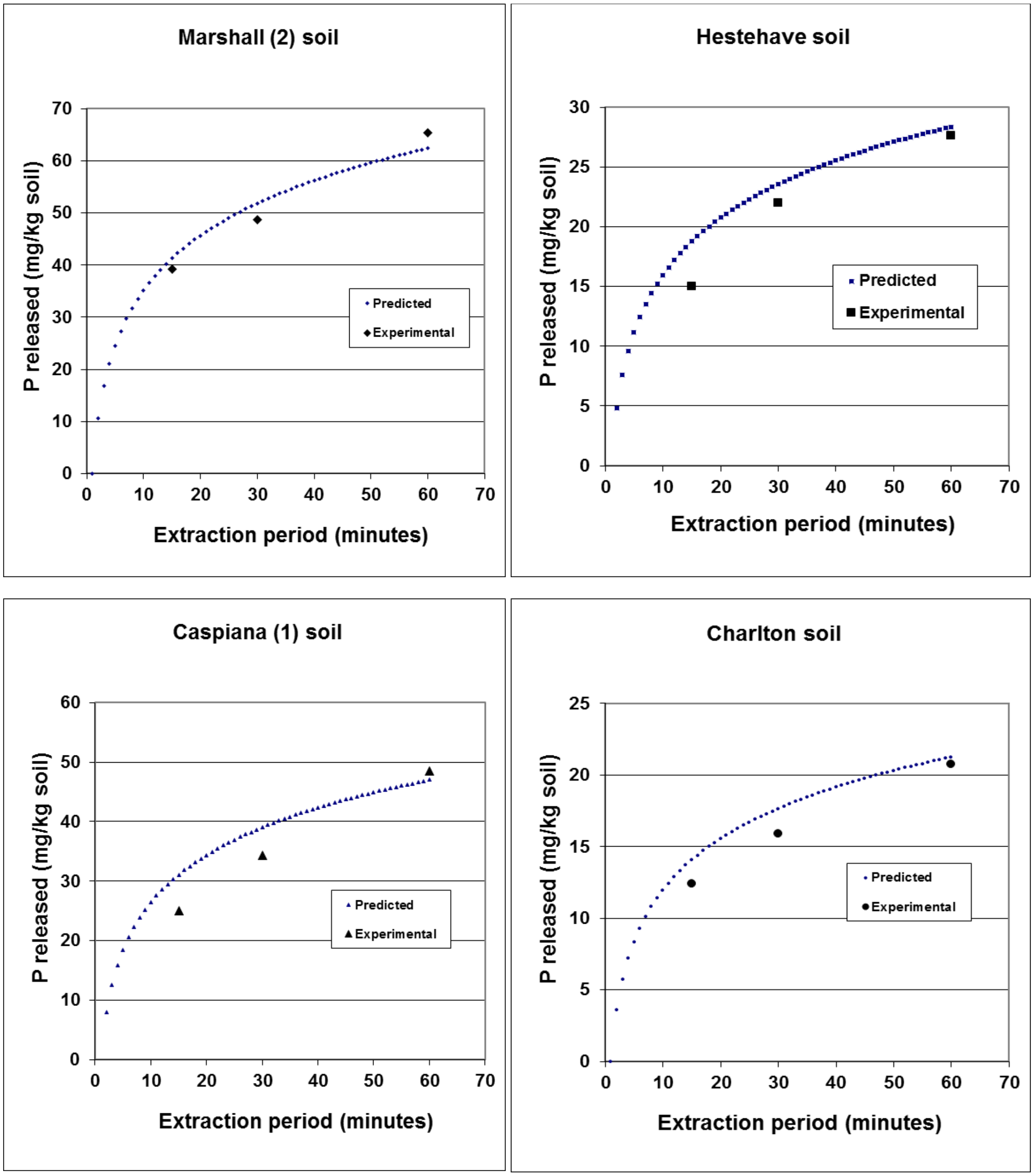


Figure 3. Predicted and experimental P released (mg/kg soil) in 1-60min extraction region for four acidic soils.

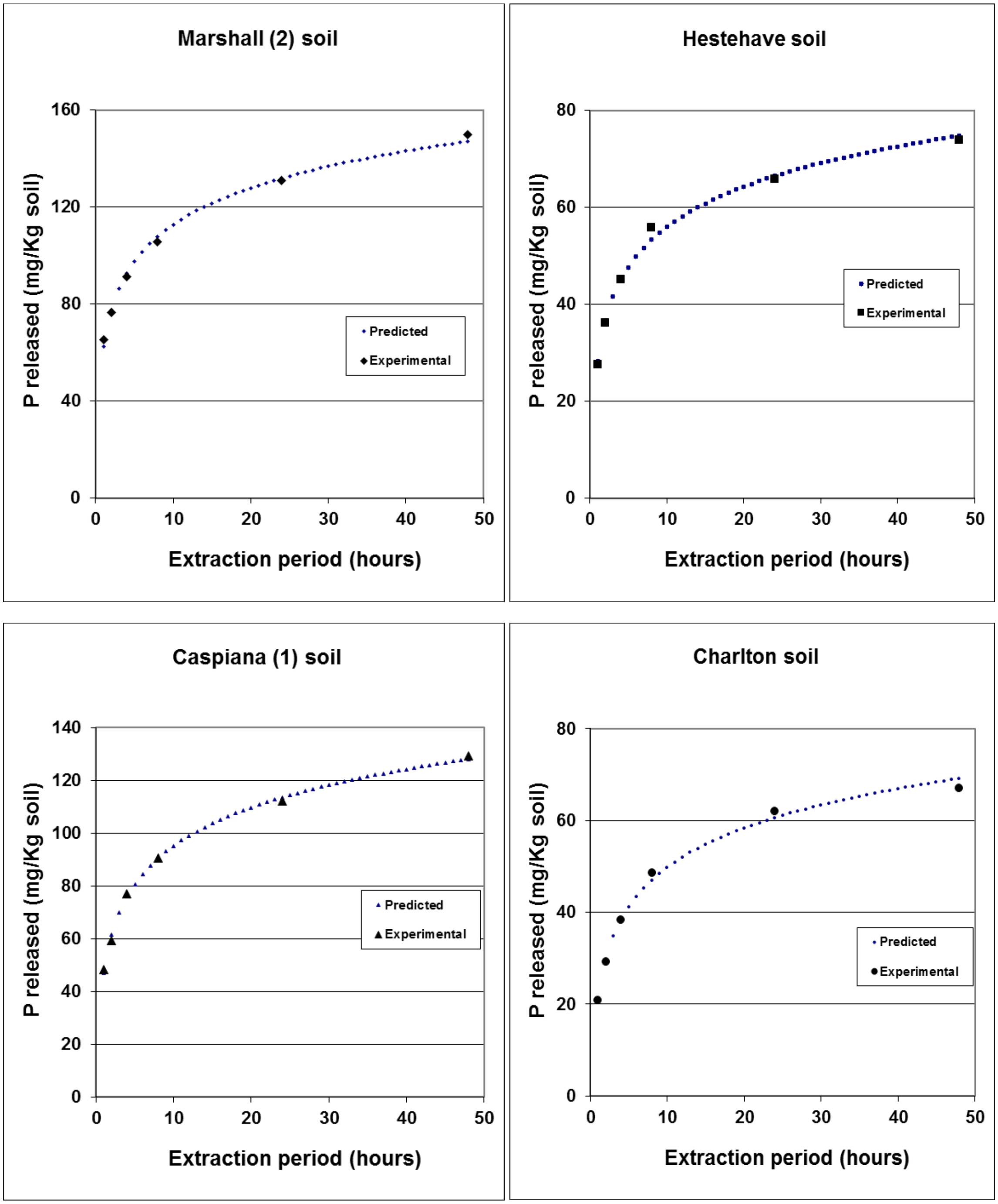


Figure 4. Predicted and experimental P released (mg/kg soil) in 1-48h extraction region for four acidic soils.

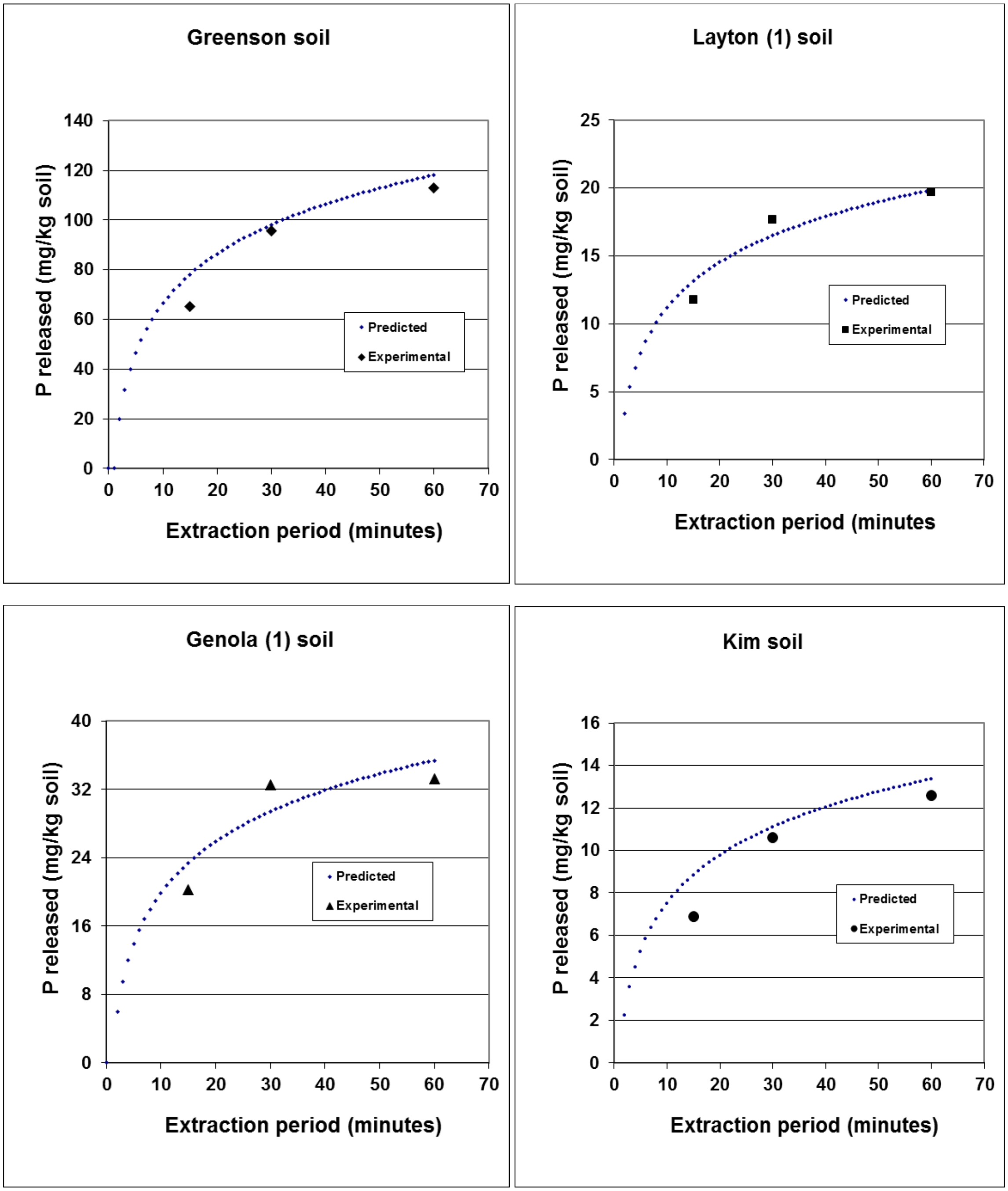


Figure 5. Predicted and experimental P released (mg/kg soil) in 1-60min extraction region for four alkaline soils.

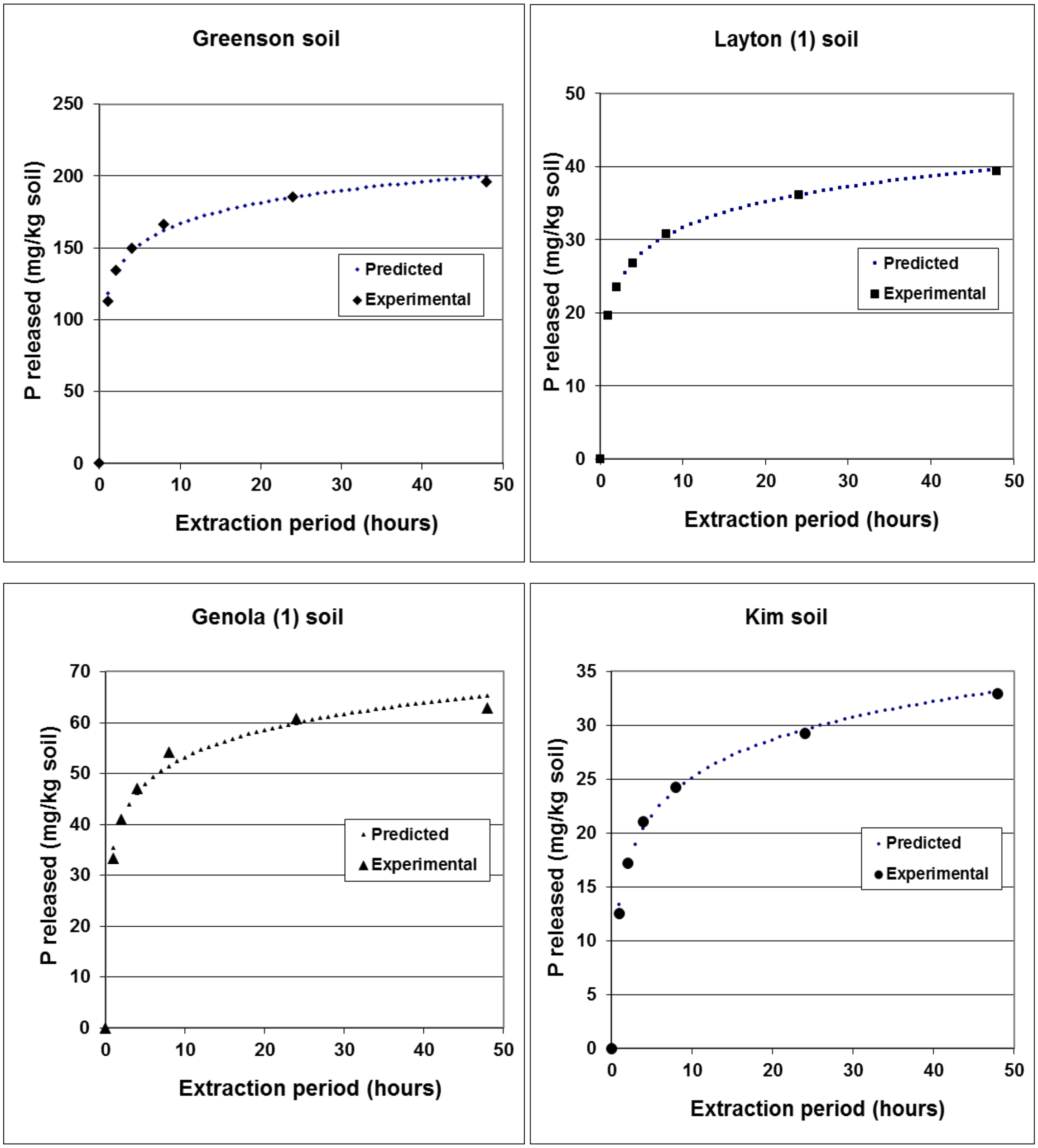
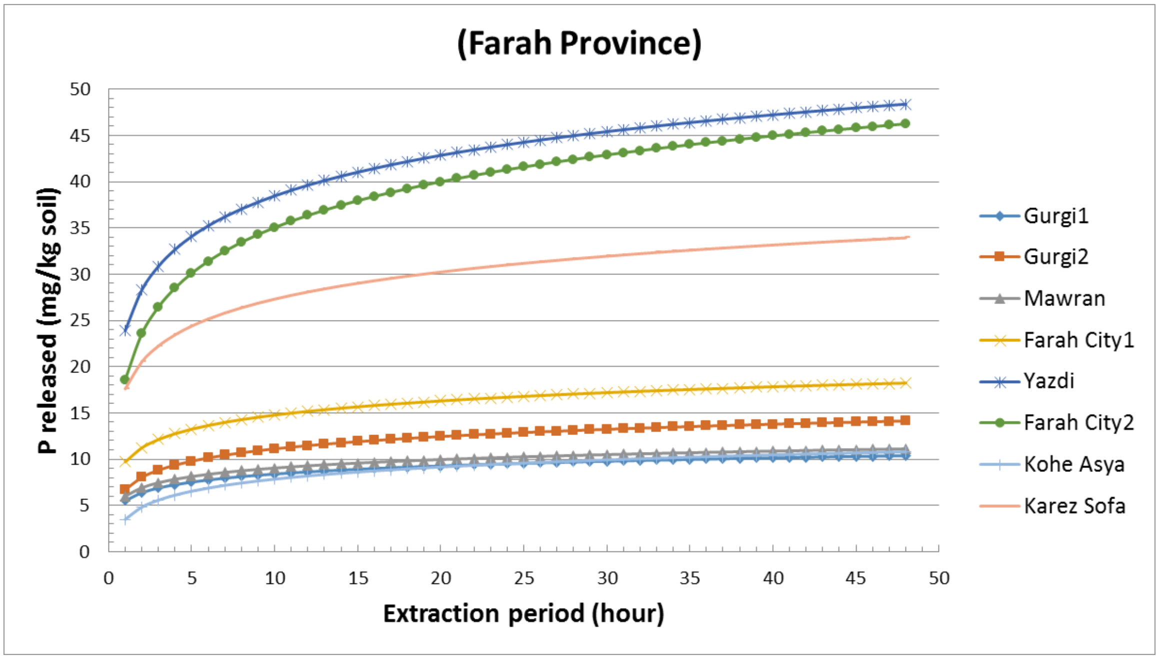


Figure 6. Predicted and experimental P released (mg/kg soil) in 1-48h extraction region for four alkaline soils.

Figure 7. Sampling locations for 14 soil pedons in Farah Province and Kunar Province, Afghanistan.



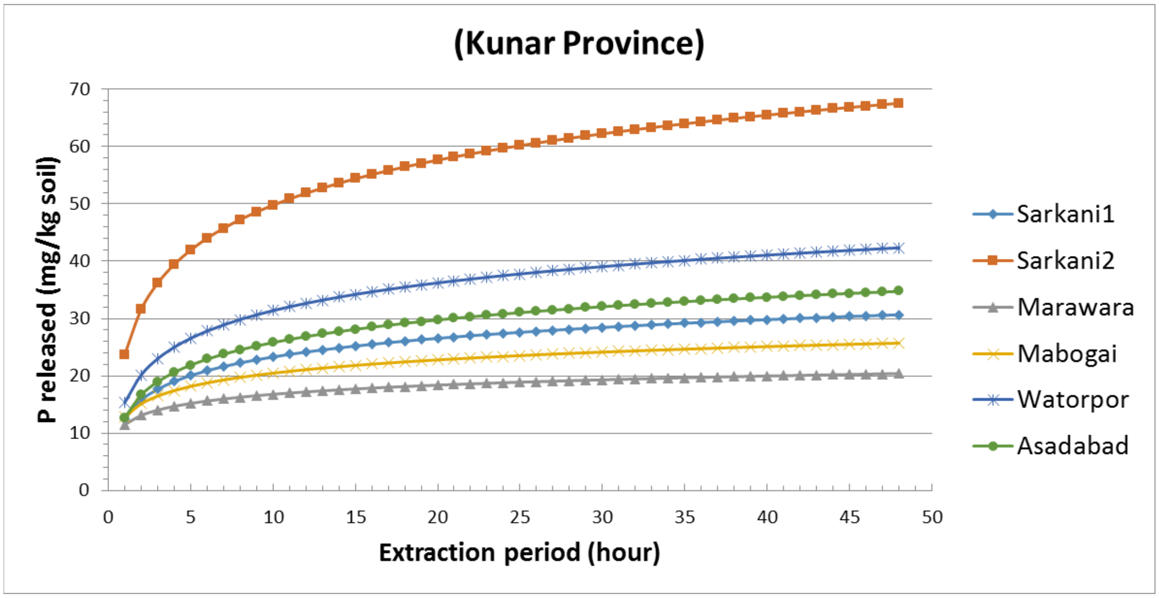
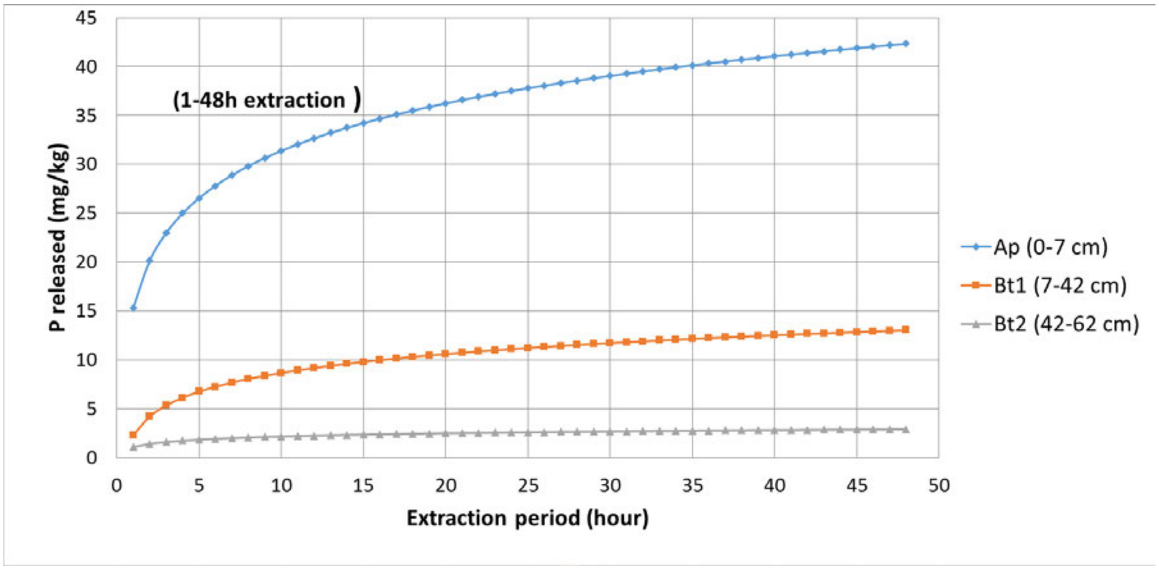


Figure 8. Relationship between extraction period (hour) and P released (mg/kg) from soil by anion exchange resin (AER) for top horizon in soil pedons collected from Farah Province (top) and Kunar Province (bottom), Afghanistan.



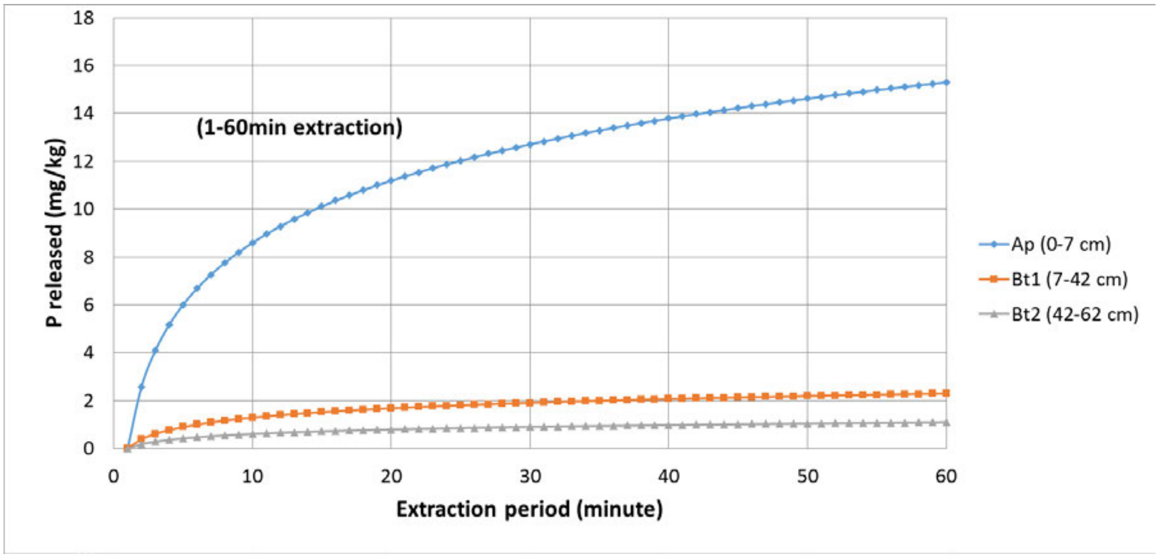
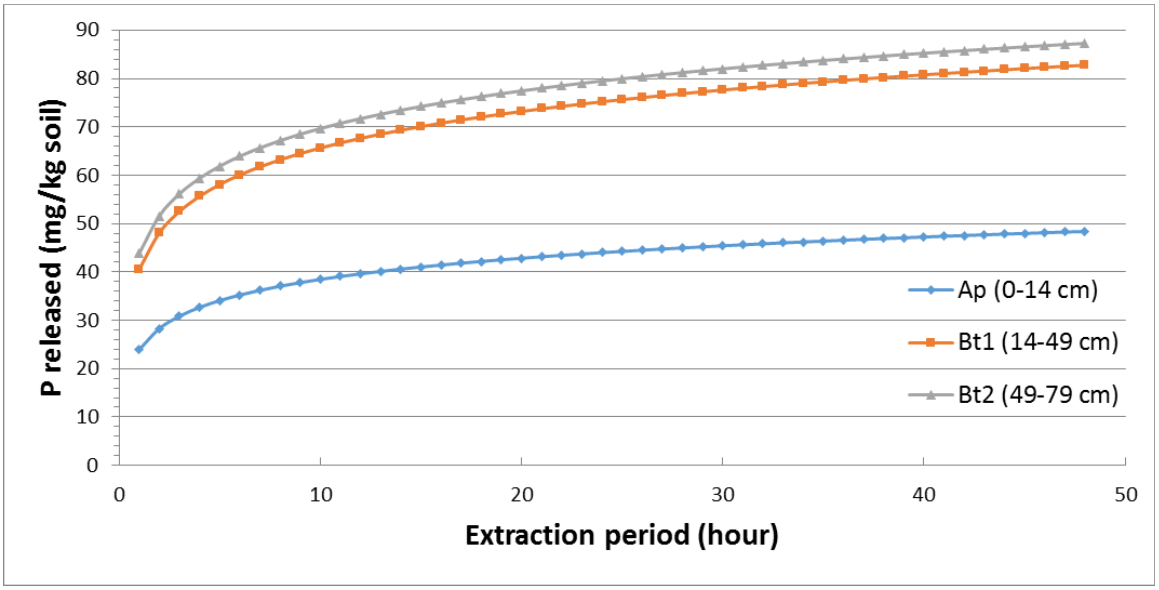


Figure 9. Predicted amounts of P released (mg/kg soil) during 1-48h (top) and 1-60min (bottom) extraction period for top three horizons in Watorpor soil pedon, Kunar Province, Afghanistan.



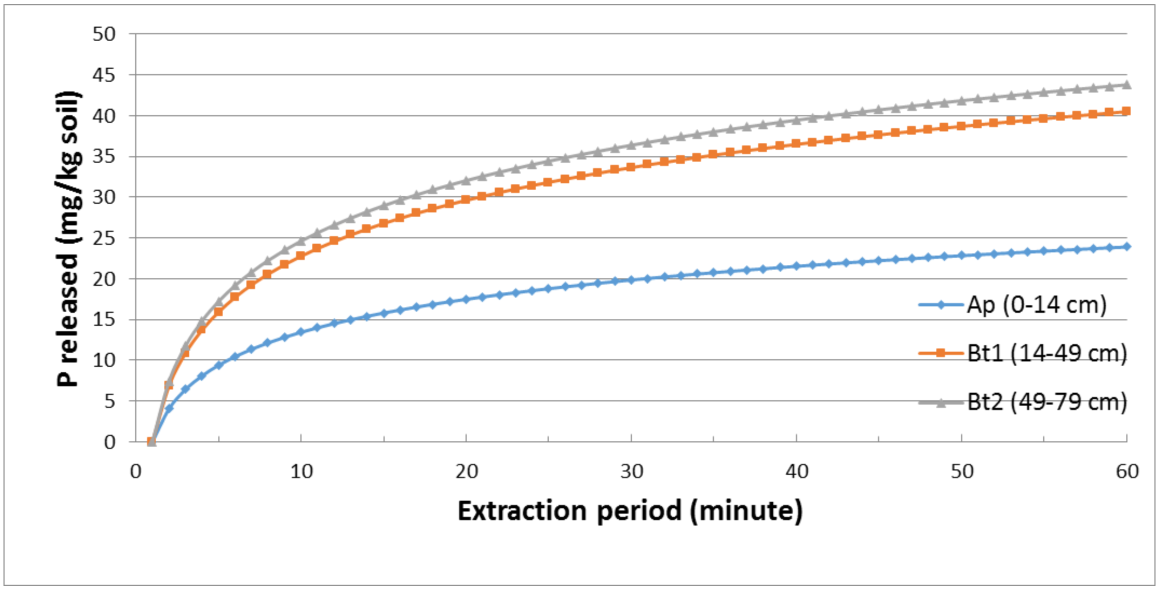
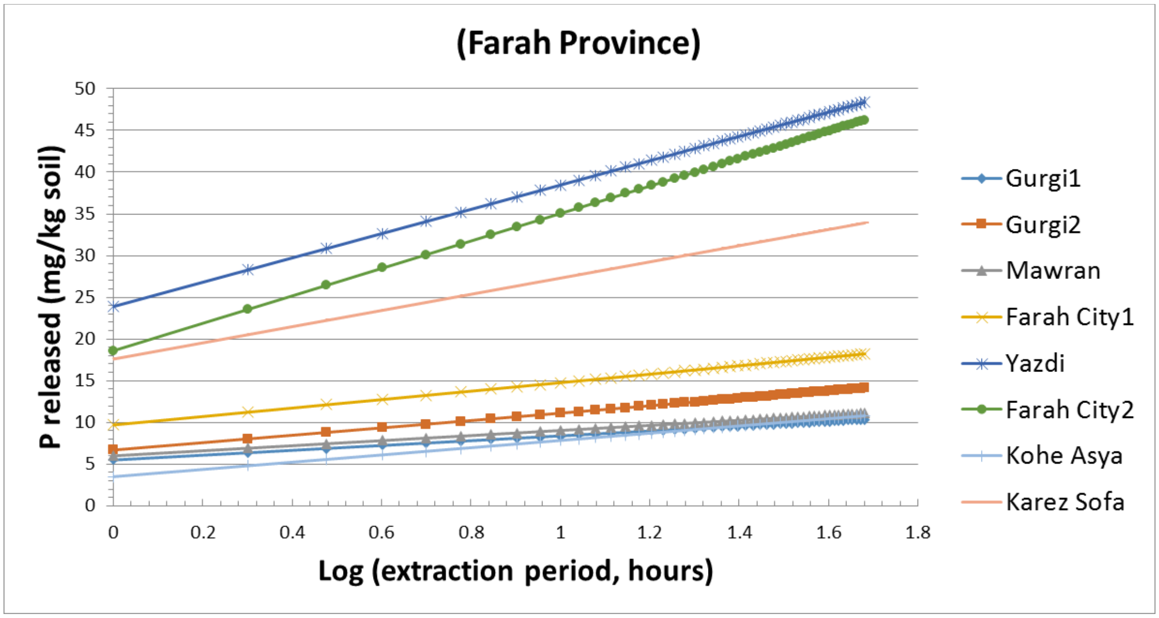


Figure 10. Predicted amounts of P released (mg/kg soil) during 1-48h (top) and 1-60min (bottom) extraction period for top three horizons in Yazdi soil pedon, Farah Province, Afghanistan.



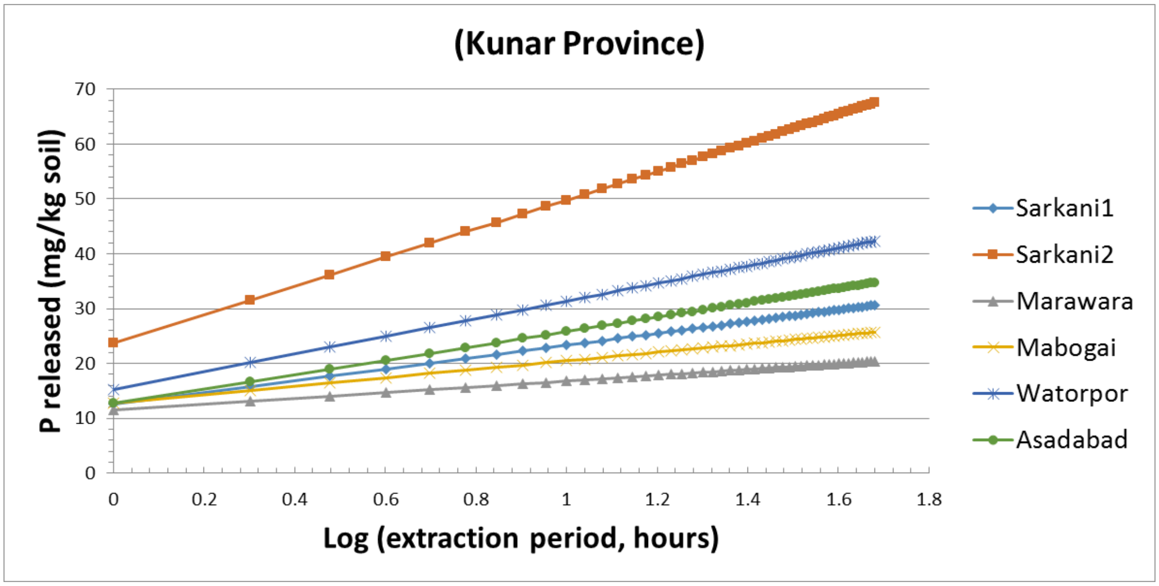
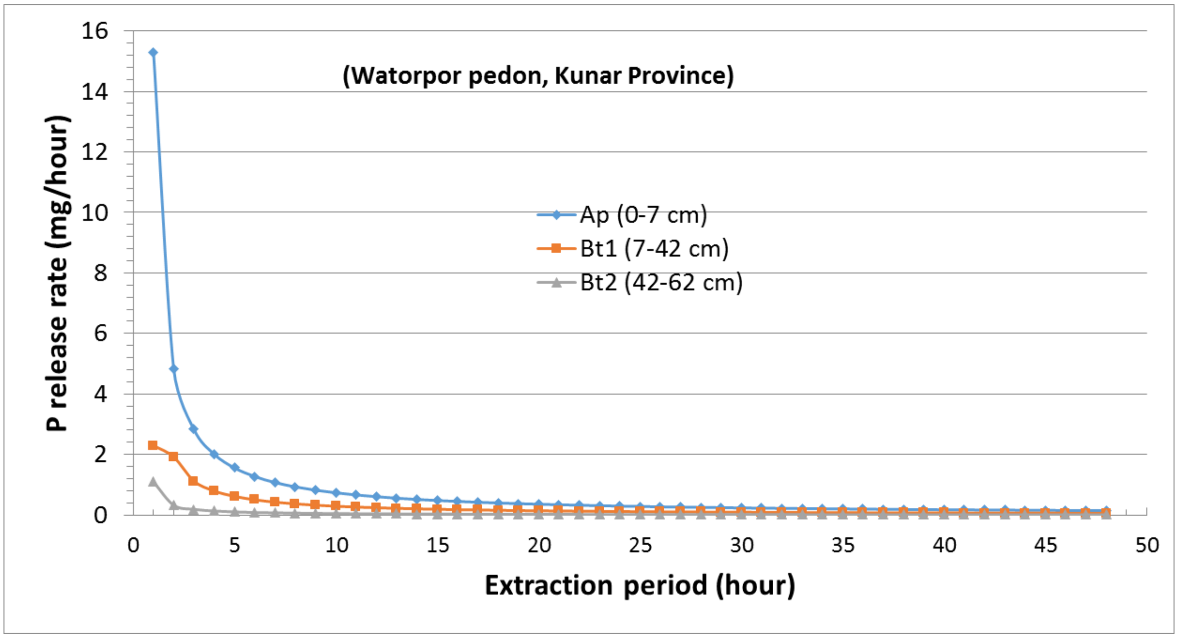


Figure 11. Relationship between Log (extraction period, hour) and P released (mg/kg) from soil by anion exchange resin (AER) for top horizon in soil pedons collected from Farah Province and Kunar Province, Afghanistan.



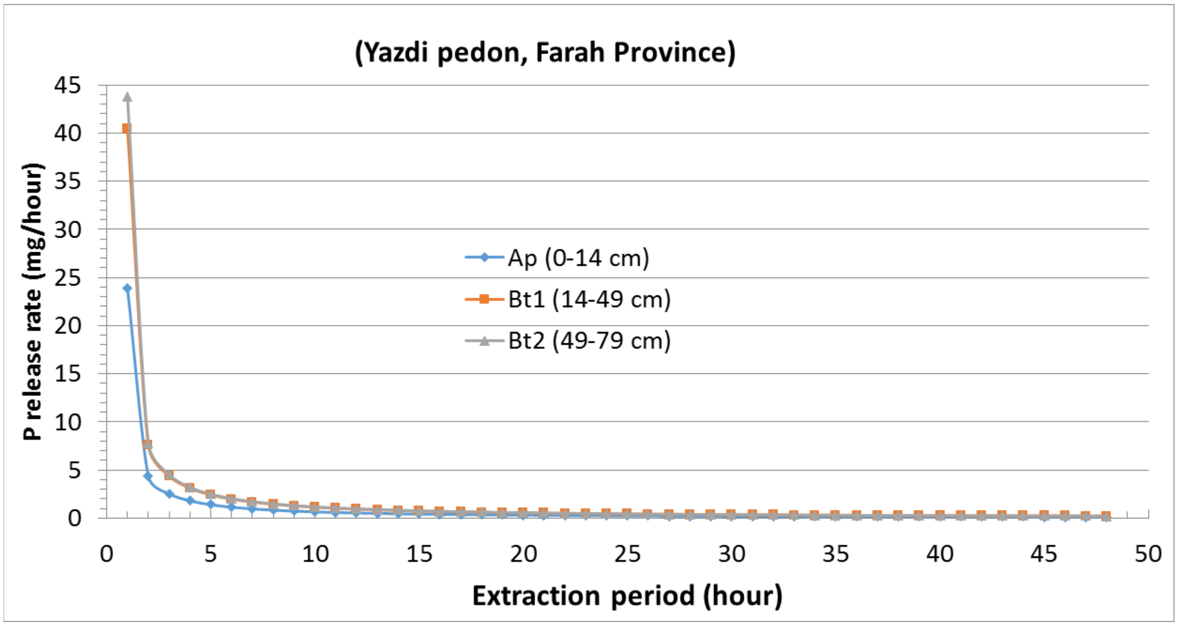


Figure 12. Rate of P release (mg/hour) at different anion exchange resin (AER) extraction periods (1-48h) for top three horizons in Watorpor pedon, Kunar Province (top) and in Yazdi pedon, Farah Province (bottom), Afghanistan.