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# Quantitative Phosphorus Measurement: A Field Test Procedure for Archaeological Site Analysis at Piedras Negras, Guatemala

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Currently there is a wide interest in the use of chemical analyses for the evaluation of anthropogenically altered soils and other archaeological deposits. Because soil phosphorus levels increase in areas of human habitation, and leave a permanent signature that can only be removed by erosion of the soil itself, phosphorus mapping has become a popular field procedure to indicate areas of habitation where overt evidence of ancient occupance is absent. We have developed a methodology to obtain accurate acid-extractable phosphorus concentrations (mg/kg) in calcareous soils under the primitive field conditions of Piedras Negras, Guatemala. Predicated on Mehlich-II acid extractant and colorimetric methods, this procedure processed 36 samples per hour at very low cost per sample. Based on eight replicate measurements of a group of samples, the coefficient of variation of the procedure was 8.3%. Subsequent analysis of 35 soil samples in a controlled laboratory revealed a moderate correlation of 0.44 between the Mehlich-extractable phosphorus and total phosphorus. The correlation was 0.91 between the Mehlich procedure and Olsen bicarbonate extractable phosphorus, indicating that Mehlich-based results are similar to those obtainable using a traditional extractable phosphorus method on soils of neutral to alkaline pH. There was a moderate correlation between Mehlich P and ring-test rating ( $r = 0.42$ ). The wider dynamic range of the Mehlich extraction, coupled with the use of a battery-operated colorimeter, facilitated the finding of a refuse midden within an area of phosphate enriched soils. Further tests indicated that phosphorus concentrations measured in the field deviated by only 7% from those made under controlled laboratory conditions. © 2000 John Wiley & Sons, Inc.

## INTRODUCTION

Among the many elements listed in the periodic table, relatively few are required in large amounts to support terrestrial life. One of these is phosphorus. Phosphorus is an essential element of living cells. It is a critical constituent in DNA, RNA, protein synthesis, and cell membrane formation. As part of the organic compound adenosine triphosphate, phosphorus is also an essential component in providing

energy to biochemical processes. Deficiencies of phosphorus stunt plant and animal growth, reduce their viability, and limit reproduction (Brady and Weil, 1996).

Despite its importance, soil phosphorus available to plants is naturally low. With the exception of unfertilized agriculture that depletes available phosphorus, human activities related to subsistence tend to concentrate the element around settlements to levels that are detectable with simple chemical testing procedures. These activities include livestock stabling, organic fertilization of backdoor gardens, and disposal of household and human waste. Because phosphorus concentrations in bone and blood are extremely high, phosphorus also accumulates in settings associated with burials and blood rituals. Furthermore, because phosphorus in soil becomes insoluble rapidly, the accretion of phosphorus is measurable centuries later unless the soil itself is removed (Eidt, 1984, 1985).

In this article, we present a method of obtaining quantitative soil phosphorus measurements under primitive field laboratory conditions using a Mehlich II acid extraction solution (Mehlich, 1978, 1984) and a battery-powered colorimeter. We developed this method in order to map soil phosphorus concentrations in the Classic Maya site of Piedras Negras, Guatemala. Our hope was that maps of soil phosphorus made and updated on a daily basis in the field might not only reveal spatial patterns in the agricultural landscape, but also detect cultural features such as middens that could guide archaeological excavation.

## PHOSPHORUS MEASUREMENT AND ARCHAEOLOGY

The first person to correlate soil phosphate to historical settlement was O. Arrhenius (1931). In his research to produce soil maps for the Swedish Sugar Manufacturing Company, Arrhenius noted that weak-acid extractable phosphate amounts increased as he neared sites of medieval settlement. The utility of soil phosphate analyses in the identification of ancient settlements and in the study of ancient activities and land use has subsequently become well established (Dauncey, 1952; Proudfoot, 1976; Hassan, 1981; Sánchez et al., 1996; Sánchez and Cañabate, 1999; Solecki, 1951; for reviews, see Hammond, 1983; Gurney, 1985; Craddock et al., 1986; Bethell and Máté, 1989; Scudder et al., 1996; Leonardi et al., 1999). Because naturally-occurring compounds in the soil rapidly fix phosphates, they tend to remain stable in soils for very long periods. Therefore, phosphate concentrations in kitchen gardens and middens are significantly higher than the natural background level, while areas of food preparation and consumption exhibit high to moderate levels of concentration (Eidt, 1984; Woods, 1977; McManamon, 1984).

Soil phosphate analyses in archaeology have been used primarily in three areas of study. First, soil phosphates are analyzed in preexcavation prospecting to locate or delimit archaeological sites before excavation. This has been the most common use of phosphate analysis in archaeology (e.g., Dauncey, 1952; Provan, 1973; Sieveking et al., 1973; Hassan, 1981; Hammond, 1983; Eidt, 1984; Ball and Kelsay, 1992). Second, phosphate analysis is used as a tool in landscape archaeology to examine past agricultural practice (Coultas et al., 1993; Lippi, 1988; Dunning, 1993; Dunning

et al., 1997, 1998). The third area is the delineation of features and activity areas through phosphate analysis during and after excavation (Solecki, 1951; Manzanilla and Barba, 1990; Sánchez and Cañabate, 1999).

Soil phosphorus (P) exists in a complex equilibrium of different forms, including fixed inorganic P absorbed to aluminum, calcium, and iron compounds; soluble and labile inorganic P; and organic P. Several analytical methods are used to measure the different portions of soil P, and their archaeological implications should be evaluated. Four general types of phosphate analysis methods have been used in archaeological studies. The first method is the chemical digestion of soil for total P analysis. A drawback of this method is that it involves the digestion of soil and is quite time- and labor-intensive. It is not feasible to perform total P analysis in a field laboratory. The second is P fractionation, which separates and measures different compounds of soil P (Eidt, 1973, 1977, 1984; Lillios, 1992). This method is very detailed and has significant potential. However, it involves intensive lab work, and the interpretation of data based on the distribution of inorganic P among three fractions remains problematic. Bethell and Máté (1989) criticize that the interpretation of P fractionation data (Eidt, 1973, 1977, 1984) does not adequately take into account complex soil processes and the widely varying properties of different soil types (White, 1978).

The third method is generally called the spot test or ring test. A small amount of soil is placed on filter article, to which drops of an acid extractant are applied, followed by the color development reagent. The concentration of P is estimated by the intensity of coloring reaction on the filter article. The merit of this method is that it can be easily conducted in the field, and the result is instantaneous. With Eidt's (1973, 1977) refinement of the method, it became quite popular among field archaeologists. On the other hand, the evaluation of ring formation and coloring is subjective, and it is not a truly quantitative method. Values may change depending on sample size, color perception, temperature, and unequal solubilization of soil phosphate types (Eidt, 1977). The fourth method consists of extracting the soluble and readily labile soil P and determining the P concentrations quantitatively with the aid of a colorimeter. Extractable P is not always proportional to the total P of the soil; however, for archaeological prospection and activity area research, the spatial patterns of phosphate levels are important, rather than the absolute concentration.

The application of soil phosphate analysis in Mesoamerican archaeology has been increasing recently. Dunning and colleagues (Dunning, 1993; Dunning et al., 1997, 1998) have investigated the paleoecology of the Petexbatún region in the Petén jungle lowlands of Guatemala using phosphate fractionation, among other techniques. The correlation between residual soil phosphate levels and intrasite land use was the focus of a study by Ball and Kelsay (1992) at sites on upper alluvial terraces above the Mopan River in west central Belize. Also in Belize, Coultas et al. (1993; cf. Healy et al., 1983) used phosphate concentrations to evaluate the effects of ancient terracing practices on the quality of soils located near the tropical lowland Maya city of Caracol. Finally, other researchers have demonstrated that

dirt and stucco floors in domestic compounds at Cobá and at Teotihuacán trapped chemical compounds derived from specific activities that were repeatedly performed in a given locale (Barba et al., 1987; Barba and Manzanilla, 1987; Manzanilla, 1987, 1996; Manzanilla and Barba, 1990; Ortiz and Barba, 1993). Combined with other lines of evidence, their analyses of stuccos and soils have helped identify areas for food preparation and consumption, storage places, refuse zones, sleeping quarters, and spaces for ritual and funerary activities.

The objectives of this research were (1) to adapt a simple field test of extractable soil phosphate for use in archaeological prospecting and (2) to use soil phosphate analysis in conjunction with a geostatistics technique to identify the location of important archaeological features of the ancient Maya city of Piedras Negras, Guatemala.

## THE CONTEXT OF PIEDRAS NEGRAS

Our development of an alternative field-executable soil phosphorus test for archaeology was not because of academic interest alone, but rather in the context of *Proyecto Piedras Negras* (Houston et al., 1998; 1999), a long-term project sponsored by Brigham Young University and the Universidad del Valle under a permit granted by the Instituto de Antropología e Historia (IDAEH). The Classic Maya city of Piedras Negras is located on the eastern bank of the Usumacinta River in the northwestern corner of the Department of the Petén, Guatemala. Although excavated by a team from the University of Pennsylvania in the 1930s, Piedras Negras itself has remained relatively untouched by archaeologists, and its hinterlands have been little affected by more recent milpa agriculture.

Geologically a karst area, Piedras Negras lies in a region of natural tropical semi-evergreen rainforest and receives approximately 200 cm of rainfall annually, most of which falls during an intermittent and periodically intense rainy season from May through December. Aliphath (1994) has described a number of soil types characteristic of the Upper Usumacinta River Basin. These include the Rendolls found throughout much of the ancient city. The focus of our study was on the N sector of the site. The soils at that location belong to the subgroup Eutropeptic Rendolls (Soil Survey Staff, 1997). The soil properties were typically neutral to alkaline pH, 7.6; high organic matter, 9.2%; high calcium carbonate equivalent, 40%; and clay loam texture.

The goals of the phosphorus testing at Piedras Negras were to detect areas of archaeological significance, detect and map the presence of infield gardens in sub-elite residential areas, measure the background phosphorus level of the Piedras Negras agricultural suburbs, and detect agricultural outfields. Because of our project goals, the analysis method had to satisfy several criteria at Piedras Negras:

1. The method had to be sensitive enough to detect differences in soil phosphorus concentrations that had archaeological significance.
2. The analysis process had to be executable under the marginal conditions of

an open-air field laboratory, poor quality river water, and limited electrical power.

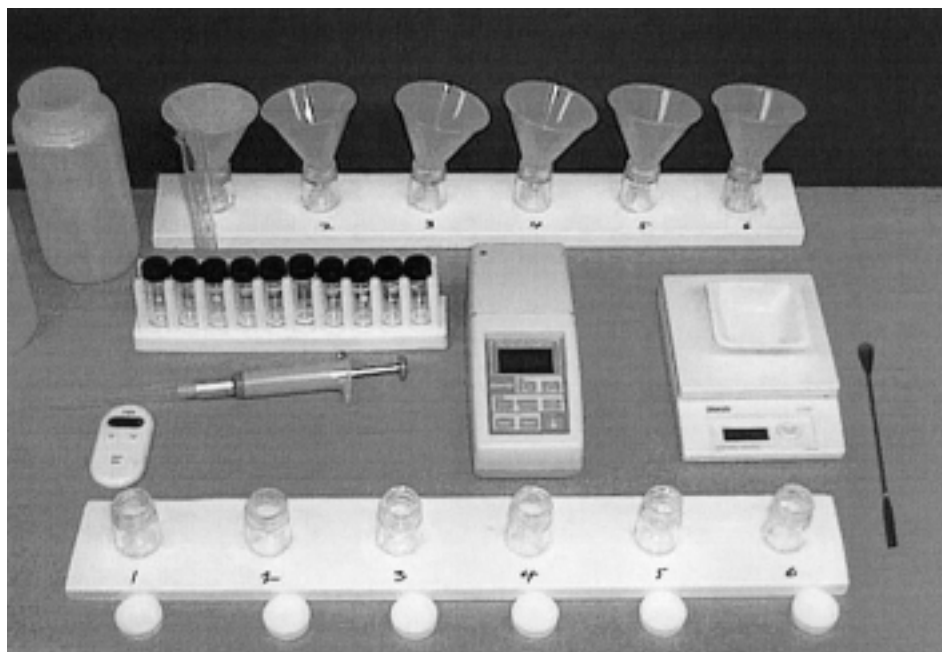
3. The capacity of the procedure to process samples had to be at least a few dozen per day both in order to meet the daily demand of the excavating archaeologists and to complete areal phosphorus mapping goals during a short field season.
4. The supplies and equipment to conduct the procedure had to be inexpensive.
5. The analysis system had to be transportable by backpack or pack animal.
6. The analysis procedure had to be simple enough to be conducted by staff unfamiliar with sophisticated chemical laboratory techniques.

## THE EXTRACTION PROCEDURE

The soil phosphate extraction procedure ultimately selected for use in the field laboratory at Piedras Negras was adapted from the Hach (Loveland, Colorado) soil test kit. We were attracted to the Hach procedure initially because it could be performed outside the laboratory and provided quantitative readings of soil phosphorus through the use of a battery-powered colorimeter (Hach Model DR-700). Available phosphorus extraction in the kit was predicated upon the Mehlich II dilute acid solution with a concentration formula of  $0.2\text{ M CH}_3\text{COOH} + 0.015\text{ M NH}_4\text{F} + 0.2\text{ M NH}_4\text{Cl} + 0.012\text{ M HCl}$  (Mehlich, 1978). The standard kit protocol required that 20 ml of extractant be first added to 2 g of air-dried sieved soil and shaken for 5 min in a 50 ml bottle. After shaking, the mixture was filtered, and 1.0 ml of the extract was dispensed into a 20 ml vial and diluted to 10 ml. The contents of a PhosVer 3 packet were added, and the vial was shaken by hand for exactly 1 min and allowed to stand an additional 4 min for color development. The concentration of phosphorus in the samples is determined on a Hach DR 700 colorimeter at a wavelength of 880 nm. The percent transmittance is converted to mg/L (ppm) by a standard curve. The appropriate dilution factors are used to convert the concentration values to mg P/kg soil. These calculations were done in the field with a laptop computer. The total time required to process a single sample using the kit protocol was 17 min.

We made several significant adaptations to the kit protocol for the Piedras Negras project (Figure 1). To speed the processing of samples generally, we cut several wooden boards 45 cm  $\times$  8 cm and used each of them to host a gang of six 50 ml bottles. This allowed six samples to be processed simultaneously rather than individually for 10 of the 17 min required for the sample set. With time allotted for cleaning glassware, a single technician new to the procedure could process approximately 15–20 samples in 1 h. Toward the end of our second season using the method, two skilled technicians were able to process 36 samples in a single hour.

During preseason experimentation, we realized that phosphate contamination could prove a major difficulty in the execution of the analysis. We projected that the two major sources of contamination would be the resident phosphate in water used throughout the procedure and any phosphate in the soap used to wash the



**Figure 1.** The equipment used in the field laboratory to conduct the phosphate extraction procedure.

laboratory equipment. The latter problem was simply solved by using only phosphate-free soaps available for laboratory use. The problem with phosphate in the water, however, required more rigorous mitigating measures. Because of their voracious appetite for generator power, portable water stills were impractical. Despite its cost, weight, and the inconvenience of shipping it to our remote Piedras Negras site, we initially determined to use distilled water designed for steam irons that we could purchase at stores in Mexico and Guatemala. However, after delivery of several dozen bottles, we discovered to our surprise that nearly all brands of the commercially available distilled water were more phosphate-rich than water available directly from the Usumacinta River, which flowed adjacent to our field laboratory. We finally decided to use water carried from the river and cleaned initially by the camp kitchen Katadyne (Scottsdale, Arizona) filter. Carbonates and organics that would interfere with phosphate extraction and color development were removed from the water by gravity-feeding it through Barnstead (Dubuque, Iowa) activated charcoal (#D0813) and deionization (#D0803) columns. The water proved to be sufficiently pure to work well with the analytical procedures in the field laboratory.

Quality control was monitored by determining extractable P of one selected soil sample with each batch of 24 samples. In conducting this quality control, a final unexpected complication in our procedure was quickly discovered—the sample-

to-sample consistency in the color development and extraction steps of the analysis were strongly dependent on temperature. At water temperatures higher than 30°C, results were widely variable. Since water and laboratory temperatures in the field frequently rose to 35°C in the afternoon, this meant that we had to limit our analytical laboratory work to the cooler evening or morning hours of the day when water temperature could be maintained between 24°C and 29°C.

Ignoring the initial startup costs of glassware (US \$100), colorimeter (US \$700), balance (US \$100), and water deionization columns (US \$150), the cost of the analysis includes the price for the Mehlich solution concentrate, filter paper, and the PhosVer chemical packets. Our working estimate of this disposable cost was US \$0.30 per sample.

With the use of the hand-held colorimeter, the total weight of the Mehlich analysis system described above is 10 kg. As long as bottles on the bottle-gang boards are not just glued to the board surface but are instead glued into holes within the boards, the gang-boards are very sturdy. All of the equipment can easily fit into a medium dufflebag.

## STATISTICAL COMPARISON AND VALIDATION

To test the applicability of the proposed field test procedure, we conducted linear regression analysis between soil phosphorus concentrations determined by the Mehlich test procedure and levels determined by three alternate field test and laboratory procedures: 1) the Olsen bicarbonate (Olsen and Sommers, 1982) extraction, 2) the perchloric acid digestion (Olsen and Sommers, 1982) method for total phosphorus determination, and 3) the Eidt ring-test rating (Eidt, 1977). These comparisons were performed on 35 soil samples from Piedras Negras subjected to all four analyses.

In contrast to the alkaline Olsen bicarbonate extraction method developed to correlate with plant-available phosphate in calcareous soils, the Mehlich II extraction solution contains dilute acids and was developed as an availability index for plant-available phosphate in acidic soils. Because of this, we anticipated that the Mehlich II procedure would extract more phosphorus from these soils than the Olsen alternative. We deemed this an advantage. Primarily, it would allow us to extract and accurately measure smaller concentrations of phosphorus, particularly if the field laboratory water contained some phosphorus itself. In contrast, the lower phosphorus values, which the Olsen method was expected to produce, might be indiscernible from the phosphorus in the field laboratory water. In other words, the Mehlich II procedure would be more immune from phosphorus-contaminated water.

We were also curious to see if the Mehlich extractable phosphorus concentrations produced under primitive field conditions at Piedras Negras could be duplicated under controlled soil laboratory conditions. For this test, we selected 33 soil samples from a Piedras Negras mound group targeted for strip excavation. These samples were returned to the laboratory in the United States where they were dried,

ground, and submitted to the same Mehlich phosphorus extraction procedure performed in the field at Piedras Negras. The phosphorus concentrations produced in the field were statistically compared to those produced in the laboratory by a paired t-test. The precision of the method was evaluated by determining extractable phosphate in six randomly selected samples, replicated eight times.

We also compared the spatial distribution of Mehlich extractable P with the distribution of ring-test ratings of surface (0–15 cm) soil samples collected from a group of sub-elite house-mounds at Piedras Negras. The computer software Surfer (Golden Software, Golden, Colorado) was used to create isoline maps of phosphorus concentrations or ratings.

## RESULTS

Table I contains a summary of the phosphorus amounts measured using Mehlich dilute acid extraction, Olsen bicarbonate extraction, perchloric acid digestion, and Eidt ring-test rating. As expected, the Mehlich procedure produced more extractable phosphorus amounts than the Olsen method. Both the Olsen and Mehlich procedures detected the midden sample (N6-7) with the highest concentration of phosphorus, and in general the rank order produced among the soils was the same. A runs test on the rank ordering produced by the two sample groups was not significant ( $n = 70$ ,  $\text{runs}_{\text{exp}} = 36$ ,  $\text{runs}_{\text{obs}} = 40$ ,  $p > 0.05$ ), indicating that there is no systematic variation among the rankings produced by the two methods. A simple linear correlation analysis further demonstrated that the relationship between the two methods was strong ( $r = 0.91$ ) and significant ( $p < 0.05$ ). In summary, the Mehlich procedure produced results higher than (but correlated with) the Olsen procedure for alkaline soils. Since the Olsen procedure cannot be performed under field conditions as easily as the Mehlich procedure, this is an important result for archaeologists mapping phosphorus in soils having high pH.

While the Mehlich procedure can be used instead of the Olsen test, the Mehlich method does not produce values that can be used to accurately estimate total phosphorus concentrations. Although the correlation between the Mehlich and perchloric acid digestion procedures was significant ( $p < 0.05$ ), the linear correlation was nonetheless only moderate ( $r = 0.44$ ). Ring-test P ratings were also compared with Mehlich P concentrations. The correlation between these two field test procedures was moderate but significant ( $r = 0.42$ ;  $p < 0.05$ ).

Of particular interest in our comparative analysis using the extraction and total analysis methods was soil sample N6-7. This sample, extremely high in Mehlich extractable phosphorus (125 mg/kg), was acquired in a systematic soil sampling of the sub-elite household mound group in sector N. Upon excavation, a large kitchen midden was found. It contained dense organic material interleaved with hundreds of sherds, all apparently swept up against a low masonry wall that had preserved it from ancient disruption (Escobedo and Houston, 1997). The two extraction procedures and total P analysis detected the peak in the phosphorus concentration at or near sample N6-7. The peak phosphorus concentration was more pronounced

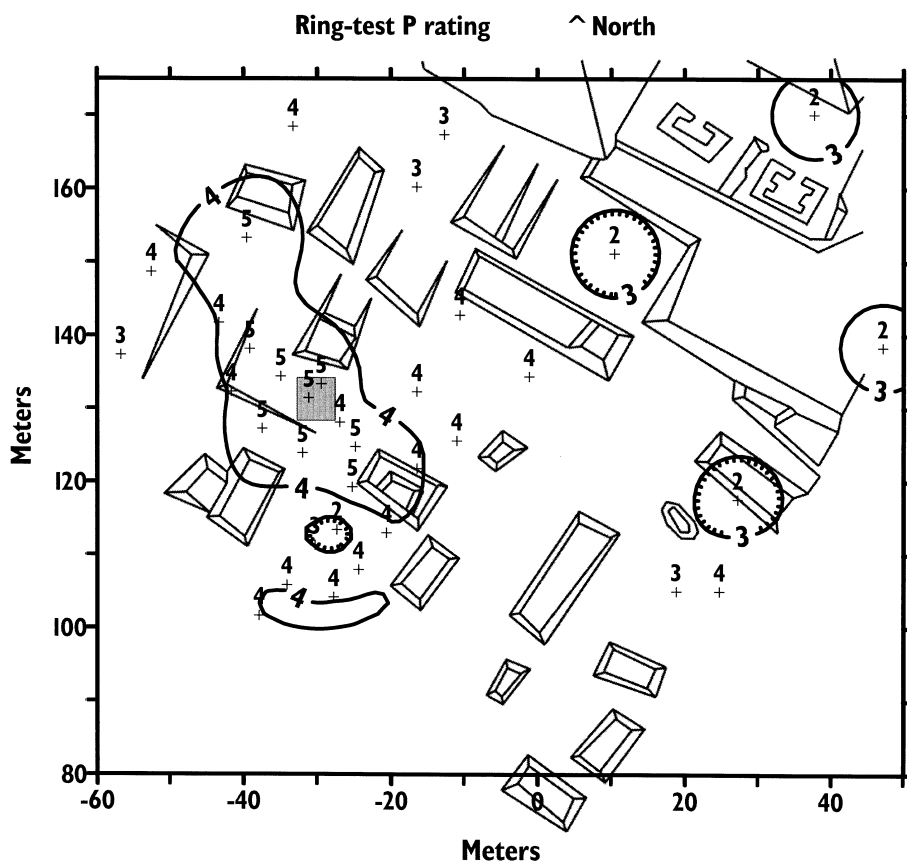


# QUANTITATIVE PHOSPHORUS MEASUREMENT

**Table I.** Phosphorus values for 35 soil samples taken at Piedras Negras, Guatemala.<sup>a</sup>

Sample	Mehlich P (mg/kg)	Olsen P (mg/kg)	Total P (mg/kg)	Ring Test Rating (1–5)
O15-1	17.3	6.5	1762	2
10G-1	18.3	6.5	1627	2
N9-10	18.9	9.4	1496	3
10H-1	20.6	4.5	1657	4
10D-4	22.0	7.0	1143	3
N9-12	23.0	10.0	1103	4
N9-8	23.0	17.0	1678	4
O17-2	23.1	15.4	1851	3
N9-6	23.3	12.8	1894	4
10C-3	23.4	9.2	1042	2
N6-12	23.4	11.8	2179	4
O30-4	24.3	20.9	1887	4
N6-1	24.9	13.9	2392	4
O22-1	25.6	13.8	1620	2
O23-1	26.4	11.4	1620	2
N9-7	26.5	14.3	1774	4
N2-1	26.8	11.2	2058	4
N6-9	27.7	18.8	1998	5
N6-13	28.0	15.8	1959	5
N6-11	29.7	7.7	1241	3
N9-11	29.8	14.7	1443	4
O17-1	30.2	18.4	1730	3
N6-2	31.0	21.8	1955	5
N6-3	31.8	21.0	1991	5
N6-6	32.8	28.0	2011	4
N6-10	33.9	12.7	1879	4
N6-5	35.1	21.5	2291	5
10L-1	35.1	21.2	2949	5
N8-2	42.7	21.6	2113	4
N8-1	46.8	29.3	1933	4
N6-4	48.5	44.5	1988	5
N8-3	48.8	33.3	1940	4
N6-8	52.2	37.4	2354	5
10H-2	54.4	32.4	1875	4
N6-7*	125.1	65.0	2476	5
Mean	33.0	18.9	1854	3.8
n	35	35	35	35

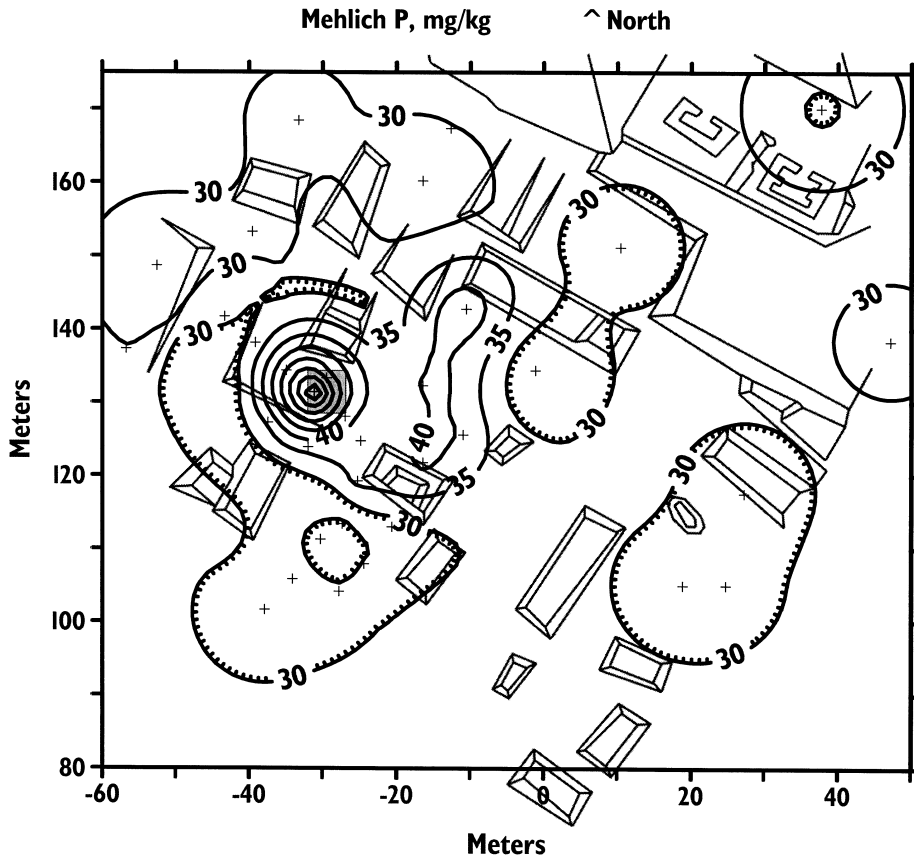
<sup>a</sup> As expected, the Mehlich procedure produced higher concentrations than the Olsen method. Because it also dissolves phosphorus from the parent material, the total phosphorus method produced much larger values than either of the extraction procedures. \* = The midden sample.



**Figure 2.** The spatial distribution of soil phosphorus ratings in the N sector of Piedras Negras. The phosphorus ratings are listed above the posted sample locations. The relative amounts of soil phosphorus estimated by the Eidt ring-test procedure are as follows: 1 = none; 2 = weak; 3 = average; 4 = good; and 5 = strong. The shaded box indicates the location of the midden.

using the Mehlich procedure than the other two procedures, however. As calculated using the data in Table I, the ratio between the peak and mean concentration for the Mehlich, Olsen, and total phosphorus procedures was 379%, 344%, and 159%, respectively. It is interesting to note that the total phosphorus procedure was less sensitive to the anthropogenic alteration in the soil than either of the available phosphorus methods. The large amount of total phosphorus in the soil apparently tends to mask the anthropogenic phosphorus enrichment.

The spatial distributions of ring-test phosphorus ratings and Mehlich extractable P concentrations in the soils of sector N are shown in Figures 2 and 3, respectively. Background levels of extractable phosphorus (17–25 mg/kg) were present on and around the raised platform in the northeast portion of the group (Figure 3). These



**Figure 3.** The spatial distribution of Mehlich II extractable soil phosphorus concentrations in the N sector of Piedras Negras. The isolines indicate concentrations of extractable soil P in units of mg/kg. The shaded box indicates the location of the midden.

levels were typical of background extractable soil P concentrations found in the ancient city (Wells et al., 2000). The background levels corresponded to a ring-test rating of 2 (Figure 2). Elevated levels of soil phosphorus were discovered in the western portion of the house-mound group. Ring-test ratings in the range of 4–5 corresponded to extractable phosphorus concentrations ranging from 35 to 125 mg/kg. The midden at sample location N6-7 was found as a result of phosphate analysis in the field laboratory. Archaeologists were immediately directed to this location for excavation and confirmation of the presence of the midden (Escobedo and Houston, 1997). It is important to note that ring-test phosphorus ratings were strong (5) in an area of approximately 1000 sq m surrounding the midden. It is unlikely that the ring-test procedure would have led to the discovery of this particular feature.

Table II summarizes the difference in Mehlich concentrations as determined in the field and under controlled laboratory conditions. There is obviously excellent agreement between the two sets of measurements on the same samples. However, as demonstrated by a paired-sample *t*-test, the difference is significant ( $n = 33$ ,  $t = 2.80$ ,  $p = 0.009$ , two-tailed). On an average, the field values are 2.8 mg/kg lower than the laboratory values -- only 7% of the mean. Differences in ambient and extracting solution temperatures as well as colorimeter calibration could be the cause of this slight difference. The coefficient of variation of the method in the laboratory was 8.3%, based on eight replicate measurements of a group of samples.

## SUMMARY

After initial startup costs of approximately \$1,000, the Mehlich II extraction procedure allows quantitative measurements of phosphorus to be made in the field. Up to 36 samples per hour can be processed at a disposable cost of \$0.30 each. While generator power is not required for the procedure, filtered water with low carbonate and phosphorus content is a necessity. Extractable phosphorus concentrations obtained under controlled laboratory conditions varied from those obtained in the field by only 7%.

The Mehlich-based phosphate extraction procedure for identifying Piedras Negras soils affected by ancient human activities is superior to the Olsen procedure. The Mehlich extraction is more sensitive at lower levels of soil phosphate, is less affected by residual phosphate in the water, and is useful on acid as well as alkaline soils. However, having reached that conclusion, we nonetheless deem the Olsen method satisfactory for the calcareous soils of the Petén when the Mehlich-based procedure is not available.

We also consider the Mehlich procedure to be superior to perchloric acid digestion procedures for total phosphorus. Besides being unable to perform the procedure in the field, the total phosphorus extraction masks anthropogenic phosphorus by also extracting the phosphorus within the humus and mineral components of the soil as well.

The wide dynamic range of phosphorus concentrations made possible by the Mehlich extraction and the continuous quantitative measurement scale of the colorimeter are important advantages of the proposed procedure. The ring-test procedure was limited in the phosphorus concentration range necessary to detect a highly concentrated phosphorus source (midden) among soils enriched in phosphate after long periods of continuous occupation.

We conclude that the Mehlich II extraction procedure as modified and tested for high-volume processing is a viable method for archaeologists who need to measure phosphorus accurately in the field. While we have tested the procedure only at the archaeological sites of Piedras Negras, Guatemala, Aguateca, Guatemala, and Cerén, El Salvador, we believe that it would be suitable for archeological prospecting and mapping in both equatorial, tropical, and midlatitude soil environments, where the soil pH is acidic to mildly alkaline. The inexpensive, rapid test

# QUANTITATIVE PHOSPHORUS MEASUREMENT

**Table II.** Comparison between field laboratory and controlled laboratory phosphorus values using the Mehlich II extraction procedure.<sup>a</sup>

Sample	Field Mehlich P (mg/kg)	Laboratory Mehlich P (mg/kg)	Difference (mg/kg)
33B-8.1	37.2	33.1	4.1
33B-1.1	25.7	20.0	5.7
33A-1.4	39.4	34.3	5.1
33B-3.1A	32.5	28.5	4.0
33A-7.2	55.2	46.0	9.2
33B-3.1B	30.3	33.0	−2.7
33A-2.2	33.3	27.3	6.0
33A-8.2	36.2	33.0	3.2
33B-4.1	29.8	23.3	6.5
33A-9.2	58.3	52.0	6.3
33B-18.2	34.3	25.3	9.0
33D-3.4	114.0	109.4	4.6
33C-4.3	35.1	26.6	8.5
33C-1.3	35.8	30.2	5.6
33C-2.1	22.1	16.7	5.4
33C-3.3	33.4	25.0	8.4
33C-4.1	8.0	7.9	0.1
33B-5.1 #1	38.2	42.1	−3.9
33B-5.1	29.6	35.3	−5.7
33A-10.2	33.3	34.0	−0.7
33A-11.2	38.4	37.6	0.8
33B-5.6 #4	34.4	40.6	−6.2
33A-12.2	22.4	24.2	−1.8
33B-6.1	21.9	11.8	10.1
33B-7.1	27.6	26.1	1.5
33B-9.1	15.2	24.9	−9.7
33B-11.1	108.8	118.7	−9.9
33B-14.1	58.0	61.2	−3.1
33B-10.1	96.5	83.2	13.3
33A-13.2	15.7	15.6	0.1
33B-14.2	42.6	40.2	2.4
33A-15.2	39.5	31.2	8.3
33A-17.2	44.9	35.4	9.5
Mean	40.2	37.4	2.8
s	24.0	24.3	5.8
n	33	33	33

<sup>a</sup> On average, the controlled laboratory-derived values were 2.83 ppm higher than those measured in the field. This represents only a 7% difference between the two environments.

allows archaeologists to undertake systematic sampling prior to excavation, thus becoming a prospecting tool as useful as ground penetrating radar or magnetic imaging.

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