Soil Sampling Methods for Phosphorus – Spatial Concerns
A SERA-17 Position Paper

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Purpose of This Publication

Knowledge of soil phosphorus (P) levels is an essential component of nutrient management planning for crop production and for tools that assess the risk of P loss from agricultural fields. Historically, soil P testing has been used to estimate P availability for crops and is now being used directly or as a component of P indices to assess the risk of P loss from fields to water resources. A basic assumption of soil testing for crop production is that the soil sample collected represents a certain area with an acceptable margin of error. Therefore, appropriate soil sampling methods are needed for effective agronomic P management and environmental P assessment. A recent SERA-17 position paper (Vadas et al., 2006) addressed the issue of soil sampling depth. This position paper summarizes important practical aspects of topsoil P variability (within 20 cm depth) across the landscape with an emphasis on within-field variability, and sampling methods that have been recommended or proposed to assess soil P and suggests practical soil sampling options for agronomic and environmental purposes.

Spatial Variability of Soil Phosphorus

Effective soil sampling methods for P (or any nutrient) requires understanding the causes and general patterns of spatial variability. Soil chemical and physical properties can lead to variability in soil P available for plants (or for algae if soil is delivered to water resources) by influencing the total amount of P, the fraction available to crops, and potential loss from the root zone. Many soil properties also can affect total and available soil P concentrations indirectly by affecting crop yield and, as a result, P removal with harvested biomass. Soil property variability arises from complex interactions among natural soil formation processes and cultural management practices. Natural soil formation processes include time, parent material, topography, climate, and organism activity. Cultural management practices such as tillage, fertilization, manure application, and others can profoundly affect, and even mask, many variability patterns associated with natural soil physical and chemical processes. Spatial and temporal variability patterns expected or observed in fields result from the complex interactions of natural soil formation processes and cultural management practices. Understanding these interactions is a key element in developing a practical soil sampling strategy.

Spatial variability of soil P is expressed at various scales, which range from a few cm to a regional scale. Producers and nutrient management planners are interested mainly in variability within fields and across fields of a farm, although monitoring larger scale nutrient variability is important for larger scale agricultural and environmental planning purposes (Gburek and Sharpley, 1998; Gburek et al., 2000; Klatt et al., 2003). In this paper we emphasize within-field soil P variability. Usually large and complex spatial variability of soil P in fields with long histories of cropping and fertilization has been recognized for a long time (Cline, 1944; Petersen and Calvin, 1965; Peck and Melsted, 1973). Within-field variability of soil P was readily recognized because of the inherently site-specific nature of soil sampling and testing required for crop production. Recent advances in variable-rate technology (VRT) have encouraged further research on soil sampling methods and ways to incorporate soil P testing into precision agriculture management systems.

Soil-test P variation due to inherent soil properties.

Numerous studies have been conducted worldwide to describe soil-test P (STP) and, to a lesser extent, soil total P variability and their relationship with other soil properties using both classical and spatial statistical methods. Within-field variation in soil parent material and topography often, but not always, determine contrasting differences in soil physical and chemical properties that result in significant STP or total P variation (Rennie and Clayton, 1960; Malo and Worcester, 1975; Roberts et al., 1985; Brubaker et al., 1993; Franzen et al., 1998; Clay et al., 2000; Page et al., 2005). Within-field soil P variability has been associated mainly with variations in soil texture, pH, Ca or $CaCO_3$ content, and organic matter, although other properties sometimes also are important. Complex inter-relationships between soil P and these soil properties have been described by several studies (Mallarino et al., 1999; Kravchenko and Bullock, 2000; Page et al., 2005) and explain why correlations between STP and soil properties often are not straightforward or valid across regions. The variability of potentially important soil P measurements for agronomic or environmental purposes other than STP and total P (such as soil P saturation, P sorption capacity, or various P fractions) have not been studied nearly as thoroughly.

Soil-test P variation due to management.

Soil-test P and total P variability can be very large even within a field that appears uniform in other soil properties, and tends to be larger in fields with long histories of cropping and fertilization. A few examples selected from numerous studies for fields managed mainly for grain production that used very dense grid sampling methods illustrate the range of results reported. Peck and Melsted (1973) found that STP from two Illinois fields sampled using a 25 m systematic grid had nearly the same mean (33 and 31 mg kg^{-1}) but coefficients of variation (CV) of 76 and 49%, respectively. Pierce et al. (1995) reported that STP of three Michigan fields sampled using a 31-m grid had means of 23, 50, and 124 mg kg^{-1} and CVs of 34, 50, and 26%, respectively. On the other hand, Han et al. (1996) reported approximately similar STP means and CV (24 mg kg^{-1} and 24%) from two adjacent center-pivot irrigation systems in Washington sampled using a 61-m grid and that in both fields the random component of the variability was larger than the spatial component. Mallarino (1996) reported that STP mean and CV for composite samples spaced 3 m along 150 m transects in eight Iowa no-tilled fields were 9-41 mg kg^{-1} and 16-56%, and that often there were cyclic trends clearly resulting from uneven fertilizer application. Lauzon et al. (2005) sampled 23 Ontario fields using a grid size of 30 m and reported mean STP ranging form 9 to 71 mg P kg^{-1} and CVs of 24 to 142%.

High STP variability also has been observed in fertilized and grazed pastures (West at al., 1989; Fisher et al., 1998; Raun et al., 1998; Daniels et al., 2001; Shi et al., 2001). For example, West et al. (1989) showed that STP in areas near water sources was up to 10-fold greater than STP in areas further away and that large small-scale variability across the pastures was attributed to uneven fertilization and feces deposition. Raun et al. (1998) reported large STP variation at a sub-meter scale for pastures that were comparable to the variation observed by Mallarino (1996) for no-till crop fields. High small-scale spatial variability of STP in no-till fields and pastures should be expected especially when fertilizers are banded or manure is applied because of limited mixing of residues, fertilizers, and manure with soil.

Studies of within-field soil-test variation with spatial statistics methods (Pierce et al., 1995; Han et al., 1996; Mallarino, 1996) have shown that the proportion of spatially structure and random variability changes significantly across fields. These and other studies also have shown that STP distributions often are skewed from a normal distribution towards positive values because of relatively greater percentage of high values. These findings suggest that, for many purposes, consideration of median values and a stratified sampling method (Cline, 1944) are more useful than the mean values or random sampling of large areas. Clusters of high STP values sometimes can be explained by differences in management practices. For example, some producers have historically applied animal manure to relatively small areas. Increasing farm and field sizes in most regions of the world have resulted in removal of buildings, feeding lots and fences. Identifying the location of these old structures has been useful for understanding STP variability and developing efficient sampling methods (Chang et al., 2003).

An obvious conclusion from most variability studies is that the amount and patterns of soil P variability change significantly depending on numerous factors and that few generalizations are possible. In regions with long histories of fertilization or manure application, within-field variability usually encompasses STP values that range from deficient for crop production to values much greater than optimum. Fields with average STP levels near optimum for crops usually have areas testing very low and areas testing very high. The strong influence of management on within-field STP variability at various scales, and the finding that the relative impacts of spatially structured vs. random spatial variability changes markedly across fields is frustrating because it limits the reliability of STP extrapolation for mapping using spatial statistical methods. A study in Kansas (Schmidt et al., 2002) suggested that a dense sampling of a few fields can provide clues for less dense sampling of other fields within a region, but our experience indicates that this approach is not viable in regions with long histories of fertilization. Because temporal STP variability is less than for more mobile nutrients (Lamb and Rehm, 2002), dense soil sampling approaches spaced over time coupled with other information (i.e., soil, elevation and yield maps; aerial or satellite imagery) may provide field-specific clues useful to develop sparser soil sampling approaches.

Soil Sampling Methods

Traditional soil sampling recommendations involve a stratified sampling approach, in which sampling areas are identified according to previous management, soil map units, and (sometimes) topography. Most protocols suggest collecting one composite soil sample made up of about 15-20 soil cores from each sampling area and some recommend a certain number of samples per unit area (4 to 8 samples ha^{-1}). This approach is based on trade-offs between the practicality of sampling and the ability to achieve a certain level accuracy and precision for the soil test in the sampling area. Swenson et al. (1984) and others have shown that the accuracy of a soil-test result increases as the number of subsamples increases. Data in Fig. 1 show that collecting 20 cores (15 to 20 cores often are recommended) would result in an accuracy of ± 15-20% from the true mean STP for the sample area at the 80 to 90% precision level. However, soil test users often take fewer than 20 cores and still expect significant accuracy and precision from soil testing. Soil test users need to be better educated about the implications for accuracy and precision of their results based on the number of soil cores collected. Research has shown that the number of cores required often does not increase significantly or proportionally with the size of the sample area (Keogh and Maples, 1967; Cameron et al., 1971; Cypra et al., 1972; Swenson et al., 1984). This is important for areas like the northeast U.S. where field size tends to be very small, often less than 5 ha. Many users tend to take even fewer cores in these small fields.

The traditional stratified sampling approach (usually based on soil-survey map units) seemed to work well until the early 1990s, when crop consultants and producers began adopting precision agriculture technologies and a dense grid soil sampling approach. These new developments lead to a full appreciation of the large differences in nutrient variability that occur in most fields; that presumed uniform map units of commonly used soil survey maps often had very high STP variability, and that variation patterns did not follow soil map units. Therefore, grid-sampling methods that ignore landscape or soil mapping units began to be adopted rapidly in the early 1990s and now are widespread in the Corn Belt and Great Plains.

Grid sampling

There are several variations of grid soil sampling (Wollenhaupt et al., 1994; Rehm et al., 2001). Grid sampling subdivides a field into a systematic arrangement of small areas or cells, from which one composite sample is collected. Early users of the method collected cores from the entire area of each cell, a method often referred to as grid-cell area sampling or block sampling. Currently, most collect cores from smaller areas (50-150 m^2) located near the center of each cell or at the intersection of grid lines, a method referred to as grid-point sampling or simply grid sampling. Practitioners soon became aware that a cell size of about 2 ha or larger failed to describe nutrient variability adequately in fields of the Corn Belt (mainly for P and K, but also pH and organic matter). Nowadays, a cell size of about 1 ha is used and 20 to 60 soil samples are collected from typically sized Corn-Belt fields where seldom more than two to six samples were collected before. Soil-test results are mapped to represent each cell area or are used to create interpolated maps using one of several methods available in computer software packages. Automatic soil samplers adapted for dense grid sampling have been proposed but at this time have not been adopted in production agriculture.

Practitioners' observations about the high sampling density needed to describe STP variability are corroborated by research results. For example, Wollenhaupt et al. (1994) and Franzen and Peck (1995) showed major differences in soil test maps for P and K based on various grid cell sizes and demonstrated that cell sizes of 0.4 and 0.1 ha greatly increase mapping accuracy. Smith et al. (1998) suggested that a grid size equal to or smaller than 6 by 18 m might be needed to assess soil nutrient status for cotton. Chang et al. (1999), McBratney and Pringle (1999), and Lauzon et al. (2005) and others, reported that the impact of grid distance on the reproducibility of spatial variability measurements decreased significantly for grid sizes larger than 20 to 30 m. This is a serious limitation to adoption of grid sampling in large fields (e. g., larger than 40 to 50 ha) typical of some regions of the U.S, such as in the Great Plains region. In regions with large fields, cell size is larger mainly to reduce sampling and testing costs, not necessarily because of lower nutrient variability. On the other hand, in other parts of the country, such as in the northeast region, some fields are only the size of typical grid cells used in the Midwest.

Sometimes, however, a dense sampling does not result in contrastingly different STP or fertilizer recommendation maps compared with sparser grids. Franzen and Peck (1995) observed that a 65 m grid size still reflected the spatial variability accurately compared with a distance of 25 m but was better than a 98 m grid. However, STP variability within cells of that size still can be very high and sampling of systematically aligned points or small areas can lead to large error when spatial patterns are cyclic (Wollenhaupt et al., 1994; Mallarino, 1996). To avoid this problem, sampling points sometimes are determined for random locations within grid cells or using a systematic yet unaligned method. Obvious conclusions from most sampling studies are that grid sampling provides excellent information about STP variability when a small grid size is used, important attributes are missed when grid size is increased, costs and labor associated with a dense sampling are high, and no general recommendation is possible across all fields.

Zone sampling

Zone sampling has recently been suggested to reduce sampling and testing costs compared with a dense grid sampling method while maintaining acceptable information about nutrient variation. Zone sampling assumes that relatively homogeneous sampling areas can be identified based on management and soil and crop characteristics with variation patterns that are likely to be temporally stable (Pocknee et al., 1996; Fleming et al., 2000; Franzen et al., 2000). Criteria used to delineate management zones vary widely. Soil series and topographic position, in addition to previous management practices, can be used to identify sampling zones. However, the scale and accuracy of common soil survey maps may not always be adequate for precision management (Mausbach et al., 1993; Fenton and Lauterbach, 1998; Mallarino and Wittry, 2004). Elevation, topography, and soil or crop canopy images can be part of the information used to identify sampling zones because they tend to reflect different soil properties and may complement the use of soil survey maps (Franzen et al., 1998; Varvel et al., 1999; Kravchencko and Bullock, 2000; Schepers et al., 2000; Franzen and Nanna, 2002). Patterns in aerial or satellite images and derived indices based on wavelength ratios can reflect soil organic matter, soil moisture content, or crop growth patterns (Varvel et al., 1999; Luchiari et al., 2000; Franzen and Nanna, 2002). Recent and old aerial images also are useful to reveal the location of previous buildings, feeding lots and fences that denote small fields have been merged into larger fields (Chang et al., 2003). Estimates of soil electrical conductivity through on-the-go measurements of soil electro-magnetic inductance or direct sensing (EC) may be a useful zoning tool because EC maps often are correlated with soil properties such as texture, cation exchange capacity, and soluble salt concentrations; topsoil depth (to a claypan or other root growth limiting layer); and sometimes crop yield (Doolittle et al., 1994; Jaynes, 1996; Sudduth et al., 1998; Luchiari et al., 2000; Clay et al., 2001; Heiniger et al., 2003; Kitchen et al., 2003).

Yield maps can be used to define soil productivity areas and may help establish sampling zones when coupled with other information layers. However, yield map interpretation for field zoning is not straightforward because stable within-field yield variation patterns over time are observed in some fields but not in others (Lamb et al., 1996; Colvin et al., 1997; Stafford et al., 1999; Boydell and Mc Bratney, 2002; Flowers et al., 2005). Research also has shown that zones with contrasting yield levels do not necessarily represent differences in soil P because other soil properties, management and weather often have a greater impact on yield in many years (Mallarino and Wittry, 2004; Flowers et al., 2005; Sawchik and Mallarino, 2007).

The variety of tools and information available to define zones determine that zoning methods used or proposed vary significantly. These methods range from simple approaches that can be used by producers and crop consultants with affordable and user-friendly computer software (Fleming et al., 2000; Franzen et al., 2000; Franzen and Nanna, 2002) to more sophisticated methods (Fraisse et al., 2001; Boydell and McBratney, 2002; Chang et al., 2003; Fridgen et al., 2004). For example, Chang et al. (2003) compared zone approaches for soil nitrate and STP based on field boundary demarcations and old homestead locations; geographical information systems (GIS) or cluster analysis of various soil attributes (EMI, elevation, and aspect); grids of several sizes; and soil survey maps in three North Dakota fields. They showed that the approach based solely on soil survey maps was the least effective in reducing within-zone STP variability, which was attributed to the impact of prior management on nutrient variability. Grid sampling (3.5 to 4.0 ha) and zoning based on old field or homestead boundaries were the most effective at reducing within-zone STP variability. Grid sampling and sampling separately old homestead or animal-impacted areas significantly reduced the area incorrectly fertilized, although the differences changed significantly across fields. Mallarino and Wittry (2004) compared sampling approaches based on soil survey maps (1:12,000 scale), detailed soil maps (< 1:5,000 scale), cells 1.2-1.8 ha in size, elevation zones, and an integrated zone approach based on several layers of information that included yield maps across six Iowa fields. No approach was always the most effective across fields in reducing the within-unit STP variability, although a sampling approach based solely on soil survey maps always was the least efficient. Across all fields, sampling approaches differed little on the proportion of the area that would have been correctly fertilized (50-59%), although differences sometimes were larger or smaller for individual fields. Flowers et al. (2005) showed that yield zones based on multi-year crop yield data from four fields were nearly as effective as grid sampling based on a 98-m grid at describing STP and other nutrients variability but was less effective than grid sampling based on a 68-m grid.

Sawchik and Mallarino (2007) used yield response to fertilization to assess the efficacy of various sampling methods for agronomic purposes. For P, strip trials were established on four fields that were evaluated the 4 years of two corn - soybean rotation sequences. Soil test values from samples collected using a very dense grid-point (DG) approach (0.08 ha) were used to simulate six sampling approaches: 1.0 ha grid cells (GC), soil series from digitized survey maps (SMZ), elevation (EZ), EC zones (ECZ), elevation and ECa (EECZ) zones, and elevation, ECa, and slope (EECSZ) zones. Yield monitors, differential global positioning systems (DGPS), and GIS were used to describe crop response to fertilization for the sampling cells or zones. Estimates of within-field STP variation were greatest for DG, intermediate for GC, and much less for the other approaches. A differential within-field response to P was identified in 10 of the 16 site-years by DG; in 7 site-years by GC; in 3 site-years by EZ, ECZ, or its combinations; and in none by SMZ. Zone approaches identified areas with different yield levels but were ineffective at describing STP variation and differential crop response to P fertilization. Usually similar mean STP explained the ineffectiveness of zone sampling across zones and high within-zone STP variation. They concluded that zone approaches might be more effective in fields with shorter fertilization histories and/or those with large variation soil properties that have a significant influence on P availability.

The results of reviewed research clearly demonstrate the difficulty for recommending cost-effective soil sampling recommendations across all conditions. No single sampling approach is superior in describing STP variability cost-effectively across all conditions. Examples for three Iowa fields included in Fig. 2 demonstrate the contrastingly different results that can be expected when using similar sampling methods in different fields. Obviously, a very dense and costly grid sampling method will describe STP variability better. Zone sampling approaches based on a variety of information layers are reasonable alternatives to a strict soil map-unit based sampling approach and dense (and costly) grid-sampling approaches. Consideration of soil sampling and testing costs and the willingness of producers or crop consultants to change methods across fields will in many instances determine the effectiveness of alternative soil sampling approaches. Research results underscore the great impact that development of sensors for directly assessing STP could have on improving P management.

Implications for Environmental Phosphorus Management

The potential for P delivery from fields is affected by soil P levels and soil properties but also by factors such as soil erosion, surface water runoff, and subsurface drainage that control P delivery. Phosphorus assessment tools, or P indices, have been developed to better estimate the risk of P loss from fields compared with estimates provided solely by STP and planned P application methods or rates. In both cases, however, soil sampling plays a key role in estimating P loss. Soil sampling studies have demonstrated that with very few exceptions, agricultural fields encompass areas with high variability in soil P levels and fertilizer need. Therefore, few argue against the potential value of dense grid soil sampling coupled with VRT for improving STP assessment and P application management. Zone sampling also adapts well to VRT because the criteria to delineate zones based on many layers of information can be adapted to essentially any desirable numbers of zones and soil sampling density. Regardless of the soil sampling method used, however, an "as best as possible" description of STP variability and associated "best as possible" P application using VRT has the major limitation of high costs. These high costs arise not only from high soil sampling and testing costs, but also costs of needed equipment (DGPS, controllers), data acquisition and processing, and the usually time-consuming intellectual investments in learning how to successfully use all components of the technology. Moreover, although several studies showed a potential benefit from VRT when dense soil sampling approaches are used, none has demonstrated consistent or large crop yield responses to the new technology package for reasons beyond the scope of this paper (Wibawa et al., 1993; Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999; Yang et al., 2001; Wittry and Mallarino, 2002; Wittry and Mallarino, 2004; Bermudez and Mallarino, 2007). However, as on-farm research (Wittry and Mallarino, 2002 and 2004) and data in Fig. 3 demonstrates, VRT and dense grid sampling can greatly improve P management, reduce excess P application across a field, and potentially reduce P loss from fields.

Studies have found that small areas of fields or watersheds usually deliver disproportionately greater amounts of P to streams or lakes (Longabucco and Rafferty, 1989; Gburek and Sharpley, 1998; Gburek et al., 2000; Needelman et al., 2001; Weld et al., 2001; Klatt et al., 2003). Moreover, field areas with the greatest risk for P loss may be smaller than, or may not fully coincide with, areas that have the highest soil P levels. A P index can be used to classify fields or field areas into classes according to the risk of P loss through various transport mechanisms and, therefore, can provide guidelines for improved soil conservation and P management practices. For example, the Iowa P index establishes that P index ratings can be estimated for conservation management units within a field as defined by the USDA Natural Resources Conservation Service (Mallarino et al., 2002) and the Iowa Department of Natural Resources allows for even more flexible criteria to establish field zones for P index calculation.

Phosphorus index ratings for different field areas could be used as another information layer to complement other information layers discussed above to establish sampling zones. The information available in digitized soil survey maps can be complemented with high-precision elevation maps (from which more accurate estimates of slopes can be obtained using GIS software), EC maps, waterway maps, or imagery of bare soil or crop canopies to produce an approximate index of the risk of P loss. Application of these concepts to several fields has shown, as expected, that within-field variation in the risk of P loss varies greatly depending on the soils, topography, and STP levels of each field (Page et al., 2005; Djodjic et al., 2001; Mallarino et al., 2001). Figure 4 illustrates the large STP variability within and across fields of an Iowa watershed. Working in a different region, Page et al. (2005) showed that topography alone was not related to the distribution of soil P in two sub-watersheds and did not provide an adequate indicator of critical source areas because of high soil P variation at a small scale. The results of many studies did show, however, that field zoning is useful to prioritize field areas that require signifcant changes in soil conservation practices or P management practices to reduce the risk of P delivery to water resources.

Recommendations

Grid and zone sampling methods used in the Corn Belt describe STP better than the traditional sampling by soil type method. However, these methods still do not describe small-scale STP variability as well as many believe. A grid-sampling approach based on a 1.0-ha grid size often is more effective than zone sampling in fields with long histories of P fertilization or manure application because more samples are taken per unit area, and it does not rely on often unproven assumptions of a good relationship between STP and stable soil properties and landscape features.

Consideration of sampling and testing costs together with uncertain yield increases and economic benefits from variable-rate fertilizer or manure P application suggests little justification for widespread adoption of dense grid-based soil sampling methods. The probability of economic benefits from grid soil sampling will be greater when the variation in yield response is large (such as in fields with large STP variation at relatively low levels) and crop or fertilizer values are high compared with soil testing and fertilizer application costs. From an economic perspective, a zone-based soil-testing approach likely is more justified than grid sampling in fields with predominantly optimum to high STP or higher. There may be more justification for dense sampling for environmental purposes, but this will likely come at a significant economic cost. Also, a frequent soil sampling (e. g., every 2 years or annual) is more justified for a zone sampling approach with fewer samples than for grid sampling.

Therefore, the SERA-17 Task Force on soil sampling supports the following recommendations:

1. With economic considerations aside, a dense grid sampling (probably 1.0-ha grids or smaller) is most likely to result in the most thorough agronomic and environmental assessment of soil P across most conditions.
2. However, neither Land Grant Universities nor regulatory agencies should recommend or require a dense and frequent (more than every 4 years) grid sampling approach because it is not more effective in all conditions and would result in a significant economic penalty to producers in many situations.
3. Land Grant Universities and regulatory agencies could discourage a strict sampling by soil map unit approach.
4. Regulatory agencies should accept grid or zone sampling approaches that are recommended by the Land Grant University for the state that the producer is operating in. We believe that producers and nutrient management planners should choose between grid sampling and zone sampling approaches that improve the traditional sampling by soil map unit or random composite sampling as much as possible based on a variety of information layers (e. g. yield maps, digitized elevation maps, aerial images of soil and canopy, and others) available to producers at a reasonable cost.
5. A significant practical issue in soil sampling that can be easily addressed at a low cost is the number of subsamples required for each composite sample to provide a reasonable estimate of the mean STP within a sampling unit. A minimum of 10 to 12 soil cores should be collected within each sampling unit, regardless of the sampling method used, if the expected soil test results are to be +/- 20% of the mean soil test with 80% precision.

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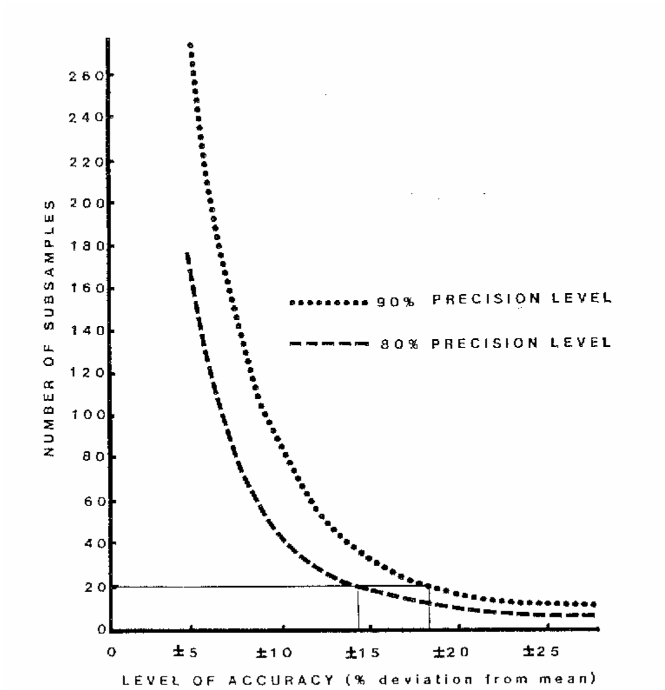

Fig. 1. Number of subsamples required for a composite soil sample for P according to various levels of accuracy at the 80% and 90% precision levels (from Swenson et al., 1984).

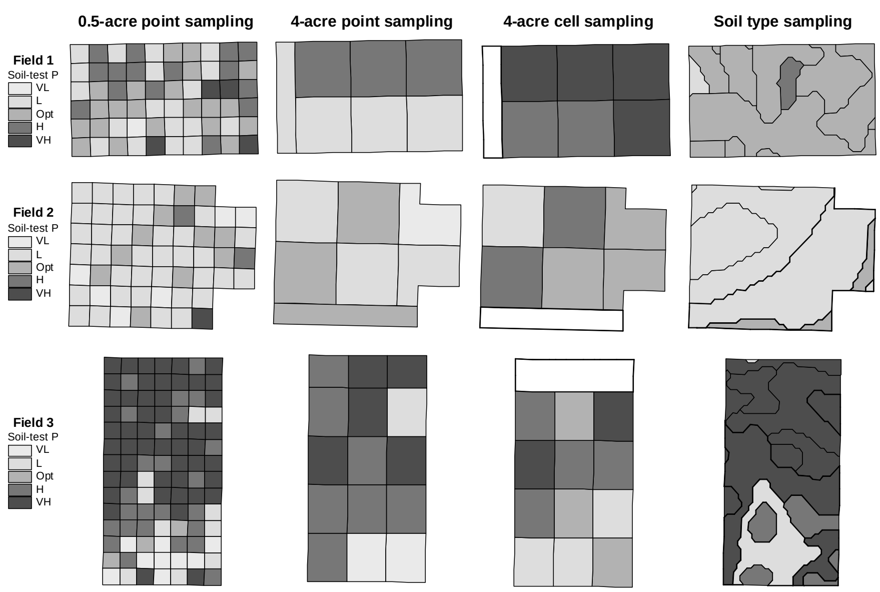

Fig. 2. Soil-test P maps based on different soil sampling methods for three Iowa field sections. Results for the 0.5-acre and grid-cell methods were based on 16- to 24-core samples. The 4-acre grid-point and soil-type methods were simulated by using one (for the grid method) or all 0.6-acre points (for the soil zones). VL, very low; L, low; Opt, optimum; H, high; and VH, very high (Iowa soil-test P interpretation classes for corn and soybean).

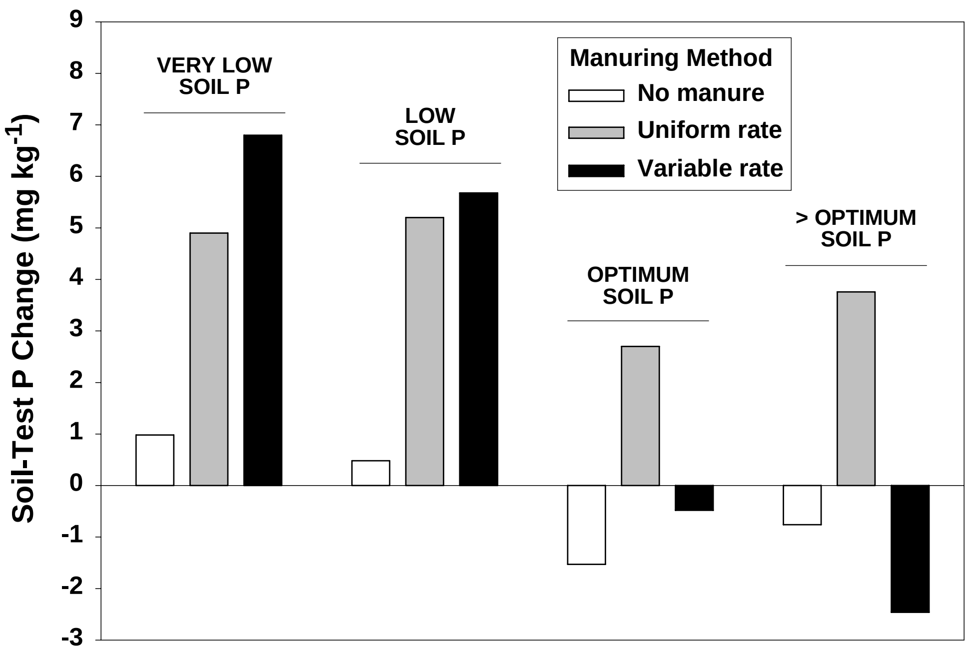

Fig. 3. Effect of uniform and variable application methods for liquid swine manure P on soil-test P change within a field after one crop harvest for various initial Iowa soil-test P interpretation classes for corn or soybean (Wittry and Mallarino, 2002).

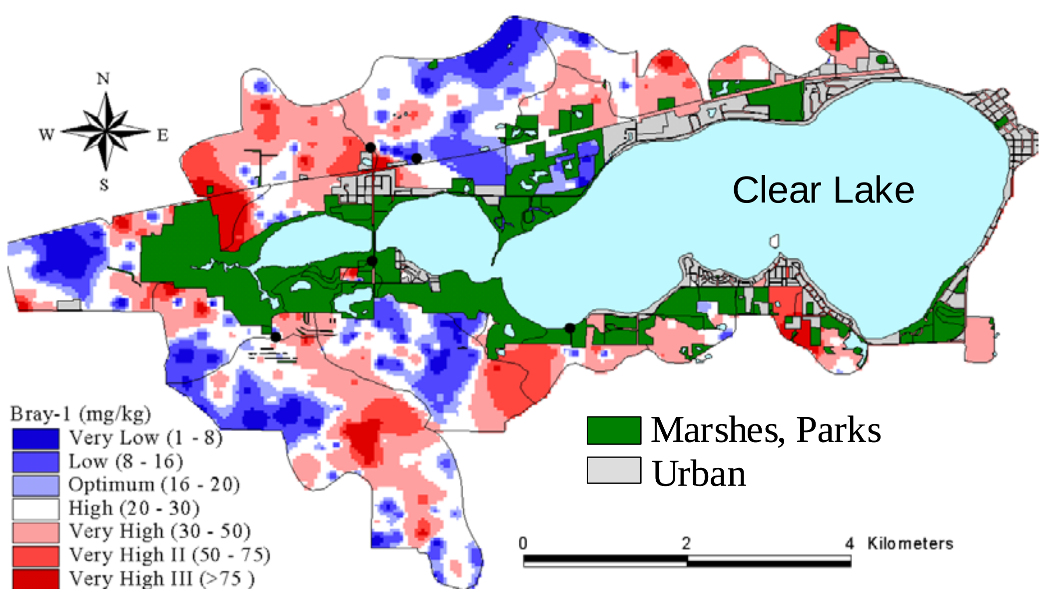

Fig. 4. Distribution of soil-test P within and across fields of the Iowa Clear Lake watershed as described by interpolation of test results from a dense zone sampling method. From original data summarized for publication by Klatt et al. (2003).