IDENTIFYING COST-EFFECTIVE SOIL SAMPLING SCHEMES FOR VARIABLE-RATE FERTILIZATIONAND LIMING

A.P. Mallarino and D.J. Wittry

Iowa State University
Ames, Iowa

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ABSTRACT

Within-field nutrient variability causes some areas of a field to be more or less responsive to fertilization. The best soil sampling and fertilization strategies are those that best estimate and apply economic optimum fertilizer rates across a field. Although current site-specific management practices could achieve this goal, questions remain concerning the cost-effectiveness of alternative sampling strategies. This study compared various soil sampling schemes in eight fields using soil test P, K, pH, and organic matter. The schemes were grid sampling, sampling by digitized and detailed soil survey map units, sampling by elevation, and a targeted sampling based on various layers of information. The soil-test variability patterns varied markedly across the fields. The schemes varied greatly in reducing the within-unit variability and in the recommended fertilizer rate, but no scheme was superior across all fields and nutrients. The efficacy of all sampling schemes was lower for P and K, probably because of the larger impact of fertilization on small-scale variability. Over all fields, only schemes based on field averages or digitized soil survey maps resulted in significantly lower correctly fertilized areas than other schemes. For P, the most highly variable nutrient, the grid and targeted schemes usually were similarly effective, although the latter sometimes required fewer sampling units. Consideration of costs, field fertilization history, and likely response to fertilization is needed to select among various similarly effective sampling strategies.

KEYWORDS: soil sampling, grid sampling, precision agriculture.

INTRODUCTION

The process of growing and harvesting crops removes nutrients from the soil. Unless the level of these nutrients are exceedingly high, these nutrients need to be replaced for the soil to remain productive. Soil testing is the most commonly used tool to determine the P and K fertilizer needs of crops. The original fertility level, the removal of nutrients in harvested products, and the replacement of these nutrients with fertilizers usually is not uniform over an entire field. The measurement of this variation is an important factor that must be considered when a soil sampling strategy is planned.

Soil variability is caused by variations in climate, topography, parent materials, vegetation, complex geological and pedological processes, and soil management practices. These factors influence variability at different scales (Cahn et al., 1994; Cambardella et al., 1994; Mallarino, 1996). At the regional scale climatic factors, land use patterns, vegetative cover, and land surface characteristics are the main factors affecting the variation. At the field scale the main factors controlling variability are soil type, topography, and previous crop and soil management practices. At smaller scales crop row orientation, the method of nutrient application, tillage, and compaction may dominate as the causes of variability.

It is the within-field variability that is of concern for soil testing and fertilizer application. Researchers and farm managers recognize that spatial variability in soil properties lead to differences in fertilizer needs and crop yields. However, traditionally fertilizer has been applied at a single rate throughout a field (Carr et al., 1991; Sawyer, 1994; Scknitkey, 1996). Considering the high variability of nutrient levels present in most fields, uniform fertilizer applications are likely to lead to excessive fertilization in some areas and inadequate fertilization in others (Wibawa et al., 1993; Mohamed et al., 1996). Many researchers have shown that soil test levels of P and K vary considerably within fields. Various studies (Cahn, 1994; Cambardella et al., 1994; Mallarino, 1996; Nolin et al., 1996; Penney et al., 1996; Schnitkey et al., 1996; Gupta et al., 1997) have shown coefficients of variation ranging from 30 to 55% for P and from 19 to 43% for K. McGraw (1994) reported that of 392 fields sampled in western and southern Minnesota using grid sampling methods, the range of nutrients encompassed four or five soil test interpretation classes in 86% of the fields for P and in 61% for K. Furthermore, the spatial structure of soil test variability often is site and nutrient specific (Mallarino, 1996; Borges and Mallarino, 1997).

Intensive sampling schemes that subdivide a field into smaller units identify more of this variability and provide more information about soil test levels (Wibawa et al., 1993; Bullock et al., 1994; Birrell et al., 1996; Gotway et al., 1996; Rehm et al., 1996). The accuracy and the cost of a sampling program depend largely on the number of subdivisions and the sample size (Wollenhaupt et al., 1994; Birrell et al., 1996; Gotway et al, 1996; Mohamed et al., 1996; Rehm et al., 1996). Several authors have recommended optimum subdivision sizes for cereal crops grown in north-central regions of the United States. Hammond (1993) recommended a grid size of approximately 60 x 60 m and suggested that subdivisions of 120 x 120 m or larger would be inappropriate. Wollenhaupt et al. (1994) recommended using grids no larger then 60 x 60 m and identifying areas that might need smaller grids. Franzen and Peck (1995) reported that a 66 x 66 m grid cell was better than a 100 x 100 m cell. Mallarino and Wittry (1997) reported that cells larger then 0.8 ha usually did not represent P and K levels appropriately. Han et al. (1994) summarized the problem well by concluding that the optimum size depends on the spatial variation and that an optimal sampling scheme will vary among fields.

Several authors (Peck and Melsted, 1973; Franzen and Peck, 1993) reported that pH, P, and K patterns are not always related to soil types and suggested that grid sampling is thus superior to soil type sampling. Rehm et al. (1996) report, however, that grid point sampling gives a poor estimate of the actual nutrient level within the grid. Furthermore, other research (Mallarino, 1996; Pocknee et al., 1996) suggests that a grid point sampling (i.e., sampling of small areas at the intersection of grid lines used to subdivide a field) can be biased if systematically aligned grids are used because periodic patterns of soil nutrients often are observed.

The objectives of this study were to compare soil sampling procedures that are being used or have been proposed to estimate soil nutrient levels within corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] fields, and to estimate the amount of P and K fertilizers that would be recommended by following each of the procedures evaluated.

METHODOLOGY

Soil samples were collected from eight Iowa corn and soybean fields. The fields were in Boone County (Fields 1 and 2), in Carroll County (Fields 3 and 4), in Linn County (Fields 5 and 6), and in Story County (Fields 7 and 8). All fields were managed with a two-year corn-soybean rotation, and samples were collected after crop harvest and before fertilization. A very intensive sampling scheme based on 0.2-ha cells was used as the base data to simulate other sampling schemes. Composite soil samples (0-15 cm depth) consisting of 20 to 24 cores were collected from an 80-m^2 circle within each cell. The sampling location within each cell was randomly chosen using geographic information systems (GIS) software. Hand-held differentially corrected global positioning system (DGPS) units were used to locate the sampling points in the field, and flags were used to mark the locations.

The soil samples were dried in a forced-air oven at 35°C, ground to pass a 2-mm screen, and analyzed in duplicates for organic matter (OM) by the Walkley-Black test, pH, P by the Bray-P_1 test, K by 1*M* ammonium acetate test, and for other nutrients that are not discussed in this report. The laboratory procedures used are described in the North Central Region Pub. 221 (Brown, 1998). Iowa State University soil-test interpretation classes for P and K for corn and soybean grain production will be used in this report (Voss et al., 1996). Ranges of values for the P interpretation classes are 0 to 8, 9 to 15, 16 to 20, 21 to 30, and more than 30 mg P/kg for very low (VL), low (L), optimum (Opt), high (H), and very high (VH), respectively. Similar ranges of values for K are 0 to 60, 61 to 90, 91 to 130, 131 to 170 and more than 170 mg K/kg.

The simulated soil sampling schemes were (1) grid sampling (Grid) using 1.8-ha rectangular (usually square) grids, (2) soil mapping unit (SMU) using the Iowa digitized soil survey database, (3) detailed soil mapping unit (DMU) using detailed soil maps, (4) elevation zones (EZ) using areas of similar elevation to define sampling zones, and (5) targeted sampling (TS) using soil surveys, aerial photos, yield maps and field history to define sampling areas. A vector map with associated information was created using GIS software for each sampling scheme either by creating appropriate polygons (i.e., for the Grid scheme) or by using available layers of information (USDA soil survey maps, detailed soil maps, elevation, aerial photos, yield maps, etc.). The soil-test values for all the points within a particular zone were averaged to estimate a value for that zone. These means should be approximately similar to the values that would be obtained by actually sampling the zones with a procedure that takes similar numbers of random samples and cores from each zone. The amount of variability and spatial patterns for each sampling procedure were studied by observation of soil test interpretation classes, maps created with GIS software, correlation coefficients, and variography. Mean soil test results for each simulated soil sampling area for each scheme were compared by observation of several descriptive statistics. In addition, an index of the efficacy of each sampling scheme to separate sampling areas was obtained by F tests of the between groups variability (i.e., between sampling units) and the within groups variability (i.e., the within sampling units). Phosphorus and K fertilization recommendations were calculated for each sampling scheme following Iowa State University's recommendations for two years of the corn-soybean rotation.

RESULTS AND DISCUSSION

Large soil test variability was observed in all fields. Soil-test P was extremely variable, and in most fields the values encompassed the five P interpretation classes used by Iowa State University. The variability for K was very high but proportionally less than for P. The K values were higher than the P values in terms of needs for optimum crop production. With few exceptions, however, the K values of each field encompassed three or four K interpretation classes. The soil-test maps that were created with the GIS software gave a good visual representation of the variability but cannot be practically shown in this article. The maps, correlation coefficients between tests, and semivariograms (not shown) showed contrastingly different variability patterns and structured variability across fields. The distributions, as expected, were positively skewed for several tests in some fields, although the degree of skewness varied greatly. The variability patterns for the different nutrients seldom were similar across fields. The within-field variation of P and K (correlation coefficients and spatial structure) often was more similar compared with the variation for pH or OM.

Analyses of the within-unit and between-unit variability were used to estimate the capacity of each sampling scheme in reducing within-unit variability and increasing between-unit variability. The result of this type of analysis was markedly different across soil tests and fields. Data in Table 1 show the estimates of within-unit soil-test P and K variability for the various sampling schemes. These estimates were calculated from the individual, randomly selected sampling points within 0.2-ha sampling cells that fell within the units of the simulated sampling schemes. The coefficients of variation calculated for each sampling unit for a particular scheme were averaged to obtain an estimate for the field. The data show that the variability within the simulated larger sampling schemes often was very similar to the variability across the field. This was particularly the case for P and K. Both the amount of variation and the differences between sampling schemes were lower for pH and OM (not shown). In some fields, however, some sampling schemes were more efficient in reducing the within-unit variability than in others.

Table 1. Mean coefficient of variation for soil-test P and K across sampling units for five simulated sampling schemes.

		Sampling scheme †					
Soil test	Field	Base	SMU	DMU	Grid	EZ	TS
		------------------------------ % ------------------------------					
P	1	46	40	38	38	40	39
	2	61	55	51	50	58	48
	3	34	32	27	34	33	20
	4	32	31	30	31	31	31
	5	38	39	32	36	38	37
	6	42	42	37	38	41	41
	7	64	63	na‡	63	62	63
	8	97	95	na	81	91	98
K	1	21	21	20	19	21	20
	2	23	20	19	21	19	19
	3	28	23	24	23	27	24
	4	17	17	16	15	17	16
	5	16	15	16	15	15	15
	6	35	33	34	31	34	31
	7	22	20	na	22	21	20
	8	27	25	na	22	19	18

† Base = 0.2-ha base sampling scheme, SMU = digitized soil survey mapping unit, DMU = detailed soil mapping unit, Grid = 1.8-ha grid, EZ = elevation zones, and TS = targeted sampling.
‡ Only six fields were used for this sampling scheme.

The data in Table 2 summarizes the efficacy of each sampling scheme in reducing the within-unit variability by showing the number of fields in which use of a scheme resulted in significantly greater ($P < 0.05$) between-unit variability than within-unit variability for each soil test. The data (number of fields) were transformed to percentages to facilitate the comparisons across fields because the DMU scheme could not be applied to two fields. The EZ scheme was among the worst for the P, K, and pH tests in most fields. Concerning the other schemes, the ranking varied markedly among the soil tests. All sampling schemes performed comparatively well in reducing within-unit OM variability. The SMU scheme was the best, however, and was followed closely by the TS and DMU schemes. For P, the TS and Grid schemes were the best, and were followed by the SMU and DMU schemes. For K, the Grid scheme was the best, the TS and DMU schemes were intermediate, and these were followed by the SMU scheme. For pH the TS scheme was the best, the Grid scheme was intermediate, and these were followed by the SMU and DMU schemes.

Table 2. Frequency for significantly lower within-unit soil-test variability than for between-unit variability.

	Sampling scheme†				
Soil test	SMU	DMU‡	Grid	EZ	TS
	--------------------------%--------------------------				
P	38	67	50	38	38
K	50	50	63	50	63
pH	62	67	88	50	100
OM	100	83	75	88	88

† See the methods section or the footnotes to Table 1 for abbreviations.
‡ Only six fields were used for this sampling scheme.

These results show that no sampling scheme was the best across all fields or soil tests. This result is reasonable because the impact of both natural and management factors on large- or small-scale variability should be expected to differ across different landscapes and nutrients. The efficacy of all sampling schemes in reducing within-unit variability was lower for P and K, intermediate for pH, and much higher for OM. These differences are reasonable given the different impact of fertilization and liming on small-scale variability. All fields had long histories of P and K fertilization and liming, although lime was applied less frequently than P or K fertilizers. These practices create very high variability over very short distances (Mallarino, 1996). Soil OM is less affected by fertilization and liming. Thus, it should not be surprising that schemes based on soil mapping units, elevation, or a directed sampling that considers several layers of information often were as efficient as grid sampling.

Tables 3 and 4 show the percent of each field that was represented by each soil-test P and K interpretation class for each sampling scheme. Similar calculations were done for liming needs (not shown). As expected, the simulated sampling schemes reduced the range of interpretation classes compared with the base sampling scheme. Most schemes tended to overestimate soil-test values (i.e, higher proportion of higher-testing areas) in some fields if one assumes that the 0.2-ha base sampling provides the best representation of the field (for example, in Fields 1 and 2). However, no clear differences are evident in other fields, and sometimes most schemes overestimated low testing areas (for example, for P in Field 6).

Table 3. Percent of the field represented by each soil-test P class.

Field	Class	Sampling scheme †					
		SMU	DMU	Grid	EZ	TS	Base
		%					
1	VH	40	25	75	83	76	43
	High	60	73	25	17	14	44
	Opt	0	2	0	0	10	9
	Low	0	0	0	0	0	4
2	VH	0	6	7	0	12	19
	High	67	85	64	88	53	37
	Opt	33	7	14	0	23	19
	Low	0	2	14	12	11	23
	VL	0	0	0	0	0	2
3	VH	0	0	0	0	0	2
	High	0	3	0	0	7	4
	Opt	7	15	16	0	27	19
	Low	93	81	84	100	68	65
	VL	0	1	0	0	0	10
4	Low	54	33	58	52	43	47
	VL	46	67	42	48	57	53
5	VH	0	3	0	0	0	7
	High	4	12	43	17	25	25
	Opt	96	69	29	83	51	35
	Low	0	16	29	0	24	31
	VL	0	0	0	0	0	2
6	High	0	7	0	0	0	17
	Opt	18	27	28	40	22	22
	Low	82	63	72	60	78	42
	VL	0	3	0	0	0	19
7	VH	0	na	0	0	0	8
	High	0	na	22	17	33	16
	Opt	92	na	45	50	50	28
	Low	0	na	33	33	17	36
	VL	8	na	0	0	0	12
8	VH	0	na	11	0	0	5
	High	0	na	0	0	0	9
	Opt	39	na	22	33	0	9
	Low	27	na	44	33	100	39
	VL	34	na	23	33	0	38

† See the footnote to Table 1 for abbreviations. Classes with a value of zero for all sampling schemes were excluded.

Table 4. Percent of the field represented by each soil-test K class.

Field	Class	Sampling scheme † SMU	DMU	Grid	EZ	TS	Base
		%					
1	VH	0	2	8	0	0	14
	High	67	85	62	83	76	40
	Opt	33	13	30	17	24	41
	Low	0	0	0	0	0	5
2	VH	0	0	0	0	0	5
	High	70	31	29	25	44	31
	Opt	30	61	71	75	56	56
	Low	0	8	0	0	0	8
3	VH	7	15	12	21	7	21
	High	93	85	88	79	93	67
	Opt	0	0	0	0	0	12
	Low	0	0	0	0	0	0
4	VH	0	0	0	0	0	17
	High	100	79	100	100	89	53
	Opt	0	21	0	0	11	30
	Low	0	0	0	0	0	0
5	VH	0	17	0	0	0	2
	High	4	0	0	0	0	8
	Opt	96	83	100	100	100	85
	Low	0	0	0	0	0	5
6	VH	0	0	0	0	0	3
	High	25	38	28	19	38	12
	Opt	73	41	43	81	52	59
	Low	2	21	28	0	10	26
7	VH	0	na	0	0	0	2
	High	6	na	0	0	0	12
	Opt	94	na	100	100	69	45
	Low	0	na	0	0	31	41
8	VH	0	na	0	0	0	9
	High	39	na	45	50	59	27
	Opt	61	na	55	50	29	50
	Low	0	na	0	0	12	14

† See the footnote to Table 1 for abbreviations. The Very Low class was excluded from all fields because it had a value of zero for all schemes.

The fact that few generalizations can be made is consistent with the fact that soil-test variability tends to be field specific and nutrient specific. This is especially the case for soil-test P, soil-test K, and pH because long histories of fertilization and liming tend to mask the natural variation over the landscape. Thus, no sampling scheme should be expected to be best across all situations. Informed decisions can be made only after an intensive (and very expensive) sampling scheme that shows the amount and structure of the variability for the different nutrients. Otherwise, knowledge of the field history (mainly the history of fertilizer and manure applications) could provide useful clues concerning likely nutrient levels and corresponding crop response to assess the potential return to expensive sampling schemes.

The proportion of the field that falls into the various soil-test interpretation classes directly impacts the amount of P and K fertilizer that would be recommended for each sampling area and for the entire field. Data in Tables 5 and 6 show the proportion of the field that would be fertilized correctly, underfertilized, or overfertilized if the data in Tables 3 and 4 were used to recommend fertilization for each sampling scheme. These data were also calculated for a scenario in which a uniform rate is applied to the entire field based on the single soil-test class that would arise from using the base 0.2-ha sampling scheme. Of course, an important underlying assumption for all scenarios is that the 0.2-ha base sampling provides the most correct recommendations, and that recommendations could be implemented with variable-rate fertilization technology.

Although the result of using the different sampling schemes varied across fields and nutrients, a few general conclusions are obvious. One significant result is that application of a uniform fertilization rate based on the average soil test class for the field tended to underfertilize larger areas than any other scenario in several fields, but resulted in similar or larger overfertilized areas compared with the other schemes in other fields. This result shows that the usual assumption (based on usually positively skewed distribution of soil test values) that sampling large units (either through mixing soil cores or averaging soil-test results) usually overestimate fertilizer needs may apply to some fields but cannot be generalized. This result is also apparent when the proportion of incorrectly fertilized areas are compared for the various sampling schemes. For example, use of the SMU and TS scheme, which usually involved large sampling units, did not result in larger underfertilized areas in all fields.

A great deal of subjective judgement is involved when deciding what percent difference is meaningful when studying the data in Tables 5 and 6. General relative trends become apparent, however, by ranking the number of fields each sampling scheme resulted in the largest correctly fertilized area across fields. For P, only the SMU and Uniform schemes clearly ranked lower than the other schemes (the Grid scheme was the best by a small margin). For K, all schemes were approximately equal. The difference between the two nutrients likely is more related to the different overall levels (higher for K) than to specific characteristics. It must be noted that even if the amounts of fertilizer recommended by some sampling schemes are similar, the location within the field that receives the fertilizer or the same rate of fertilizer likely is different.

Table 5. Percent of the field that would be correctly or incorrectly fertilized with P when different sampling schemes are used.

Field	Phosphorus fertilization	Sampling scheme † SMU	DMU	Grid	EZ	TS	Uniform
		-------	-------	-------	%	-------	-------
1	Underfertilized	34	39	30	37	33	46
	Correct	49	55	61	57	61	54
	Overfertilized	17	6	9	6	6	0
2	Underfertilized	39	40	28	35	30	44
	Correct	53	57	63	60	58	56
	Overfertilized	8	3	9	5	12	0
3	Underfertilized	13	18	19	10	31	10
	Correct	63	63	62	65	57	65
	Overfertilized	24	19	19	25	12	25
4	Underfertilized	28	10	24	23	20	53
	Correct	50	64	63	58	56	47
	Overfertilized	22	26	13	19	24	0
5	Underfertilized	35	29	32	37	30	33
	Correct	35	42	50	43	44	35
	Overfertilized	30	29	18	20	26	32
6	Underfertilized	40	34	28	36	43	25
	Correct	50	53	57	55	50	58
	Overfertilized	10	13	15	9	7	17
7	Underfertilized	42	na	30	27	41	49
	Correct	28	na	50	52	46	28
	Overfertilized	30	na	20	21	13	23
8	Underfertilized	13	na	13	8	0	0
	Correct	20	na	28	18	38	38
	Overfertilized	67	na	59	74	62	62

† See the methods section or the footnote to Table 1 for abbreviations.

Several aspects must be carefully considered when interpreting the results of our study. One aspect is that the large simulated sampling areas (usually the SMU and TS schemes) included more samples than smaller sampling areas. Thus, estimates for these schemes likely are better (more reliable means because more soil cores were collected from the field and more chemical analyses were done in the lab) than actual estimates in production agriculture. Another aspect is that our results are less prone to sampling or lab error because common sampling procedures used in production agriculture often include fewer samples or cores per sample than those used in this study.

Table 6. Percent of the field that would be correctly or incorrectly fertilized with K when different sampling schemes are used.

	Potassium	Sampling scheme ‡					
Field	fertilization	SMU	DMU	Grid	EZ	TS	Uniform
		--------------------------- % -----------------------					
1	Underfertilized	13	11	13	13	9	13
	Correct	87	88	87	87	87	87
	Overfertilized	0	1	0	0	4	0
2	Underfertilized	34	17	17	14	25	8
	Correct	60	61	65	68	65	56
	Overfertilized	6	22	18	18	10	36
3	Underfertilized	12	12	12	12	12	12
	Correct	88	88	88	88	88	88
	Overfertilized	0	0	0	0	0	0
4	Underfertilized	31	20	31	31	24	31
	Correct	69	69	69	69	72	69
	Overfertilized	0	11	0	0	4	0
5	Underfertilized	8	19	5	5	5	5
	Correct	84	73	85	85	85	85
	Overfertilized	8	8	10	10	10	10
6	Underfertilized	24	31	29	35	26	18
	Correct	44	41	43	33	44	42
	Overfertilized	32	28	28	32	30	40
7	Underfertilized	44	na	41	41	23	41
	Correct	44	na	45	45	50	45
	Overfertilized	12	na	14	14	27	27
8	Underfertilized	32	na	36	36	36	14
	Correct	50	na	49	53	52	50
	Overfertilized	18	na	15	11	12	36

† See the methods section or the footnote to Table 1 for abbreviations.

CONCLUSIONS

The spatial variability of soil tests was very high for P and K, intermediate for pH, and significantly lower for OM. The intensive (0.2-ha) base sampling described much variability that cannot be described with the larger area strategies. Such an intensive sampling scheme cannot possibly be economically justified when costs and likely response of crops such as corn and soybean are considered. Although the sampling schemes differed in their efficacy to maximize the between-unit soil-test variability, no scheme was superior for all fields or soil tests. This result is reasonable given that the impact of both natural and management factors on spatial variability is expected to differ across different landscapes and nutrients at either large or small scales. The efficacy of all sampling schemes was lower for P and K, intermediate for pH, and much higher for OM, probably because of the larger impact of P and K fertilization on small-scale variability. When all fields and nutrients were considered, only schemes based on field averages or digitized soil survey maps resulted in significantly lower correctly fertilized areas than other schemes. For P, the most highly variable nutrient, the grid and targeted schemes usually were similarly effective, although the latter sometimes required fewer sampling units. Consideration of costs, field fertilization history, and likely response to fertilization is needed to select among various similarly effective sampling strategies.

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