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Soil Test, Aerial Image and Yield Data as Inputs for Site-specific Fertility and Hybrid Management Under Maize

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Abstract. Several potential sources of information exist to support precision management of crop inputs. This study evaluated soil test data, bare-soil remote sensing imagery and yield monitor information for their potential contributions to precision management of maize (*Zea mays* L.). Data were collected from five farmer-managed fields in Central New York in 1999, 2000, and 2001. Geostatistical techniques were used to analyze the spatial structure of soil fertility (pH, P, K, NO_3 and organic matter content) and yield variables (yield, hybrid response and N fertilization response), while remote sensing imagery was processed using principal component analysis. Geographic information system (GIS) spatial data processing and correlation analyses were used to evaluate relationships in the data. Organic matter content, pH, P, and K were highly consistent over time and showed high to moderate levels of spatial autocorrelation, suggesting that grid soil sampling at 2.5–5.5 ha scale may be used as a basis for defining fertility management zones. Soil nitrate levels were strongly influenced by seasonal weather conditions and showed low potential for site-specific N management. Aerial image data were correlated to soil organic matter content and in some cases to yield, mainly through the effect of drainage patterns. Aerial image data were not well correlated with soil fertility indicators, and therefore were not useful for defining fertility management zones. Yield response to hybrid selection and nitrogen fertilization rates were highly variable among years, and showed little justification for site-specific management. In conclusion, we recommend grid-based management of lime, P, and K, but no justification existed within our limited study area for site-specific N or hybrid management.

Keywords: precision agriculture, remote sensing, site-specific management, field variability, hybrid

Introduction

Precision agriculture, as defined by Cambardella and Karlen (1999), is the application of computerized data acquisition and analysis systems to crop and soil management, and requires databases that provide the necessary information to develop an appropriate crop input response to a combination of site-specific conditions. An accurate description of soil fertility patterns within each field is especially important, as it serves as the foundation for site-specific applications of fertilizers and lime. Soil properties can vary considerably within short distances, and examples exist where 20–60% of the total variation in soil properties occurs for samples located < 10 m apart (Webster, 1984). Therefore, the traditional approach of determining the central tendency of soil fertility indicators across an entire field is often inadequate for precision management, and intense grid-based soil sampling and geostatistical analysis are recommended to characterize spatial patterns and produce accurate soil fertility maps (Wollenhaupt *et al*., 1997; Goovaerts, 1999; Webster, 2000).

Aerial and satellite images of bare soil may also aid in defining management zones. Bare soil reflectance has been related to soil organic matter and phosphorus content (Varvel *et al*., 1999), soil nitrate uptake (Tomer *et al*., 1997) and soil moisture and drainage patterns (Tomer *et al*., 1997; Senay *et al*., 2000), all of which frequently influence crop and soil management as well as crop yield. An additional consideration for precision farming is that variable rate application of nutrients based on soil sampling often fails to correct spatial variability in crop growth and yield (Varvel *et al*., 1999), due to the fact that yield does not depend solely on soil fertility. Given that precision fertilizer management aims to optimize yield and reduce the environmental impacts of agricultural production, spatially distributed yield data (the response variable) may be an important information source for defining management zones.

The objectives of this study were to accurately describe soil fertility patterns in five farmer-managed fields located in central New York State, examine their temporal consistency and evaluate their relationship to bare soil reflectance (based on digital color-infrared aerial imagery) and yield data for the purpose of supporting precision fertilizer, lime and maize hybrid management decisions.

Materials and methods

Study sites

Five fields on three cooperator farms in Central New York, USA were selected for this study, which was conducted in 1999, 2000, and 2001. Three of the fields, located in Seneca County (denoted as Seneca 1, 2 and 3), were dedicated to cash crop production. The other two fields, located in Onondaga County (denoted as Onondaga 1 and 2), were part of a dairy farm and regularly received manure. Table 1 contains general descriptions of each field, including their size, location, soil types (USDA, 1972, 1973) and the number of soil samples taken. Figure 1 shows soil sample locations, overlain on each field's bare soil digital aerial image.

Prior to the field trials in 1999, Onondaga 1 and 2 had been in alfalfa (*Medicago sativa* L) from 1994 to 1997 and in maize in 1998. Seneca 1, 2 and 3 had been under a maize-soybean (*Glycine max* L.) rotation during the 1990s, with soybeans planted in 1998. Throughout the 3-year trial, all fields were planted to maize each spring and were left fallow during the winter months. Seneca 1, 2 and 3 received a traditional chemical fertilization scheme common to cash cropped fields, while Onondaga 1 and 2 received 93500 L ha^{-1} of liquid dairy manure in both the fall and spring of each year of the study in order to match an expected maize nitrogen demand of 170 kg N ha^{-1} in the following growing season, based on the farmer's nutrient management plan.

Experimental design

A systematic experimental design was used to balance the need for replication with simplicity of plot layout for on-farm studies. Maize yield response to hybrid type and

Table 1. Geographic location and soil descriptions for each research site

Field	Area (ha)	No. soil samples	Geographic location (Lat, Long)	Soil type	USDA Soil Taxonomy Classification	Extent (% of field area)
Onondaga 1	5.67	24	42.93N, 76.38W	Angola-Darien silt loams (AnB)[a]	Fine-loamy, mixed, mesic Aeric Ochraqualf	96.1
				Honeoye silt loam (HnC)	Fine-loamy, mixed, mesic Glossoboric Hapludalf	1.7
				Kendaia silt loam (KeA)	Fine-loamy, mixed, nonacid, mesic Aeric Haplaquept	2.2
Onondaga 2	9.71	52	42.93N, 76.36W	Lima silt loam (LtB)	Fine-loamy, mixed, mesic Glossoboric Hapludalf	1.3
				Honeoye silt loam (HnC)	Fine-loamy, mixed, mesic Glossoboric Hapludalf	9.0
				Honeoye silt loam (HnB)	Fine-loamy, mixed, mesic Glossoboric Hapludalf	89.7
Seneca 1	14.97	70	42.81N, 76.91W	Madalin and Odessa silty clay loams (Ma)	Fine, illitic, mesic Mollic Ochraqualf	0.6
				Ilion silty clay loam (Is)	Fine-loamy, mixed, mesic Mollic Ochraqualf	25.5
				Lakemont silty clay loam (LcA)	Fine, illitic, mesic Udollic Ochraqualf	0.2
				Ovid silt loam (OvA)	Fine-loamy, mixed, mesic Aeric Ochraqualf	2.6
				Cazenovia silt loam (CeB)	Fine-loamy, mixed, mesic Glossoboric Hapludalf	16.5
				Darien-Danley-Cazenovia silt loams (DdB)	Fine-loamy, mixed, mesic Aeric Ochraqualf	54.6
Seneca 2	5.67	37	42.89N, 76.89W	Collamer silt loam (ClB)	Fine-silty, mixed, mesic Glossoboric Hapludalf	5.2
				Collamer silt loam (CoB)	Fine-silty, mixed, mesic Glossoboric Hapludalf	14.7
				Dunkirk silt loam (DuB)	Fine-silty, mixed, mesic Glossoboric Hapludalf	71.3
				Collamer silt loam (CoA)	Fine-silty, mixed, mesic Glossoboric Hapludalf	8.8
Seneca 3	7.29	28	42.86N, 76.89W	Collamer silt loam (ClB)	Fine-silty, mixed, mesic Glossoboric Hapludalf	100.0

[a]Soil Survey map unit identification shown in parenthesis. Differences between the same soil types are due to slope (e.g. HnB versus HnC).

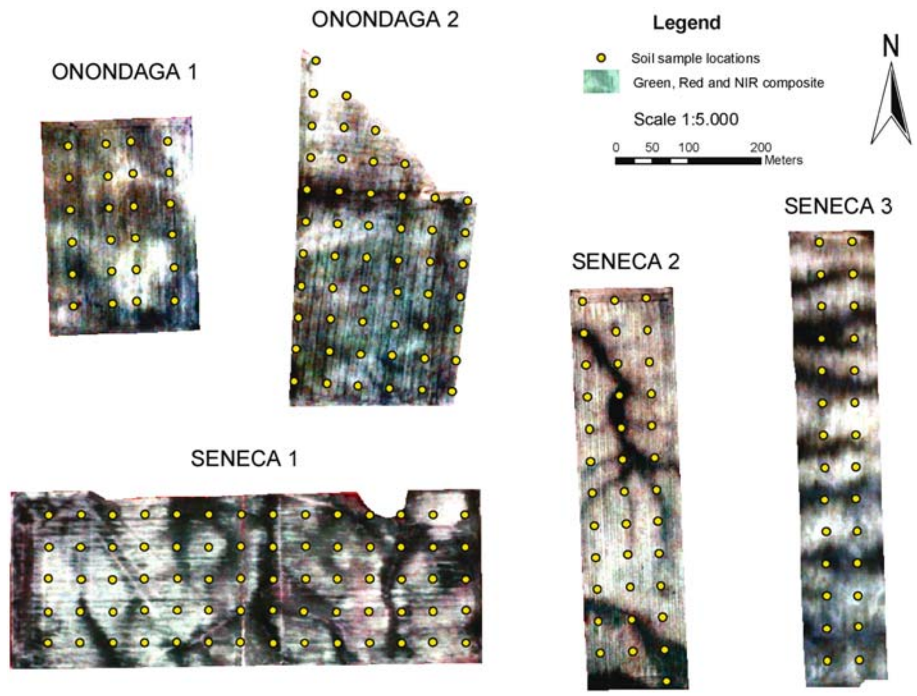

Figure 1. Bare soil reflectance images and soil sampling locations for each research site.

nitrogen fertilization rates was evaluated through field scale strips involving combinations of two maize hybrids and two nitrogen fertilization rates. A split-planter technique with 12-row planters was used to obtain 12 adjacent rows of one hybrid alternated with 12 adjacent rows of the other, at a row spacing of 0.76 m. Two rates of sidedress nitrogen were applied to alternate bands of six rows of maize each, resulting in the twelve adjacent rows of one hybrid subdivided into six rows of low N and six rows of high N (Figure 2). In total there were 9, 11, 12, 7 and 6 field scale replications of each treatment at the Onondaga 1, Onondaga 2, Seneca 1, Seneca 2 and Seneca 3 study sites, respectively.

The maize hybrids used were Pioneer 37M81 and Pioneer 3752, which have the following characteristics, respectively: 1210 and 1200 growing degree units to silk, 2320 and 2320 growing degree units to physiological maturity, ratings of 8 and 7 for yield at maturity, ratings of 8 and 6 for adaptability to high population density, ratings of 7 and 7 for adaptability to low population density and ratings of 7 and 7 for tolerance to drought (based on a scale from 1 to 9, 1 being poor, 9 being excellent; Pioneer Hi-Bred International, Inc., 2002). These hybrids were selected because they had shown hybrid by location interactions under New York conditions (D. Specker, personal communication).

Primary and secondary tillage were performed in the spring at all sites. Maize was planted in early to mid May at a rate of 80,000 kernels ha^{-1}. After planting, Cornell-recommended pest management practices were implemented to control insects and

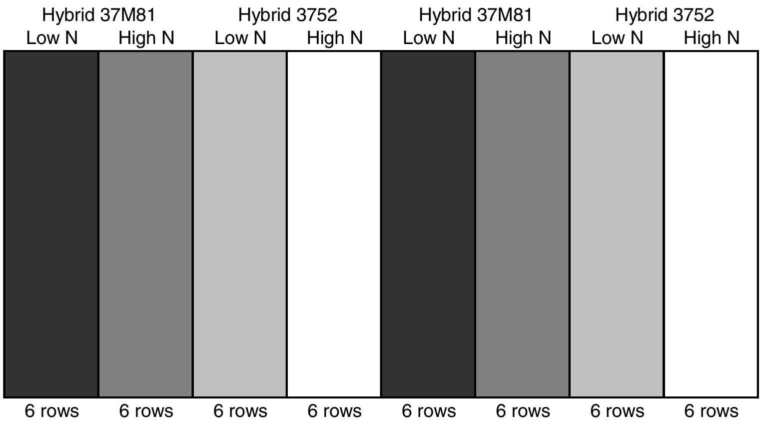

Figure 2. Generalized experimental design for each research site. Replications of each treatment were: 9 for Onondaga 1, 11 for Onondaga 2, 12 for Seneca 1, 7 for Seneca 2 and 6 for Seneca 3.

weeds (Cornell Cooperative Extension, 1998, 1999, 2000). The only field that suffered serious weed infestation was Seneca 1 in 1999, which was reflected in the yield harvested and in the bare soil aerial image taken that year.

Sidedress nitrogen was applied as liquid urea ammonium nitrate in early July each year (after soil sampling). At the three Seneca sites, sidedress N rate varied according to starter fertilization rates and N credit from cropping history (Table 2). Approximately 30 kg N ha^{-1} above and below the Cornell-recommended rate (135 kg N ha^{-1} for maize following soybeans and 160 kg N ha^{-1} for maize following maize; Cornell Cooperative Extension, 1998) were applied. In 1999, totals of approximately 110 and 170 kg N ha^{-1} were applied, while in 2000 and 2001, totals of approximately 130 and 185 kg N ha^{-1} were applied as the low and high N rates, respectively.

The N fertilization rates were lower at the Onondaga sites as it was estimated that 120 and 20 kg N ha^{-1} remained available for crop growth from the preceding fall and spring manure applications, respectively (Cox and Cherney, 2002). In 1999, the preceding alfalfa crop was estimated to provide 55 kg N ha^{-1}, and pre-sidedress

Table 2. Starter, Sidedress and Total N application rates for each research site

	Starter N fertilizer (kg N ha^{-1})			Sidedress N fertilizer (kg N ha^{-1})						Total N fertilization (kg N ha^{-1})					
				1999		2000		2001		1999		2000		2001	
Site	1999	2000	2001	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Onondaga 1	29	27	31	0	0	0	56	0	56	29	29	27	83	31	87
Onondaga 2	22	27	31	0	0	0	56	0	56	22	22	27	83	31	87
Seneca 1	65	45	45	56	112	84	140	84	140	121	177	129	185	129	185
Seneca 2	56	34	45	56	112	95	151	84	140	112	168	129	185	129	185
Seneca 3	39	34	39	67	123	95	151	90	146	106	162	129	185	129	185

nitrate tests (Magdoff, 1991) indicated a field average of 100 mg kg^{-1} NO_3-N, so no sidedress nitrogen was applied that year (Table 2). In 2000 and 2001, N credit from alfalfa was estimated to be low (16 kg N ha^{-1} in 2000 and 0 kg N ha^{-1} in 2001), so 56 kg N ha^{-1} was sidedressed as the high N rate treatment, while the low N rate treatment received no additional nitrogen. In total, the low N rate treatment received approximately 170 kg N ha^{-1}, while the high N rate treatment received about 225 kg N ha^{-1} in 2000 and 2001.

Differences in yield between the two nitrogen rates serve as an indicator of localized N fertilizer response, which generally depends on growing-season weather conditions (Sogbedji *et al.*, 2001), and was included in the experimental design in order to evaluate the potential for site-specific N application (Katsvairo *et al.*, 2003a,b).

Soil sampling

Soil samples were taken during mid June of 1999, 2000 and 2001 based on a 45 by 45 m regular grid (Figure 1). Sample locations were identified and their coordinates were recorded in 1999 using a Trimble Pathfinder Pro XRS differentially-corrected global positioning (DGPS) unit (Trimble, Sunnyvale, CA, USA) with a horizontal accuracy of < 1 m in the field (Trimble Navigation Limited, 1998). The same DGPS unit was used in 2000 and 2001 to locate the original sample locations for repeat soil sampling. A total of 10 soil cores taken to a depth of 305 mm within a radius of 3 m of each sample location were composited, sub-sampled, and analyzed for: pH (in water), organic matter content (OM, based on loss on ignition), and plant available P, K, and NO_3 after extraction with Morgan's solution (Cornell University Nutrient Analysis Laboratory, 2002). No lime was applied during this study, and P and K fertilizer was applied at uniform rates based on field-average soil test results at the Seneca sites.

Aerial image analysis

Color-infrared georeferenced digital aerial images of bare soil (pre-emergence) were taken by Emerge/MPower[3] (Andover, MA, USA) during May 1999 and June 2000. The image resolution was 1 by 1 m pixels on the ground, and provided information on green (510–600 nm), red (600–700 nm) and near-infrared (800–900 nm) reflectance from the soil surface (Emerge, 2002). The images were received in geo-TIFF format and imported into ERDAS IMAGINE 8.1 (ERDAS, Atlanta, GA USA), where they were cropped to the extent of each field and the individual bands were extracted in order to treat them as separate layers of information. Principal component analysis was then used to assess the data structure of the bands, and to combine all three bands into one new image for each field. The data were then exported to ESRI grid format and incorporated into a GIS (ArcGIS 8.1, Environmental Systems Research Institute, Redlands, CA, USA).

Yield monitor data

An Ag Leader 2000$^{\text{TM}}$ yield monitor was used at the Seneca 2 and 3 sites, while John Deere GreenStar$^{\text{TM}}$ yield monitors were used at the Onondaga 1 and 2 and Seneca 1 sites. The yield monitors were linked to DGPS receivers and used to monitor the harvest of six rows (one entire treatment, Figure 2) done in one continuous pass, with yield measurements taken every second. Yield monitors were calibrated at the start of each field harvest and intermittently throughout the process for both grain flow and grain moisture content. Weigh wagons equipped with calibrated load cells were used to compare the yields of each pass (one hybrid and one N rate) with the average yield estimated by the yield monitor. Differences between the two measurements were always below 3% (Katsvairo *et al.* 2003a). Yield data were imported into the GIS as point files, where head and side-lands were excluded from each dataset. Treatments were then separated into individual layers of information, giving rise to continuous rows of points separated by approximately 18 m from each other, across each field.

To reduce localized errors in yield measurements (Blackmore and Moore, 1999; Arslan and Colvin, 2002), an 18 by 18 m non-overlapping moving window was used to calculate local yield means. This procedure smoothed the yield data and produced a regular 18 by 18 m grid of points for each treatment. Values from all treatments in the field were then joined based upon their spatial location, generating one 18 by 18 m grid of points containing information for all four treatments in a given year. New yield variables were then defined as follows:

$$\mathrm{YIELD} = \frac{\mathrm{Yield}_{37M81,\mathrm{High}N} + \mathrm{Yield}_{3752,\mathrm{High}N}}{2} \tag{1}$$

$$\begin{aligned}\mathrm{HRESP} = &\left[\frac{\mathrm{Yield}_{37M81,\mathrm{High}N} + \mathrm{Yield}_{37M81,\mathrm{Low}N}}{2}\right] \\ &- \left[\frac{\mathrm{Yield}_{3752,\mathrm{High}N} + \mathrm{Yield}_{3752,\mathrm{Low}N}}{2}\right]\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{NRESP} = &\left[\frac{\mathrm{Yield}_{37M81,\mathrm{High}N} + \mathrm{Yield}_{3752,\mathrm{High}N}}{2}\right] \\ &- \left[\frac{\mathrm{Yield}_{37M81,\mathrm{Low}N} + \mathrm{Yield}_{3752,\mathrm{Low}N}}{2}\right]\end{aligned} \tag{3}$$

HRESP and NRESP refer to hybrid and nitrogen fertilization response, respectively. $\mathrm{Yield}_{37M81,\ \mathrm{High}N}$ represents the yield of hybrid 37M81 under the high nitrogen rate, etc. YIELD was determined by using the results of the high N treatments only, so that it would represent maize yield unaffected by possible nitrogen limitations.

Site-specific weather data, including precipitation and growing-degree days (GDD) were obtained from Emerge/MPower[3] for the five study sites.

Geostatistical analysis

The distributions of soil fertility parameters and yield variables were checked for normality using histograms and normal probability plots and were log-transformed where necessary. Trend analysis was also performed, but no significant field-scale trends were observed. Semivariograms, considering anisotropy, were modeled to half the maximum distance for the sampling grid in each field using the Geostatistical Analyst Extension in ArcGIS 8.1.

Spherical semivariogram models were found to give adequate fits to all the soil and yield variables that were modeled. Ordinary kriging was performed in order to generate geographically referenced soil fertility and yield variable maps within the GIS framework for joint analysis with the other sources of data. Grid cell size for the kriged maps was set to 1 by 1 m.

Following Cambardella and Karlen (1999), the semivariogram models were grouped into four spatial dependence classes by expressing the nugget as a percentage of the total sill (sill plus nugget) for each model. Strong, moderate, weak and random spatial dependence classes were defined as values of ≤25%, between 25% and 75%, between 75% and 99% and 100%, respectively.

GIS and statistical analysis

In order to construct one data set containing all the variables of interest at a common spatial scale, circles of 10 m radius were centered on each soil sample location. Aerial image data (green, red, near infrared and the first and second principal components of the PCA analysis, denoted PC1 and PC2) and kriged yield variables (YIELD, HRESP and NRESP) were averaged over each circle. Soil test values (pH, P, K, OM and NO_3, which were sampled from a location at the center of each circle) were deemed to adequately represent their corresponding circular areas, regardless of the spatial structure modeled in their semivariograms, so their values were combined directly with the average values of the aerial image and yield variables. This resulted in a dataset containing soil fertility, aerial image and yield variable values for each soil sampling location in each field (211 locations in total). Correlations were then computed to assess the relationships between these three sources of data. This method provided an adequate number of points per field (Table 1), while reducing the effect of spatial autocorrelation of the variables on the results of the correlation analyses.

Results and discussion

Within any year, precipitation (Table 3) and GDD were very similar for all five fields. Important differences occurred between years: 1999 and 2001 were both dry, while 2000 experienced more than twice the precipitation and approximately 10% less GDD for all fields. In general, total GDD at each site was fairly constant over the 3 years of the study, with an average of 1396 and a standard deviation of 82 (°C).

Summary statistics were developed for soil, aerial image and yield variables (Table 4). The soil fertility values shown in this table are field-wide averages based on all of the soil samples taken at each field. The distributions of individual sample

Table 3. Precipitation for each research site during the 1999, 2000 and 2001 growing seasons

	Onondaga 1 Precip. (mm)	Onondga 2 Precip. (mm)	Seneca 1 Precip. (mm)	Seneca 2 Precip. (mm)	Seneca 3 Precip. (mm)
1999					
Apr	60	60	62	61	61
May	33	33	34	36	35
June	55	55	64	71	67
July	97	96	83	83	83
Aug	57	55	62	76	70
Sept[a]	–	–	–	–	–
Total	302	299	305	327	316
2000					
Apr	122	121	109	115	113
May	168	170	160	168	166
June	108	109	121	118	119
July	144	144	213	182	193
Aug	78	80	98	89	91
Sept	119	114	129	128	118
Total	739	738	830	800	800
2001					
Apr	30	30	30	30	30
May	37	38	38	38	41
June	90	89	77	77	79
July	53	53	48	48	57
Aug	90	90	70	70	41
Sept	–	–	–	–	–
Total	300	300	263	263	248

[a]Maize attained black layer formation during mid-September in 1999 and 2001, so September precipitation was not included for those years.

results for pH, P, K and NO_3 were examined for each field in order to assess the need for site-specific application of lime and fertilizers, based on the guidelines published by Cornell Cooperative Extension. The majority of the individual sample values for pH fell in the adequate and high categories. Few samples in each field warranted the application of lime to increase pH to optimal levels for maize growth. Most individual results for P fell in the medium to high ranges for the Onondaga sites, and in the medium range for the Seneca sites. The majority of the results for K were in the high to very high ranges for the Onondaga sites, and in the medium to high ranges for the Seneca sites. Although results for pH, P and K were generally consistent from year to year, soil NO_3 contents showed high levels of annual variation (Table 4). At the manured Onondaga sites, nitrate contents in the dry years 1999 and 2001 were high enough to pose leaching concerns. Values at the Seneca sites tended to be much lower, and many samples indicated a need for sidedress N (< 25 mg kg^{-1}). This analysis indicated that several areas of the fields justified lime and fertilizer applications, even though this was not reflected in the field-wide averages.

Table 4. Summary Statistics for soil, aerial image and yield data for each research site

	Onondaga 1			Onondaga 2			Seneca 1			Seneca 2			Seneca 3		
Variable[a]	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
pH 1999	6.38	0.49	0.08	6.55	0.57	0.09	7.83	0.20	0.03	6.76	0.50	0.07	6.79	0.60	0.09
P 1999	12.00	4.96	0.41	38.54	20.59	0.53	11.04	8.11	0.73	13.46	5.40	0.40	7.60	3.75	0.49
K 1999	196.16	51.68	0.26	357.60	85.31	0.24	144.87	29.45	0.20	133.18	30.37	0.23	137.98	22.94	0.17
OM 1999	4.18	0.81	0.19	4.17	0.64	0.15	3.98	0.99	0.25	2.52	0.64	0.25	2.60	0.42	0.16
NO_3 1999	117.97	29.42	0.25	104.78	24.21	0.23	19.48	11.70	0.60	29.53	6.57	0.22	39.09	12.54	0.32
pH 2000	6.70	0.51	0.08	6.90	0.50	0.07	7.67	0.24	0.03	6.83	0.42	0.06	6.92	0.62	0.09
P 2000	10.97	5.09	0.46	22.90	17.02	0.74	7.57	6.26	0.83	10.93	4.08	0.37	7.20	3.74	0.52
K 2000	275.10	90.77	0.33	369.34	103.16	0.28	103.84	33.95	0.33	138.03	35.00	0.25	100.80	28.64	0.28
OM 2000	4.05	0.94	0.23	3.84	0.65	0.17	3.69	0.95	0.26	2.42	0.66	0.27	2.50	0.43	0.17
NO_3 2000	39.15	14.73	0.38	30.84	10.37	0.34	17.38	6.29	0.36	18.89	6.46	0.34	15.36	5.76	0.37
pH 2001	6.51	0.52	0.08	6.73	0.54	0.08	7.89	0.29	0.04	6.86	0.41	0.06	7.09	0.60	0.08
P 2001	15.12	6.36	0.42	24.59	18.01	0.73	9.34	8.41	0.90	8.19	3.04	0.37	6.20	3.19	0.51
K 2001	362.60	109.19	0.30	366.57	101.48	0.28	126.88	38.67	0.30	112.22	25.79	0.23	98.80	20.46	0.21
OM 2001	4.29	0.87	0.20	3.61	0.61	0.17	4.00	1.04	0.26	2.29	0.60	0.26	2.48	0.45	0.18
NO_3 2001	114.57	23.11	0.20	58.86	11.62	0.20	18.99	10.60	0.56	14.28	3.31	0.23	12.96	3.41	0.26
GREEN[b] 1999	156.74	14.06	0.09	146.27	22.26	0.15	187.06	19.47	0.10	198.91	25.39	0.13	194.82	21.92	0.11
RED 1999	175.91	16.83	0.10	142.01	22.85	0.16	187.29	20.29	0.11	196.00	29.22	0.15	192.74	24.11	0.13
NIR 1999	117.79	13.35	0.11	39.92	17.85	0.45	181.47	21.69	0.12	176.95	45.95	0.26	169.37	32.32	0.19
GREEN 2000	180.93	13.07	0.07	130.02	36.59	0.28	157.73	31.83	0.20	145.09	34.96	0.24	171.92	24.27	0.14
RED 2000	184.87	20.83	0.11	104.08	40.22	0.39	144.43	35.55	0.25	121.24	39.20	0.32	159.32	28.26	0.18
NIR 2000	91.32	11.37	0.12	64.92	25.95	0.40	92.10	30.75	0.33	100.17	42.84	0.43	140.96	32.44	0.23
PC1[c] 1999	113238	111	0.00	112836.35	204.73	0.00	113462.95	96.12	0.00	113410.73	263.92	0.00	113428.15	166.10	0.00
PC2 1999	109581	968	0.01	111959.84	64.94	0.00	52094.87	43125.81	0.83	111973.75	89.37	0.00	111623.62	106.63	0.00
PC1 2000	113260	116	0.00	112722.18	352.59	0.00	113018.21	311.45	0.00	112876.35	371.72	0.00	113221.11	230.18	0.00
PC2 2000	110671	92	0.00	107110.73	5359.30	0.05	110797.01	518.99	0.00	111034.88	110.48	0.00	111122.38	64.00	0.00
YIELD 1999	8.85	1.16	0.13	9.71	0.56	0.06	3.24	1.16	0.36	6.11	1.02	0.17	6.57	1.39	0.21

HRESP 1999	0.21	0.18	0.86	0.52	0.23	2.31	0.07	0.39	5.54	0.24	0.23	0.97	−0.27	0.22	−0.82
NRESP 1999	NA	NA	NA	NA	NA	NA	0.03	0.23	7.51	−0.04	0.22	−5.55	−0.11	0.15	−1.38
YIELD 2000	7.06	0.80	0.11	7.09	0.26	0.04	6.87	0.68	0.10	7.72	0.41	0.05	7.40	0.32	0.04
HRESP 2000	0.12	0.13	1.08	1.17	0.15	0.13	0.42	0.23	0.53	0.57	0.44	0.77	0.23	0.43	1.83
NRESP 2000	0.31	0.20	0.65	0.00	0.21	−49.87	1.15	0.29	0.25	0.15	0.25	1.63	0.37	0.17	0.47
YIELD 2001	8.00	1.50	0.19	10.02	0.36	0.04	8.09	0.45	0.06	8.67	0.92	0.11	7.34	1.35	0.18
HRESP 2001	1.08	0.54	0.50	0.55	0.23	0.41	−0.16	0.30	−1.84	−0.11	0.23	−2.14	−0.40	0.19	−0.48
NRESP 2001	0.08	0.03	0.38	0.11	0.25	2.31	0.38	0.23	0.60	0.13	0.22	1.64	0.48	0.23	0.47

[a]Units for soil fertility and yield variables are kg ha^{-1} and Mg ha^{-1}, respectively. Data for OM are expressed as % by weight.
[b]Green, Red and NIR reflectance from the soil surface has a range of 0 to 255, with 0 representing no reflectance and 255 indicating 100% reflectance.
[c]PC1 and PC2 are the result of weighted linear combinations of Green, Red and NIR reflectance, using the coefficients shown in Table 6.

Spatial patterns of soil fertility and yield variables

Semivariogram analysis of soil fertility and yield data showed spatial dependences ranging from strong to random (data not shown, Magri, 2003). Most models (78 out of 118) were isotropic (ratio of major and minor axis = 1). Although it is difficult to compare semivariogram models due to differences in sampling schemes, analysis methods and specific semivariogram models used in different studies, the parameters obtained based on our data are similar to those reported by others (Cambardella and Karlen, 1999; McBratney and Pringle, 1999; and Whelan and McBratney, 2000).

A summary of the semivariograms for soil and yield variables (Table 5) shows frequent occurrences of strong and moderate spatial correlation at the manured Onondaga sites, while the Seneca sites had a high percentage of moderate spatial relationships, suggesting that potential for site specific management and practical management zone identification exists at all sites.

Values for pH showed the greatest tendency to strong spatial relationships, especially at the Onondaga sites. Moderate spatial relationships predominated for P at all sites, while K showed a wide range of spatial dependence at the Onondaga sites, but 100% moderate spatial relationships at the Seneca sites. Both OM and NO_3 showed greater occurrences of moderate than other spatial relationships for all sites. Average ranges of influence were between 180 and 266 m, suggesting that soil fertility management zones in these fields should generally be between 2.5 and 5.5 ha in size, depending on the soil property in question (calculated by taking half the semivariogram range to represent the radius of each management zone).

Yield variables showed significant variation over time and from field to field (Table 4). Yield showed a clear tendency towards strong and moderate spatial dependence, behaving similarly at all sites. N response generally had greater spatial dependence at the manured Onondaga sites, which may possibly have been related to non-uniform manure applications. Spatial dependence of hybrid response was similar for all sites, with a tendency towards moderate and weak spatial relationships.

From this analysis, the spatial relationships for pH and P indicate good potential for site-specific management, but for K this holds only for the cash crop sites (Seneca 1, 2 and 3). NO_3 showed limited potential for site-specific application, mostly due to large and apparently unpredictable variations in spatial patterns from year to year. N and hybrid response data also showed limited potential for site-specific management, which is in accordance with the conclusions of Katsvairo *et al.* (2003a) and Kahabka *et al.* (2004).

Aerial image analysis

Field-scale means for green, red and near infrared reflectance, and PC1 and PC2 values were very consistent over time and from field to field (Table 4). The only exception was PC2 for Seneca 1 in 1999, due to significant weed infestation. The first two principal components explained nearly all the variability in the data (Table 6). PC1 alone generally explained over 96% of the variability. The only exception was the Seneca 1 site in 1999 as a result of partial weed cover at the time the image was

Table 5. Summary of semivariogram model parameters for soil fertility and yield variables

	Spatial Dependence Class (% of models in each class)									
	Strong		Moderate		Weak		Random		Average range (m)	
Parameter	Onondaga	Seneca	Onondaga	Seneca	Onondaga	Seneca	Onondaga	Seneca	Onondaga	Seneca
PH	83.3	11.1	16.7	77.8	0.0	0.0	0.0	11.1	180.8	202.2
P	33.3	0.0	50.0	66.7	0.0	33.3	16.7	0.0	230.8	236.7
K	33.3	0.0	0.0	100.0	16.7	0.0	50.0	0.0	212.3	208.9
OM	0.0	0.0	100.0	77.8	0.0	22.2	0.0	0.0	266.7	212.2
NO_3	16.7	22.2	50.0	55.6	16.7	0.0	16.7	22.2	208.3	233.3
YIELD	50.0	22.2	50.0	66.7	0.0	11.1	0.0	0.0	198.3	156.1
NRESP	0.0	0.0	75.0	11.1	0.0	33.3	25.0	55.6	207.5	168.9
HRESP	0.0	0.0	50.0	44.4	33.3	55.6	16.7	0.0	155.0	173.3

Table 6. Principal component analysis of bare soil reflectance for the five research sites

	1999		2000	
	PC1	PC2	PC1	PC2
Onondaga 1				
Nir	0.51[a]	−0.78	0.44	−0.90
Red	0.65	0.07	0.75	0.32
Green	0.56	0.63	0.50	0.30
% Var. explained	96.29	3.71	93.19	6.81
Onondaga 2				
Nir	0.60	−0.78	0.43	−0.88
Red	0.59	0.27	0.67	0.15
Green	0.54	0.57	0.60	0.45
% Var. explained	96.03	3.97	97.81	2.19
Seneca 1				
Nir	0.57	−0.82	0.54	−0.84
Red	0.59	0.40	0.62	0.42
Green	0.57	0.41	0.56	0.34
% Var. explained	81.31	18.69	98.13	1.87
Seneca 2				
Nir	0.76	−0.66	0.63	−0.77
Red	0.49	0.54	0.58	0.39
Green	0.43	0.52	0.52	0.51
% Var. explained	97.44	2.56	98.85	1.15
Séneca 3				
Nir	0.70	−0.68	0.65	−0.76
Red	0.53	0.27	0.57	0.44
Green	0.49	0.68	0.50	0.49
% Var. explained	97.54	2.46	98.92	1.08

[a]Eigenvectors indicate relative loading of the spectral band to the principal component.

taken. Apart from partially obscuring the bare soil reflectance captured by the image, the weeds also caused high green and near infrared band reflectance values in the parts of the field they had infested, increasing data variability and decreasing the amount of variation explained by the first principal component. Hence, the Seneca 1 data were analyzed using PC1 from the image taken in 2000 instead of 1999. PC1 from 1999 images were used for all other fields.

In all cases, PC1 was an evenly weighted combination of all three bands, as evidenced by the commensurate eigenvectors for each, implying that PC1 images represent the general brightness or intensity of bare soil reflectance. Overall reflectance has been inversely related to both soil surface organic matter content (Varvel *et al.*, 1999) and to surface soil moisture (Muller and Décamps, 2000; Senay *et al.*, 2000; Lobell and Asner, 2002). The principal component analysis therefore suggests that the more complex processing required to analyze three-band images may not provide farmers with better information on field patterns of these properties than panchromatic images would, and that more sophisticated remote sensing methods may be required to obtain useful data on soil fertility patterns (Ehsani *et al.*, 1999; Chang *et al.*, 2001).

Correlations between soil fertility parameters, aerial image data and yield variables

Correlations of soil variables measured over the duration of the study were determined in order to assess temporal consistency. This is an important consideration in precision agriculture, as high temporal consistency provides confidence in the reality of fertility patterns, and may reduce the need for frequent soil sampling and soil fertility mapping. All soil properties showed high temporal correlation coefficients, the majority of which were highly significant (Table 7). The notable exception was NO_3, which showed high variability and almost no temporal consistency from year to year, which is explained by annual weather patterns during the study. Year 2000 exhibited high rainfall and low temperatures, which cause lower N mineralization rates and higher losses from leaching and denitrification (Sogbedji *et al*., 2001), while 1999 and 2001 were drier and warmer years, resulting in higher soil nitrate levels.

Cross-correlations between soil variables generally lacked consistency, except for P and K, which showed significant correlation for all years and all fields (Table 8). This supports the notion that fertility patterns for P and K are similar and that these nutrients may be managed jointly within common management zones in both dairy and cash crop systems, as is often done in practice. Correlation coefficients between bare soil reflectance (PC1) and OM were consistently negative, averaging −0.63 over all fields and years (Table 9), indicating that aerial imagery may provide potentially useful information on this fundamental contributor to soil health (Magdoff and van Es, 2000).

Significant correlations between PC1 and other soil fertility parameters (Table 9) can be explained through their correlations with soil organic matter content. For example, PC1 showed significant negative correlations with NO_3 for both Onondaga 2 and Seneca 1 in 1999, for Seneca 1 in 2000 and Onondaga 2 in 2001 (Table 9). However, there were significant positive correlations between OM and NO_3 for those fields and years (Table 8), suggesting that the relationships between PC1 and NO_3 were not direct, but rather the result of relationships between PC1 and OM, and OM and NO_3 contents. The same situation occurred for K at Seneca 1 in all three years, P at Seneca 1 in 1999 and 2000 and for pH at Seneca 2 and Seneca 3 in all three years. Overall, the aerial image data did not correlate well enough with pH, P, and K to serve as a predictor for fertility management zones.

Correlations between soil properties and yield showed general inconsistencies among years and fields (Table 10), suggesting that these soil properties alone do not constitute good predictors of yield. Remediation of soil fertility patterns in a field does not necessarily translate into uniform yields across the field, making it challenging to define yield prediction models (Varvel *et al*., 1999). There were, however, some relationships between soil variables and yield that were common for the dry years (1999 and 2001). At Onondaga 1 and 2, pH was well correlated to yield in 1999 and 2001, and for Onondaga 1 and Seneca 1 and 2 OM was significantly correlated to yield in 1999 and 2001. The lack of significant correlations between these variables and yield in 2000 and the fact that 2000 was significantly different from 1999 and 2001 in terms of weather conditions suggests that pH, OM, drainage patterns and growing season weather are jointly correlated with yield in these fields. Soil P and K generally showed little correlation with yield.

Table 7. Temporal correlation coefficients for soil properties among the years 1999, 2000 and 2001

	Onondaga 1		Onondaga 2		Seneca 1		Seneca 2		Seneca 3	
	X 2000	X 2001	X 2000	X 2001	X 2000	X 2001	X 2000	X 2001	X 2000	X 2001
pH 1999	0.86***	0.95***	0.91***	0.95***	0.80***	0.81***	0.85***	0.80***	0.95***	0.95***
pH 2000		0.91***		0.91***		0.83***		0.83***		0.92**
P 1999	0.65**	0.57**	0.83***	0.80***	0.68***	0.58***	0.41*	0.51**	0.91***	0.80***
P 2000		0.42*		0.78***		0.76***		0.76***		0.75***
K 1999	0.81***	0.81***	0.53***	0.67***	0.63***	0.63***	0.67***	0.87***	0.72***	0.76***
K 2000		0.73***		0.57***		0.72***		0.71***		0.67***
OM 1999	0.90***	0.95***	0.88***	0.91***	0.97***	0.91***	0.95***	0.96***	0.84***	0.83***
OM 2000		0.94***		0.90***		0.91***		0.95***		0.89***
NO_3 1999	0.20	0.58**	0.29*	0.45**	0.44***	−0.01	0.13	0.09	0.26	0.46*
NO_3 2000		0.32		0.34*		0.17		0.62***		0.55**

*, **, ***: signifiacant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.

Table 8. Cross-correlations between soil properties in 1999, 2000 and 2001

	Onondaga 1				Onondaga 2				Seneca 1				Seneca 2				Seneca 3			
	pH	P	K	OM	pH	P	K	OM	pH	P	K	OM	pH	P	K	OM	pH	P	K	OM
1999																				
P	0.52**				0.69 ***				0.12				0.59 ***				0.13			
K	−0.10	0.58 **			−0.03	0.52 ***			−0.09	0.64 ***			0.10	0.36 *			−0.30	0.56 **		
OM	−0.05	0.17	−0.10		−0.14	0.02	0.03		−0.09	0.40 ***	0.42 ***		0.40 **	0.47 **	0.44 **		0.52 **	0.36	0.23	
NO_3	−0.11	−0.03	0.27	0.39	0.17	0.40 **	0.49 ***	0.42 **	0.03	0.52 ***	0.55 ***	0.67 ***	−0.27	0.19	0.17	0.24	−0.35	0.24	0.35	0.13
2000																				
P	0.06				0.50 ***				0.26 *				0.36 *				0.05			
K	−0.42	0.64 ***			−0.33 *	0.32 *			−0.15	0.57 ***			−0.06	0.35 *			−0.54 **	0.38 *		
OM	−0.27	0.38	0.12		−0.27	0.13	0.34 *		−0.11	0.30 **	0.40 ***		0.31	0.43 **	0.50 **		0.43 *	0.55 **	0.03	
NO_3	−0.74	0.26	0.59 **	0.21	−0.28 *	0.20	0.44 ***	0.55 ***	−0.04	0.46 ***	0.30 *	0.53 ***	−0.32	−0.04	−0.36 *	−0.23	−0.29	0.49 **	0.47 *	0.21
2001																				
P	0.43 *				0.44 ***				0.12				0.16				0.03			
K	−0.31	0.49 *			0.32 *	0.46 ***			−0.23	0.58 ***			−0.09	0.41 **			−0.58 ***	0.47 *		
OM	−0.15	0.17	−0.14		0.51 ***	0.11	0.47 ***		−0.04	0.17	0.30 *		0.39 **	0.58 ***	0.43 **		0.38 *	0.59 ***	0.08	
NO_3	−0.07	0.23	0.18	0.40	0.55 ***	0.47 ***	0.57 ***	0.56 ***	−0.26 **	0.33 **	0.52 ***	0.02	−0.16	0.13	−0.27	−0.11	−0.37	0.57 ***	0.41 *	0.26

*, **, ***: significant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.

Table 9. Soil property correlations with bare soil PC1

	Onondaga 1	Onondaga 2	Seneca 1	Seneca 2	Seneca 3
	PC1 1999	PC1 1999	PC1 2000	PC1 1999	PC1 1999
1999					
PH	−0.36	−0.03	−0.07	−0.40 *	−0.53 **
P	−0.38	0.06	−0.27 *	−0.37 *	−0.18
K	0.12	−0.03	−0.35 **	−0.06	0.17
OM	−0.64 ***	−0.52 ***	−0.62 ***	−0.73 ***	−0.56 **
NO_3	−0.31	−0.45 ***	−0.55 ***	−0.03	−0.10
2000					
PH	−0.36	0.05	−0.13	−0.35 *	−0.57 ***
P	−0.33	0.12	−0.28 **	−0.17	−0.26
K	0.16	−0.13	−0.27 **	0.00	0.12
OM	−0.49 **	−0.52 ***	−0.62 ***	−0.74 ***	−0.68 ***
NO_3	0.29	−0.20	−0.40 ***	−0.08	0.05
2001					
PH	−0.37	−0.04	−0.12	−0.41 **	−0.47 **
P	−0.27	0.12	−0.10	−0.19	−0.30
K	0.27	−0.05	−0.27 **	0.04	0.19
OM	−0.62 ***	−0.61 ***	−0.64 ***	−0.71 ***	−0.74 ***
NO_3	−0.21	−0.29 **	0.04	0.06	−0.14

*, **, ***: significant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.

Highly significant correlations of HRESP and NRESP to soil variables were observed in some cases, but inconsistent patterns among years and fields indicate low predictive potential for site-specific N application and hybrid selection.

Analysis of yield consistency over time (Table 11) shows that site-specific yield measurements correlate well for the dry years 1999 and 2001. Yields of the wet year (2000) generally did not correlate well with 1999 or 2001 data or were negatively correlated. In wet years, lower elevations in the field are generally wetter, producing lower yields than higher (drier) areas, and vice versa for dry years. Only Seneca 3 showed significant positive correlations for site-specific yield between all three years, implying a consistent yield pattern across the field.

Correlation coefficients for yield variables and PC1 were not consistent (Table 12). Seneca 1 and 2 showed negative correlations between PC1 and yield in 1999 and 2001, and positive correlations in 2000, presumably reflecting the effect of drainage patterns and soil organic matter distributions on yield in dry and wet years, respectively. The other three sites do not show such clear annual patterns. For the Onondaga sites, this may in part be related to the high amounts of manure applied to these fields, and its effect on soil structure and water holding capacity. Hybrid and N response variables did not show consistent correlations to PC1, indicating that aerial imagery provided little information to support site-specific N application and hybrid selection.

Cross-correlations among HRESP, NRESP and YIELD were inconsistent and showed different behavior in each field and from year to year (Table 13). These results further corroborate the conclusions reached by Katsvairo *et al.* (2003a) regarding limited potential for site-specific hybrid selection and nitrogen fertilization.

Table 10. Correlations between soil and yield variables in 1999, 2000 and 2001

	Onondaga 1			Onondaga 2			Seneca 1			Seneca 2			Seneca 3		
	Yield	Hresp	Nresp	Yield	Hresp	Nresp	Yield	Hresp	Nresp	Yield	Hresp	Nresp	Yield	Hresp	Nresp
1999															
PH	0.538 **	−0.134	NA†	−0.438 ***	−0.416 **	NA	−0.083	−0.12	0.009	0.367 *†	0.241	0.448 **	−0.307	−0.432 *	−0.17
P	0.277	−0.31	NA	−0.275 *	−0.153	NA	0.316 **	−0.043	0.071	0.236	0.239	0.151	0.232	0.309	−0.276
K	0.279	−0.068	NA	0.151	0.122	NA	0.255 *	−0.089	−0.005	−0.058	−0.084	0.33 *	0.172	0.489 **	−0.304
OM	−0.408 *	−0.098	NA	−0.08	0.184	NA	0.63 ***	−0.046	−0.006	0.533 ***	−0.193	0.241	0.127	0.065	−0.33
NO_3	0.256	0.325	NA	−0.037	0.006	NA	0.686 ***	−0.235 *	0.073	0.129	−0.278	−0.28	0.592 ***	0.291	0.272
2000															
pH	−0.064	−0.459 *	−0.053	0.48 ***	0.087	0.369 **	−0.268 *	0.042	0.342 **	−0.514 ***	−0.371 *	−0.095	−0.52 **	−0.678 ***	0.474 *
P	0.194	−0.125	−0.002	0.45 ***	0.33 *	0.24	−0.042	0.112	−0.247 *	−0.104	0.047	−0.053	0.278	0.197	−0.28
K	0.269	0.224	0.061	0.017	0.407 **	0.076	0.055	0.255 *	−0.484 ***	0.273	0.267	0.138	0.563 **	0.609 ***	−0.471 *
OM	0.037	−0.041	0.181	0.121	0.482 ***	0.094	−0.197	−0.095	−0.012	0.008	−0.161	0.142	0.096	−0.085	−0.103
NO_3	0.302	0.418 *	0.196	0.147	0.434 ***	0.009	−0.147	0.091	−0.167	0.086	0.046	0.288	0.512 **	0.643 ***	−0.533 **
2001															
PH	0.506 *	−0.422 *	0.366	−0.439 ***	−0.039	−0.302 *	0.079	−0.185	−0.017	0.158	0.056	−0.195	−0.388 *	0.108	−0.282
P	0.277	−0.076	−0.007	−0.386 **	−0.313 *	−0.444 ***	−0.226	0.222	−0.137	0.373 *	0.193	−0.101	0.485 **	−0.409 *	0.19
K	0.079	0.014	−0.309	−0.123	0.042	−0.247	−0.202	0.387 ***	−0.152	−0.213	0.244	−0.233	0.294	−0.083	0.331
OM	−0.585 **	0.534 **	−0.203	−0.071	0.178	−0.196	0.49 ***	−0.115	0.333 **	0.353 *	0.02	−0.056	0.185	−0.205	0.07
NO_3	−0.009	−0.172	0.085	−0.179	−0.193	−0.351 *	−0.134	0.188	−0.079	0.201	0.353 *	−0.482 **	0.755 ***	−0.613 ***	0.243

*, **, ***: significant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.
† NA: not applicable (no N treatment at Onondaga sites in 1999).

Table 11. Temporal consistency correlations for yield variables among the years 1999, 2000 and 2001

	Onondaga 1		Onondaga 2		Seneca 1		Seneca 2		Seneca 3	
	X 1999	X 2000	X 1999	X 2000	X 1999	X 2000	X 1999	X 2000	X 1999	X 2000
Yield 2000	0.218		−0.14		−0.528 ***		0.011		0.818 ***	
Yield 2001	0.853 ***	0.195	0.594 ***	−0.174	0.575 ***	0.003	0.83 ***	0.202	0.969 ***	0.782 ***
Hresp 2000	−0.05		0.288 *		0.373 ***		−0.271		0.569 **	
Hresp 2001	−0.011	0.152	0.055	−0.002	0.423 ***	0.113	0.078	0.483 **	−0.506 **	−0.246
Nresp 2000	NA		NA		0.25 *		−0.37 *		−0.16	
Nresp 2001		0.425 *		0.013	0.309 **	0.354 **	0.229	0.162	−0.012	−0.567 **

*, **, ***: significant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.
NA: not applicable (no N treatment at Onondaga sites in 1999).

Table 12. Correlations between bare soil PC1 and yield variables

	Onondaga 1	Onondaga 2	Seneca 1	Seneca 2	Seneca 3
	PC1 1999	PC1 1999	PC1 2000	PC1 1999	PC1 1999
Yield 1999	−0.02	0.14	−0.58 **	−0.61 ***	−0.25
Hresp 1999	−0.21	0.02	0.20	−0.06	0.35
Nresp 1999	NA	NA	−0.07	−0.09	−0.13
Yield 2000	−0.11	−0.20	0.53 ***	0.26	−0.06
Hresp 2000	0.26	−0.36 **	−0.08	0.25	0.27
Nresp 2000	−0.07	0.07	0.01	−0.25	−0.11
Yield 2001	0.06	−0.17	−0.23	−0.48 **	−0.16
Hresp 2001	0.05	0.12	0.14	0.27	0.27
Nresp 2001	−0.14	0.23	−0.10	−0.29	0.09

*, **, ***: significant at the $\alpha = 0.05$, 0.01, and 0.001 error level, respectively.
NA: not applicable (no N treatment at Onondaga sites in 1999).

Table 13. Cross-correlations between yield variables

	Onondaga 1		Onondaga 2		Seneca 1		Seneca 2		Seneca 3	
	Yield	Hresp	Yield	Hresp	Yield	Hresp	Yield	Hresp	Yield	Hresp
1999										
HRESP	0.006		0.293 *		−0.399 ***		−0.262		0.434 *	
NRESP	NA	NA	NA	NA	0.187	−0.468 ***	0.053	0.237	0.33	0.036
2000										
HRESP	0.359		0.546 ***		0.182		0.338 *		0.675 ***	
NRESP	0.412 *	−0.106	0.084	0.136	−0.274 *	−0.211	0.447 **	−0.008	−0.801 ***	−0.609 ***
2001										
HRESP	−0.827 ***		0.085		−0.411 ***		−0.312		−0.761 ***	
NRESP	0.477 *	−0.402	0.621 **	0.586 ***	0.606 ***	−0.153	0.316	−0.622 ***	0.338	−0.35

*, **, ***: significant at the α = 0.05, 0.01, and 0.001 error level, respectively.

In light of the sources of variability found at the field scale, Whelan and McBratney (2000) concluded that both spatial and temporal variability should be considered in defining management zones, and that differential treatment based only on spatial information may increase the risk of economically and environmentally inappropriate actions. They also suggest that under high temporal variability, fields be treated as homogeneous management zones in order to reduce risk.

Conclusions

Although the creation of management zones within fields is challenging, several soil fertility parameters showed strong or moderate spatial structure in the field, indicating that grid soil sampling at a 2.5–5.5 ha scale may be used in the initial determination of soil fertility levels. Classifying and grouping areas according to their fertilization needs could then define management zones. Additionally, all soil fertility indicators proved to be highly consistent over time, except for NO_3 which was greatly influenced by annual weather patterns. This suggests that grid-based soil testing does not need be performed frequently to define management zones.

Aerial image data were closely related to both soil organic matter content and drainage patterns, both of which affect yield potential under varied climatic conditions. Bare soil imagery can be useful in determining areas of high or low yield potential under specific weather conditions, but the annual inconsistency of this relationship limits its predictive potential. Also, these images showed little correlation with soil fertility indicators and did not serve as good predictors of field-scale fertility patterns.

Yield response to hybrid selection and nitrogen fertilization rates were too variable to warrant recommendations regarding site-specific hybrid selection or nitrogen fertilization.

Annual weather variability proved to be an important driving factor influencing yield potential, yield harvested and soil nitrate distributions across the fields.

Based on the results of this study, we recommend site-specific management of lime, P and K based on (unaligned) grid-based soil testing, although this may be alternated with field-average sampling. Uniform rates of N application are recommended and fields are best planted with a single hybrid. These recommendations may be pertinent to similar soils, climatic and management conditions.

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