Need for a Soil-Based Approach in Managing Nitrogen Fertilizers for Profitable Corn Production

R. L. Mulvaney,* S. A. Khan, and T. R. Ellsworth

ABSTRACT

Nitrogen fertilization for corn (*Zea mays* L.) production has relied extensively on yield-based recommendations that were developed to represent regional averages, yet are routinely applied to individual fields, on the assumption that fertilizer N serves as the major supply for crop N uptake. Using data from 102 on-farm N-response studies, an evaluation was conducted of the Illinois proven-yield (PY) method for accuracy and economic profitability on a site-by-site basis. As additional objectives, the Illinois soil N test (ISNT) was evaluated for detecting whether N fertilization was economical, and for quantifying crop response to N fertilization relative to soil and management factors. For 18% of the site-years studied, N recommendations by the PY method were accurate to within 20 kg ha^{-1}, whereas 13% were underfertilized by 25 to 129 kg ha^{-1} (60 kg ha^{-1} on average) at a current cost of \$5 to \$170 ha^{-1} (\$75 ha^{-1} on average), and 69% were overfertilized by 21 to 235 kg ha^{-1} (103 kg ha^{-1} on average) at a cost of \$12 to \$130 ha^{-1} (\$57 ha^{-1} on average). The latter group included 30 site-years that were completely nonresponsive to N fertilization, all but two of which were predicted by site-average ISNT values assuming a critical test level of 230 mg kg^{-1}. This level was exceeded for 19 of 69 responsive site-years, mostly during 2001–2003 when corn followed soybean (*Glycine max* L. Merr.) with high plant populations. A higher critical test level would have been required under such conditions, owing to more extensive residue inputs that would promote microbial N immobilization, and increased crop uptake of mineralized soil N. The ISNT was significantly related to crop N requirement, and was the most powerful predictor of error in PY recommendations ($P < 0.001$).

Since the 1970s, N fertilizer recommendations for midwestern corn production have relied on a yield-based system, whereby an expected yield goal is multiplied by a constant factor (typically 19.4–24.2 kg N Mg^{-1} or 1.1–1.4 pound N bushel^{-1}), with adjustments to account for N credits from previous cropping or the recent use of manure (e.g., Illinois Agronomy Handbook, 2002). This system utilizes a mass balance approach that assumes constant efficiency in crop uptake of fertilizer and soil N (Stanford, 1973; Meisinger, 1984; Meisinger et al., 1992). Yield-based systems were originally intended as a first approximation in making generalized fertilizer N recommendations for long-term periods on a regional scale, but have been applied indiscriminately to fertilize individual fields in a particular growing season.

Implicit to yield-based N recommendations is the presumption that mineralization is a negligible source for crop N uptake, which would necessarily imply that yield in the absence of applied N supplies a fixed proportion of crop N uptake that is substantially less than that from fertilizer. Yet unfertilized (check) plot yields in N-response studies often exceed the yield increase obtained with fertilization (Lory and Scharf, 2003), and in many of these studies, sites have been detected where corn is completely nonresponsive to fertilizer N (e.g., Bundy and Malone, 1988; Blackmer et al., 1989; Fox et al., 1989; Schmitt and Randall, 1994). Such sites have often been excluded in averaging response data to evaluate yield-based N recommendations (e.g., Vanotti and Bundy, 1994; Brown, 1996; Lory and Scharf, 2003; Nafziger et al., 2003), but even so, the recommended rates tend to be excessive. This was the case, for example, with 96% of 193 responsive site-years analyzed by Lory and Scharf (2003), for which the recommended N rate exceeded the economically optimum N rate (EONR) by up to 227 kg ha^{-1} (90 kg ha^{-1} on average). More importantly, recommended and optimum N rates were not correlated significantly ($r = 0.04$) in the latter study, suggesting that yield-based N recommendations lack predictive value. The same concern has been raised previously by researchers in Iowa (Peterson and Corak, 1993; Blackmer et al., 1997), Wisconsin (Vanotti and Bundy, 1994; Bundy, 2000), Pennsylvania (Fox and Piekielek, 1995), and Ontario (Kachanoski et al., 1996).

The only hope for improving fertilizer N recommendations for corn production in a humid region such as Illinois is to account for a soil's capacity to supply plant-available N through mineralization. The usual approach has been to measure soil NO_3^-, either before or after planting. Some success has thereby been achieved in detecting nonresponsive sites (e.g., Bundy and Malone, 1988; Blackmer et al., 1989; Schmitt and Randall, 1994), although complications arise from the need for special sampling protocol and from spatial and temporal variability in soil NO_3^- concentrations, which depend on numerous N-cycle processes, including mineralization, immobilization, nitrification, denitrification, leaching, and plant uptake.

A better approach would focus on the soil's N-supplying capacity by estimating mineralizable organic N, which is subject to fewer N-cycle processes than NO_3^- and should thus be less dynamic. Research since the 1950s has provided growing support for the concept that soil organic matter is not uniformly mineralizable, but consists primarily of a passive fraction accompanied by a less extensive pool of biologically active organic N asso-

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Published in Soil Sci. Soc. Am. J. 70:172–182 (2006).
Nutrient Management & Soil & Plant Analysis
doi:10.2136/sssaj2005.0034

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Abbreviations: ANOVA, analysis of variance; EONR, economically optimum N rate; EOY, economically optimum yield; FNUE, fertilizer N uptake efficiency; ISNT, Illinois soil N test; PY, proven-yield; SD, standard deviation.

ciated with microbial biomass (e.g., Jansson, 1958; Paul and Juma, 1981; Mengel, 1996). The latter constituents are identified largely as α-amino N and (amide + amino sugar)-N, both of which have been linked to net mineralization and/or crop N uptake in pot experiments (Mengel, 1996).

Several attempts were made during the 1960s and 1970s to provide a chemical basis for soil management effects on crop growth and fertilizer N response under field conditions; however, the results generally indicated little variation in the distribution of N, and the usual conclusion was that no particular fraction of hydrolyzable soil N is more labile than others (e.g., Keeney and Bremner, 1964; Khan, 1971; Meints and Peterson, 1977). This conclusion has been widely accepted, but must be questioned in light of recent evidence that conventional steam-distillation methods do not permit quantitative analyses for amino sugar N or amino acid N (Mulvaney and Khan, 2001). Based on the latter finding, simple diffusion methods were developed for N-distribution analysis of soil hydrolysates that are accurate, specific, and reliable.

In subsequent work by Mulvaney et al. (2001), the newly developed diffusion methods were applied to soil samples collected by Brown (1996), from sites that differed in whether corn had been responsive to N fertilization. The results showed a much higher concentration of amino sugar N for nonresponsive than for responsive soils, whereas no consistent difference was detected in their concentrations of total hydrolyzable N, hydrolyzable NH_4^+–N, or amino acid N. Upon incubation, mineral N production was found to be much more extensive by nonresponsive than by responsive soils, and to be accompanied by a net decrease in amino sugar N but not in amino acid N (Mulvaney et al., 2001). Based on these findings, a simple soil test, the so-called Illinois soil N test (ISNT), was developed that estimates amino sugar N without the need for hydrolysis (Khan et al., 2001). When this test was applied to 25 site-average soil samples collected by Brown (1996) to a depth of 30 cm, a critical range of 225 to 240 mg kg^{-1} completely resolved 12 nonresponsive from 13 responsive soils.

The present study originated with the objective of evaluating the effectiveness of the ISNT in differentiating responsive from nonresponsive site-years under a wide range of soil and cropping conditions. As additional objectives, the database thereby generated was used to assess (i) how these conditions might influence a quantitative relationship between ISNT values and crop responsiveness to N fertilization; and (ii) the accuracy and economic consequences of N recommendations by the PY method, primarily on a site-by-site basis. Very little peer-reviewed information is available on the latter issue, despite the fact that this method has been promoted for several decades in many states through university extension publications.

MATERIALS AND METHODS

Field Plot Management

The work reported herein involved 102 N-response experiments located throughout Illinois, largely on farmer fields. Of these experiments, 51 were reported by Brown (1996), including 11 conducted in 1990, 18 in 1991, and 22 in 1992. An additional 51 experiments included 14 in 2001, 16 in 2002, and 21 in 2003. In each case, N rates were applied according to a randomized complete block design with four replicates, by sidedressing urea-NH_4NO_3 solution (360 g N L^{-1}) when corn was 15 to 30 cm tall. In 1990, 1991, and 1992, plots measured approximately 4 m in width × 15 m in length, and N applications were based on a PY recommendation, assuming soil productivity under high management (Fehrenbacher et al., 1978). Nitrogen was applied at 0, 20, 40, 60, 80, or 100% of the recommended rates in 1990, and at 0, 25, 50, 75, 100, or 125% of these rates in 1991 and 1992. In 2001, 2002, and 2003, plots measured approximately 5 m in width × 15 m in length, and N applications ranged from 0 to 235 kg ha^{-1}, in equal increments of 33.6 kg ha^{-1}. At each site, an adapted corn hybrid was planted in rows spaced 76 cm apart in April or May. Thinning was done before N application at V3 to V6, so as to obtain a uniform population within the experimental area. At physiological maturity, grain yield was determined by hand-harvesting 9 m of the two middle rows, and was adjusted to a constant moisture content (155 g kg^{-1}).

Soil Samples

Soil samples were collected from the experimental area at each site in late March or early April, including surface (0–18 cm) samples for routine soil fertility assessment (pH, P, and K) and profile samples for NO_3^- testing (1990–1992) or the ISNT (2001–2003). Surface samples were collected as a 5-core composite from the entire experimental area, using a 2.5-cm diam. probe. The cores were dried at room temperature (1990–1992) or in a forced-air oven at 40°C (2001–2003), crushed with a mechanical grinder to pass a 2-mm screen, and then mixed thoroughly before analyses for pH, available P, and exchangeable K as described by Mulvaney et al. (2001), and for organic C and total N as described by Khan et al. (2000). The data are summarized by Table 1, according to soil series for site-years identified as responsive or nonresponsive to N fertilization.

Profile samples were collected to depths of 0 to 30 and 30 to 60 cm in 1990–1992, and from 0 to 15, 15 to 30, and 30 to 60 cm in 2001–2003. In each case, five soil cores were collected from each block using a 5-cm (for 0- to 30-cm samples) and then a 2.5-cm (for 30- to 60-cm samples) diam. probe, combined by depth, and subsequently frozen (–10°C) within 12 h after collection. Before use, core samples collected in 1990–1992 were allowed to thaw at room temperature, screened while still field-moist to <2 mm, and then air-dried at room temperature, with subsequent transfer for storage in polyethylene or paper bags. In 2001–2003, profile samples were dried in a forced-air oven at 40°C, and were then crushed in a hammer mill to <2 mm.

Analytical Methodology

The N test described by Khan et al. (2001) was performed as specified in a technical note (^{15}N Analysis Service, 2004) concerning the ISNT, which describes three modifications to improve the uniformity of heating with the griddle employed (Model 76220; West Bend, West Bend, WI): (1) replacement of the original temperature controller with an electronic unit, (2) enclosure of the griddle within a polyethylene box as a draft shield, and (3) rotation of jar positions after heating for 1.5 and 3 h. To ensure the validity of ISNT data, care was taken that heating was always done at the same measured temperature (54°C), samples were analyzed in triplicate (for

Table 1. Characterization of soils for site-years studied in N-response experiments.

Soil		Site-year(s)					Available	
Series	Subgroup	Type	No.	pH	Organic C	Total N	P†	K‡
					$\mathrm{g\ kg^{-1}}$		$\mathrm{mg\ kg^{-1}}$	
Andres	Fine-loamy, mixed, superactive, mesic Aquic Argiudolls	Responsive	1	6.3§	18.6	1.6	21§	168§
Atterberry	Fine-silty, mixed, superactive, mesic Udollic Endoaqualfs	Responsive	1	6.1§	8.8	0.8	32§	86§
Bloomfield	Sandy, mixed, mesic Lamellic Hapludalfs	Responsive	1	6.8	7.8	0.6	54	175
Bluford	Fine, smectitic, mesic Aeric Fragic Endoaqualfs	Nonresponsive	1	6.3	10.7	1.0	122	259
Bonfield	Loamy-skeletal, mixed, superactive, mesic Aquic Hapludolls	Responsive	1	6.4§	18.4	1.8	23§	182§
Catlin	Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls	Responsive	2	5.6–6.1	16.4–28.5	1.4–2.2	28–34	175–297
Cisne	Fine, smectitic, mesic Mollic Albaqualfs	Nonresponsive	1	5.2§	14.3	1.1	110§	116§
		Responsive	8	5.5§–7.3§	8.8–18.5	0.8–1.6	20§–95	73§–252§
Downs	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs	Nonresponsive	2	6.5§–6.9§	14.3–26.2	1.6–2.6	43§–76§	120§–303§
		Responsive	1	6.1§	31.9	2.6	100§	226§
Drummer	Fine-silty, mixed, superactive, mesic Typic Endoaquolls	Nonresponsive	5	5.5–7.1§	22.2–34.3	1.8–3.5	16–100§	176§–400§
		Responsive	9	5.0–7.7	12.7–22.1	1.1–1.9	14–54§	113§–196§
Elburn	Fine-silty, mixed, superactive, mesic Aquic Argiudolls	Nonresponsive	2	7.0–7.1	15.9–17.3	1.4–1.5	24–46	113–174
		Responsive	3	5.3–7.1	15.3–23.7	1.4–1.8	23–97	103–186
Flanagan	Fine, smectitic, mesic Aquic Argiudolls	Nonresponsive	6	5.3§–6.8§	19.4–31.0	2.0–2.4	30§–100§	180§–400§
		Responsive	2	6.3–7.0	15.2–21.1	1.5–1.7	101–122	259–290
Griswold	Fine-loamy, mixed, superactive, mesic Typic Argiudolls	Responsive	1	6.9	14.7	1.4	151	351
Hartsburg	Fine-silty, mixed, superactive, mesic Typic Endoaquolls	Responsive	1	6.2§	20.3	1.7	50§	126§
Harvard	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs	Nonresponsive	1	6.6§	21.3	1.9	132§	490§
Herrick	Fine, smectitic, mesic Aquic Argiudolls	Nonresponsive	3	6.3–6.9	12.8–18.5	1.3–1.6	49–83	156–391
		Responsive	7	5.9–7.1	12.2–18.4	1.0–1.8	20–110	126–391
Ipava	Fine, smectitic, mesic Aquic Argiudolls	Nonresponsive	1	6.2	21.0	1.7	38	207
		Responsive	5	5.8§–6.8§	14.9–22.3	1.5–1.8	38§–63§	149§–322§
Iva	Fine-silty, mixed, superactive, mesic Aeric Endoaqualfs	Responsive	1	5.3§	12.8	1.3	10§	200§
Joy	Fine-silty, mixed, superactive, mesic Aquic Hapludolls	Nonresponsive	3	5.9–6.3	18.3–19.2	1.6	68–132	276–303
		Responsive	2	6.4	18.8–19.6	1.6–1.7	49–80	256–269
Lawson	Fine-silty, mixed, superactive, mesic Aquic Cumulic Hapludolls	Nonresponsive	1	6.5	11.4	1.3	35	166
		Responsive	1	6.7	17.8	1.4	140	414
Marine	Fine, smectitic, mesic Aeric Albaqualfs	Responsive	1	6.6	11.1	1.0	115	206
Maumee	Sandy, mixed, mesic Typic Endoaquolls	Nonresponsive	1	6.3§	13.2	1.3	66§	182§
		Responsive	2	6.4–6.9§	8.7–12.2	0.8–1.2	25–53§	91–176§
Milford	Fine, mixed, superactive, mesic Typic Endoaquolls	Nonresponsive	1	5.7§	20.3	2.3	86§	268§
Muscatine	Fine-silty, mixed, superactive, mesic Aquic Hapludolls	Nonresponsive	1	5.7§	16.3	1.9	71§	210§
		Responsive	2	6.7§–6.9§	19.2–21.2	1.4–1.6	51§–56§	230§–245§
Port Byron	Fine-silty, mixed, superactive, mesic Typic Hapludolls	Nonresponsive	4	5.4–7.2	15.2–23.4	1.4–1.9	38–80	146–256
Raddle	Fine-silty, mixed, superactive, mesic Typic Hapludolls	Responsive	1	5.2	11.7	1.2	130§	322§
Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls	Responsive	2	6.1–6.6	23.3–27.0	1.9–2.2	27–33	178–200
Stronghurst	Fine-silty, mixed, superactive, mesic Aeric Endoaqualfs	Responsive	1	6.4§	5.8	0.6	49§	126§
Tama	Fine-silty, mixed, superactive, mesic Typic Argiudolls	Responsive	6	5.2§–7.0§	7.8–19.3	0.7–1.7	30§–130§	181§–400§
Varna	Fine, illitic, mesic Oxyaquic Argiudolls	Responsive	4	6.1§–6.8	14.6–27.3	1.3–2.2	12–35	190§–233
Virgil	Fine-silty, mixed, superactive, mesic Udollic Endoaqualfs	Responsive	1	6.0§	12.4	1.1	56§	200§
Waupecan	Fine-silty, mixed, superactive, mesic Typic Argiudolls	Responsive	1	6.4§	21.7	1.7	60§	244§
Will	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls	Responsive	1	6.0§	29.2	2.9	35§	205§

† Determined as Bray-1 P.

‡ Determined as 1 *M* $NH_4C_2H_3O_2$-extractable K.

§ Obtained from Brown (1996).

2001–2003 samples) or quadruplicate (for 1990–1992 samples), and a reference soil sample was included on each griddle.

For 1990–1992 site-years, analyses by the ISNT were performed on a composite sample of air-dried soil (0–30 cm) prepared by combining an equal weight of soil collected from each block. For 2001–2003 site-years, block samples were analyzed individually, and ISNT data for 0 to 30 cm were generated by averaging values measured for 0 to 15 and 15 to 30

Table 2. Characterization of nonresponsive site-years.†

Soil							ISNT value††			Error in PY recommendation§§	
No.	Series	Year	Previous crop‡	Tillage§	Manure N applied¶	Plant population#	Mean	SD	Yield without sidedressed N‡‡	Magnitude	Economic cost
					kg ha^{-1}	plants ha^{-1}	—mg kg^{-1}—		Mg ha^{-1}	kg ha^{-1}	\$ ha^{-1}
1	Bluford	2002	C	M	70(S_l)	68 900	389	2.9	10.9	93	51
2	Cisne	1991	C	M	0¶¶	66 700	248	0.2	10.2 (30)	155	85
3	Downs	1990	C	M	0¶¶	51 700	237	2.5	8.8	199	110
4		1991	S	M	92(P)##	64 600	380	2.6	12.3	62	34
5	Drummer	1990	C	C	0¶¶	45 900	436	5.4	7.7	207	114
6		1991	S	N	0	68 900	305	3.5	7.0	162	89
7		1992	C	M	>1120(S)	66 700	305	1.5	14.0	0	0
8		1992	C	M	2510(S)	60 300	435	2.2	12.1	0	0
9		2001	A	C	0	64 600	321	3.0	10.9 (40)	123	68
10	Elburn	2001	S	M	60(S_l)	63 100	224	3.1	11.9	134	74
11		2002	S	M	60(S_l)	64 600	249	2.8	11.8	155	85
12	Flanagan	1991	A	C	0	65 700	284	3.5	10.9	105	58
13		1992	A	C	0	62 400	276	2.6	12.8	105	58
14		1992	S	M	100(D)	47 400	366	2.8	9.1	74	41
15		1992	S	M	0¶¶	60 300	371	5.0	12.5 (36)	172	95
16		2002	C	C	0¶¶	77 500	335	1.6	11.6	235	130
17		2003	C	C	0¶¶	NA	369	1.6	12.4	235	130
18	Harvard	1990	C	M	0¶¶	57 400##	318	2.8	7.7	177	98
19	Herrick	2002	C	M	62(B)	66 000	260	2.6	9.3	159	88
20		2002	S	M	62(B)	66 000	257	2.6	8.3	114	51
21		2003	C	M	0¶¶	70 300	185	2.2	12.4	221	122
22	Ipava	2001	S	N	0	68 900	291	2.8	11.4	186	102
23	Joy	2001	C	M	202(S_l)	71 800	261	3.5	14.6	38	21
24		2002	C	M	202(S_l)	74 600	260	1.6	14.8 (34)	38	21
25		2003	C	M	141(S_l)	80 400	260	4.0	9.0	99	54
26	Lawson	2002	A	C	0	71 800	300	2.0	12.0	118	65
27	Maumee	1992	S	M	500(S_l)	58 100	247	4.0	13.7	0	0
28	Milford	1990	S	M	60(S_l)##	57 400	302	0.9	9.3	71	39
29	Muscatine	1991	S	N	81(S_l)##	58 100	275	4.9	10.6 (22)	99	54
30	Port Byron	2001	A	C	49(B)	80 400	269	1.8	10.5	76	42
31		2001	S	M	81(S_l)	73 200	257	2.1	12.6	112	62
32		2002	S	M	09(S_l)	63 100	246	1.4	13.6	84	46
33		2003	S	M	0¶¶	68 900	273	3.9	13.1	193	106

† Soil series, year, previous crop, tillage, manure N applied, plant population, yield without sidedressed N, and preseason application of $(NH_4)_2HPO_4$ obtained from Brown (1996) for 1990–1992 site years.

‡ C, corn (*Zea mays* L.); S, soybean (*Glycine max* L. Merr.); alfalfa (*Medicago sativa* L.).

§ M, mulch; C, conventional; N, no-till.

¶ Values indicate N applied as manure for the growing season studied, estimated as the product of manure application rate and average N concentration (Illinois Agronomy Handbook, 2002). Abbreviations in parentheses indicate the type of manure applied: S_l, liquid swine (*Sus scrofa domesticus*); P, poultry; S, swine (solid); B, beef cattle (*Bos taurus*); D, dairy cattle.

NA, not available.

†† ISNT, Illinois soil N test. Data are reported as a mean of four (1990–1992 site-years) or 12 (2001–2003 site-years) replicate values. SD, standard deviation.

‡‡ Grain yields are reported as a mean from four replicate check plots. Values in parentheses indicate N applied (kg ha^{-1}) as $(NH_4)_2HPO_4$ prior to sidedressing.

§§ PY, proven-yield method as described in the Illinois Agronomy Handbook (2002). Recommended N rates were determined using productivity indices for high management, according to Fehrenbacher et al. (1978) for 1990–1992 site-years, or according to Olson and Lang (2000) for 2001–2003 site-years.

¶¶ Manure applied 2 to 5 yr prior to the growing season studied.

Correction was made to data reported by Brown (1996).

cm. Analyses were also performed on the 30- to 60-cm samples collected for the latter group, but are reported for only a single site-year to demonstrate an interaction with crop N response.

Experimental Site-Years

The 102 site-years studied are characterized by Tables 2 and 3, which show the soil series; the year when N response was studied; the previous crop; the tillage system in use; the source and amount of manure N applied for the growing season studied, as well as residual manuring within the previous 2 to 5 yr; plant population estimated from stand counts; a site-average ISNT value and the standard deviation (SD) computed from four (1990–1992) or 12 (2001–2003) replicate values; check-plot corn yield data; and the magnitude of the error in the PY recommendation and the corresponding economic cost. For each site-year, a recommended N rate was determined as described in the Illinois Agronomy Handbook (2002), using productivity indices reported by Fehrenbacher et al. (1978) for high management (1990–1992 site-years) or by Olson and Lang (2000) for optimum management (2001–2003 site-years). In the case of nonresponsive site-years (Table 2), the magnitude of error in the PY recommendation was obtained as the recommended N rate, and the economic cost was calculated on the assumption that fertilizer N costs \$0.55 kg^{-1}.

Site-years were identified as nonresponsive (Table 2) or responsive (Table 3) for N fertilization of corn, based on regression analyses performed by fitting a linear, linear plateau, quadratic, or quadratic plateau model to N-rate and mean yield data using Microsoft Excel 2003 software (Microsoft Corp., Redmond, WA) configured with Solver as an add-in. A response model was selected for each site-year on the basis of residual analysis and the Chi-Square test for goodness of fit. In the case of responsive site-years, economically optimum yield (EOY) and EONR were computed by the resulting regression equation assuming a value of 0.1 for the N/corn price ratio; delta yield (Kachanoski et al., 1996) was obtained as the difference between the EOY and check-plot yield

Table 3. Characterization of responsive site-years.†

Soil							ISNT value††						Error in PY recommendation†††	
No.	Series	Year	Previous crop‡	Tillage§	Manure N applied¶	Plant population#	Mean	SD	Yield without sidedressed N‡‡	Delta yield§§	EONR¶¶	FNUE##	Magnitude	Economic cost
					kg ha^{-1}	plants ha^{-1}			Mg ha^{-1}		kg ha^{-1}	kg grain kg^{-1}	kg ha^{-1}	\$ ha^{-1}
34	Andres	1992	S	N	0	60 300	245	2.2	9.2 (17)	2.0	83	24	67	37
35	Atterberry	1991	W	M	0	62 400	117	1.4	6.9 (35)	3.3	186	18	15	8
36	Bloomfield	2001	C	M	0	66 000	83	2.5	5.9	7.1	143	50	9	5
37	Bonfield	1992	S	M	0	62 400	221	1.5	6.7 (7)	3.4	62	55	50	28
38	Catlin	2002	S	C	0	77 500	163	2.2	10.2	2.7	161	17	20	11
39		2003	S	N	0	70 300	226	3.2	11.2 (30)	3.6	64	56	118	65
40	Cisne	1990	C	M	0	58 800‡‡‡	212	0.8	7.1 (13)	0.6	83	7	72	40
41		1990	S	M	0	45 900	158	5.2	8.7	1.2	60	20	49	27
42		1991	C	M	0	60 300	153	1.6	5.0	3.4	113	30	41	22
43		1991	W	C	0	53 800	145	2.4	2.5§§§	1.7	49	35	105	58
44		1992	C	M	0	64 600	169	2.3	7.0	5.2	154	34	0	0
45		2001	S	M	0	66 000	154	1.9	6.4 (30)	4.3	188	23	–52	33
46		2002	S	M	0	NA	212	1.9	4.6 (30)	4.2	265	16	–129	170
47		2003	S	M	0	68 900	134	2.7	7.9 (30)	5.1	148	34	–11	0
48	Downs	1992	S	M	92 (P)‡‡‡	77 500	199	2.2	9.8	3.0	133	23	–74	95
49	Drummer	1990	S	N	0	60 300	212	0.5	8.6 (78)	2.3	110	21	53	29
50		1990	S	M	0	50 200	185	3.0	7.9 (36)	0.5	47	11	115	63
51		1991	S	M	0	56 000	211	1.1	9.9	0.9	49	18	113	62
52		1992	S	M	0	51 700	166	4.9	7.6 (30)	2.1	120	17	43	24
53		1992	S	M	0	66 700	219	1.0	9.2	2.9	102	28	60	33
54		2001	S	M	0	73 200	282	3.0	6.2	3.1	95	33	95	52
55		2003	S	M	0¶¶¶	71 800	246	2.9	6.6	6.8	235	29	–45	74
56		2003	S	M	43 (B)	71 800	287	2.8	9.7	3.5	49	7	85	47
57		2003	S	M	0	68 900	280	2.5	11.1 (40)	2.7	111	24	80	44
58	Elburn	2002	S	M	0	64 600	199	2.0	10.7 (40)	1.9	176	11	19	10
59		2003	S	M	0	68 900	281	2.9	10.6	1.9	118	16	77	42
60		2003	S	M	0¶¶¶	NA	205	2.9	7.6	2.4	111	22	84	46
61	Flanagan	2002	S	M	0¶¶¶	77 500	287	1.7	9.7 (40)	1.2	152	8	38	21
62		2003	S	M	0¶¶¶	NA	209	4.2	7.3	5.1	190	27	0	0
63	Griswold	2001	C	M	0	74 600	209	2.1	6.6	5.0	110	45	80	44
64	Hartsburg	1991	S	M	0	62 400	201	2.7	8.5 (52)	2.6	147	18	21	12
65	Herrick	2001	S	M	0	68 900	171	2.9	8.5	1.6	81	20	95	52
66		2001	S	M	55 (B)	68 900	237	1.9	10.8	3.6	202	18	–87	106
67		2001	S	M	0¶¶¶	83 200	197	1.9	4.8	5.7	235	24	–59	159
68		2002	C	M	0¶¶¶	66 000	219	2.6	6.8	2.9	171	17	49	27
69		2002	WS	M	0	68 900	146	2.0	5.8 (34)	4.3	269	16	–48	66
70		2003	S	M	0	80 400	174	3.7	6.0 (67)	4.5	205	22	–29	83
71		2003	S	M	0	64 600	180	3.1	8.2	5.5	130	42	46	25
72	Ipava	1990	S	N	0	51 700	190	2.1	6.2	3.8	119	32	56	31
73		1990	S	M	0	64 600	184	3.0	5.6	4.2	83	51	92	51
74		1991	S	N	0	64 600	199	1.6	10.2	1.2	98	12	76	42
75		1992	C	N	0	60 300	223	2.3	8.7 (34)	1.1	144	8	75	41
76		2003	S	N	0	71 800	260	3.2	7.0	6.0	86	70	20	11
77	Iva	1992	WM	M	0	60 300	187	2.3	6.9 (25)	5.6	202	28	–18	9
78	Joy	2002	C	M	0¶¶¶	74 600	217	1.9	12.6	2.1	84	25	156	86
79		2003	C	M	0¶¶¶	80 400	253	5.9	8.5	0.8	104	8	136	75
80	Lawson	2003	S	N	0	66 000	192	4.0	7.9	6.6	202	33	–17	22
81	Marine	2003	C	M	0¶¶¶	66 000	182	1.8	12.0	2.1	101	21	74	41
82	Maumee	1992	S	M	0	64 600	115	1.8	8.7 (50)	3.6	160	22	–66	106
83		2003	A	C	0	NA	125	2.7	7.9	2.9	168	17	–4	4
84	Muscatine	1990	C	N	0	61 700	201	1.0	9.0	1.1	90	12	134	74
85		1991	C	N	0	60 300	265	2.2	9.1 (12)	0.7	116	6	108	60
86	Raddle	1991	S	M	0	53 800	158	2.3	8.8	2.6	46	57	110	61
87	Sable	2003	S	M	0	66 000	306	2.6	6.2	6.8	213	32	–25	5
88		2003	S	M	0	68 900	273	1.6	9.8	4.7	223	21	–35	5
89	Stronghurst	1991	WS	N	0	53 800	72	2.0	4.0 (16)	4.9	190	26	–4	0
90	Tama	1991	C	M	85 (B)	64 600	285	0.3	11.2 (27)	0.6	84	7	41	22
91		1991	C	M	0	62 400	195	2.0	5.3§§§	1.2	76	16	132	73
92		1992	S	M	0¶¶¶	60 300	244	1.7	8.5	1.2	126	10	37	20
93		1992	S	M	0	60 300	174	1.0	10.5 (34)	2.7	143	19	20	11
94		1992	C	M	0	62 400	218	3.6	12.5	1.8	113	16	130	72
95		1992	C	M	0	62 400	245	2.2	8.2	1.4	62	23	147	81
96	Varna	1992	S	N	0	58 100	172	3.2	8.8	3.7	81	46	40	22
97		1992	S	M	0	60 300	159	4.2	5.6	6.9	112	62	9	5
98		2001	S	M	0	71 800	323	3.0	10.5 (40)	2.3	146	16	0	0
99		2002	S	M	0	64 600	202	1.2	6.5 (40)	3.9	210	19	–65	26
100	Virgil	1991	C	C	0	53 800	141	1.0	7.5	1.9	125	15	74	41
101	Waupecan	1991	S	M	0	58 100	286	5.1	5.5§§§	1.4	64	22	92	51
102	Will	1991	S	N	0	53 800	338	4.5	1.9§§§	4.4	179	25	−67	49

† Soil series, year, previous crop, tillage, manure N applied, plant population, yield without sidedressed N, and preseason applications of $(NH_4)_2HPO_4$ obtained from Brown (1996) for 1990–1992 site-years.

‡ S, soybean (*Glycine max* L. Merr.); W, wheat (*Triticum aestivum* L.); C, corn (*Zea mays* L.); WS, double-cropped wheat and soybean; WM, double-cropped wheat and milo (*Sorghum bicolor maili*).

§ N, no-till; M, mulch; C, conventional.

¶ Values indicate N applied as manure for the growing season studied, estimated as the product of manure application rate and average N concentration (Illinois Agronomy Handbook, 2002). Abbreviations in parentheses indicate the type of manure applied: P, poultry; B, beef cattle (*Bos taurus*).

NA, not available.

†† ISNT, Illinois soil N test. Data are reported as a mean of four (1990–1992 site-years) or 12 (2001–2003 site-years) replicate values. SD, standard deviation.

‡‡ Grain yields are reported as a mean from four replicate check plots. Values in parentheses indicate N applied (kg ha^{-1}) as $(NH_4)_2HPO_4$ prior to sidedressing.

§§ Calculated as economically optimum yield – yield without sidedressed N, where economically optimum yield was estimated by regression, assuming \$0.28 kg^{-1} of fertilizer N and \$98.42 Mg^{-1} of corn grain.

¶¶ EONR, economically optimum N rate.

FNUE, fertilizer N uptake efficiency. Calculated as 1000 × delta yield/EONR.

††† PY, proven-yield method as described in the Illinois Agronomy Handbook (2002). Recommended N rates were determined using productivity indices for high management, according to Fehrenbacher et al. (1978) for 1990–1992 site-years, or according to Olson and Lang (2000) for 2001–2003 site-years.

‡‡‡ Correction was made to data reported by Brown (1996).

§§§ Subject to drought.

¶¶¶ Manure applied 2 to 5 yr prior to the growing season studied.

Table 4. Effectiveness of the proven-yield (PY) method for site-years under different management.

			Error in PY recommendation			
	Site-year(s)		Magnitude		Economic cost	
Soil management†	Type	No.	Range	Mean‡	Range	Mean
			kg ha^{-1}		\$ ha^{-1}	
Manured within 1 yr	Nonresponsive	18	0 to 159	78	0–88	42
	Responsive	4	−87 to 85	72	22–106	68
Continuous corn	Nonresponsive	7	155 to 235	204	85–130	112
	Responsive	16	0 to 156	88	0–86	49
Corn after soybean	Nonresponsive	4	162 to 193	178	89–106	98
	Responsive§	45	−129 to 118	55	0–170	40
Corn after alfalfa	Nonresponsive	4	105 to 123	113	58–68	62
	Responsive	1	–	4	–	4
Corn after wheat	Responsive¶	3	−18 to 105	46	8–58	25
All site-years	Nonresponsive	33	0 to 235	121	0–130	66
	Responsive	69	−129 to 156	62	0–170	42
	Total	102	−129 to 235	81	0–170	50

† Site-years identified by crop rotation had not received manure for at least 1 yr prior to the growing season studied.
‡ Calculated as an absolute value.
§ Includes two site-years where corn (*Zea mays* L.) followed double-cropped wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L. Merr.).
¶ Includes one site-year where corn followed double-cropped wheat and milo (*Sorghum bicolor maili*).

[which in some cases was achieved with a fall application of 7–78 kg N ha^{-1} as $(NH_4)_2HPO_4$]; fertilizer N uptake efficiency (FNUE) was estimated as delta yield/EONR; and error in the PY recommendation was calculated from the difference, recommended N– EONR. To estimate an economic cost for overfertilized site-years, the latter difference was multiplied by \$0.55 kg^{-1} N, whereas with an insufficient N recommendation, a cost was computed assuming \$98.42 Mg^{-1} for yield loss estimated by regression and a credit of \$0.55 kg^{-1} for unused N.

Analysis of Variance

After excluding 18 site-years involving an obvious limitation to crop growth or fertilizer N response (site-years 2, 10, 11, 17, 21, 34, 41, 43, 50, 52, 54, 57, 77, 91, 92, 99, 101, and 102), plus two others where corn followed wheat (site-years 35 and 43), the Proc MIXED procedure within SAS (SAS Institute, 1998) was employed to examine the effects of both categorical [year (treated as a random effect); previous crop; tillage; manuring (current and residual or residual only)] and continuous (population and ISNT value) variables on soil organic C, sidedressed N, EOY, delta yield, EONR, FNUE, and PY error (kg ha^{-1}) as dependent variables. Tukey-Kramer tests were performed in carrying out pairwise comparisons of treatment means.

RESULTS AND DISCUSSION

Evaluation of Yield-based Nitrogen Management

The importance of fertilizer N management in corn production is clearly evident from the economic costs that often exceed \$100 per hectare. The rationale for this investment resides in the PY method, whereby crop N uptake is ascribed largely to N fertilization. The resulting recommendations have been widely adopted on the premise that yield must not be limited by inadequate N supply, yet have seldom been evaluated relative to grain yield with a lower (or higher) rate of N fertilization, or for accuracy in fertilizing individual sites where N-response studies have been conducted to determine an EONR. Such studies provide the basis for the evaluations reported in Tables 2 and 3, which indicate the magnitude of the error in the PY recommendation for each site-year studied and the corresponding economic cost estimated for a single input. Table 4 summarizes the latter information for site-years under different crop rotations or with current manuring.

Tables 2 and 3 provide good reason to question the validity of the PY method, as check-plot yields ranged from 1.9 to 13.1 Mg ha^{-1} (8.2 Mg ha^{-1} on average, representing 77% of the average EOY) for the 52 site-years that received no input of N from sidedressing, manuring, or fall-applied $(NH_4)_2HPO_4$. The implicit capacity of the soil to provide plant-available N, as reflected in these values, cannot be adequately accounted for in making PY recommendations, which assumes that the soil supplies a constant proportion of crop N uptake.

Considering all 102 of the N-response trials reported herein, PY recommendations were accurate to within 20 kg ha^{-1} for only 18 of the site-years studied, while 69% of these recommendations were excessive, involving the majority of both nonresponsive and responsive site-years. Underfertilization occurred with 13% of the latter group, and accounted for the most serious economic loss observed. There were four cases where N utilization was limited by a prolonged moisture stress; the usual and expected result was overfertilization.

In 22 of the N-response experiments reported, manure had been applied for the growing season studied, so the PY recommendation was adjusted to incorporate standardized credits for manure N (Illinois Agronomy Handbook, 2002). The adjustment proved inadequate, except for identifying three nonresponsive site-years where the manure credit exceeded the N requirement estimated for the yield goal. Of the 19 remaining currently manured site-years, 15 were completely nonresponsive to N fertilization, but would have received 38–159 kg N ha^{-1} by the PY method at a cost of \$21 to \$88 ha^{-1}. Fertilization also would have been recommended for the four additional site-years where a yield response was observed. Three of the latter cases involved a corn–soybean rotation, and the combined N credits would have led to underfertilization. In contrast, the PY method would have overfertilized a responsive site-year under continuous corn, for which the manure credit was inadequate. The implication is that a credit approach cannot provide a reliable basis for quantifying manure N availability, as has been reported previously (Hansen et al., 2004). This would indeed be expected given the inherent complications associated with such factors as manure C and N concentrations, N losses through NH_3 volatilization, and inaccuracies in manure application.

A further problem arises because the PY method does not account for residual availability of manure N, which can persist for several years after application (Eghball and Power, 1999; Eghball et al., 2004). The resulting impact on soil N availability was verified in the present project by using Fisher's Exact Test to evaluate the effect of manure history on crop N response for site-years under continuous corn or in a corn–soybean rotation without current manuring. A significant difference at $P < 0.01$ was thereby found, in which 82% of the nonresponsive site-years in this group had a history of manuring, as compared with 16% of those that were responsive. Residual manure was a more common occurrence when corn was grown continuously than in rotation with soybean. The latter difference is particularly apparent for nonresponsive site-years that were not currently manured, among which were all seven of those under continuous corn but only two of four that were in a corn–soybean rotation. The PY recommendations were always excessive for continuous corn (by 49–235 kg N ha^{-1}, at a cost of \$27–\$130 ha^{-1}), with or without a response to N fertilization, whereas either under- or overfertilization occurred when there was a manure history for corn in rotation with soybean.

As with current manuring, fixed N credits are utilized in PY recommendations when corn is grown after a legume. The present project involved 54 such site-years that had not been manured for at least 1 yr before the growing season studied, including 49 in a corn–soybean rotation and five where first-year corn followed alfalfa. Of the latter group, four site-years were nonresponsive to N fertilization, but would have been fertilized with 105 to 123 kg N ha^{-1} by the PY method at a cost of \$58 to \$68 ha^{-1}, even after maximizing the alfalfa credit (112 kg N ha^{-1}). The error was more extensive in magnitude (162–193 kg N ha^{-1}) and cost (\$89–\$106 ha^{-1}) for four nonresponsive site-years where corn followed soybean, involving either no-till (site-years 6 and 22) or residual manuring (site-years 15 and 33). In contrast, underfertilization often occurred when a yield response was obtained with soybean as the previous crop, whereas no such occurrences were observed with continuous corn, suggesting a greater need for N fertilization when corn follows soybean. The latter difference was substantiated, after excluding manure and tillage effects, by an ANOVA that showed significant ($P < 0.0001$) increases in EONR and delta yield when the previous crop was soybean rather than corn. The EONR estimated for corn after soybean was significantly ($P < 0.0001$) greater for 2001–2003 (153 kg N ha^{-1}) than for 1990–1992 (96 kg N ha^{-1}) site-years, suggesting that current production practices have increased the fertilizer N requirement of corn within this rotation. Such an increase is likely attributable to greater nutrient demand by improved hybrids selected for maximal yields with high planting rates.

These findings raise serious questions about the use of standardized credits for estimating the fertilizer value of legume-derived N, which ranges widely with species and environmental conditions (Heichel and Barnes, 1984). An inherent difficulty arises, for example, because plant uptake of mineral N reduces symbiotic fixation (e.g., Giöbel, 1926; Thornton, 1946), and thus a single legume credit cannot suffice for soils that differ considerably in their capacity for mineralization (Kurtz et al., 1984). In the case of soybean, a positive credit may often be inappropriate, because the grain has a higher N concentration than with corn, and soil N removal can be much more extensive (Gentry et al., 1998). In the present project, a soybean credit was inappropriate for nonmanured site-years under a corn–soybean rotation, as one-third of this group would have been underfertilized by the PY method, at an average cost of \$57 ha^{-1}.

Lacking any N credit for management history, PY recommendations were excessive for all but one of the 23 site-years under continuous corn that had not received manure for the growing season studied (although in almost 50% of these cases, manure had been applied within the previous 2–5 yr). Almost one-third of this group was nonresponsive to N fertilization, as compared with <10% of the 49 site-years in a corn–soybean rotation with no manure credit. While on average both groups were overfertilized by the PY method, the error was much more extensive (128 versus 46 kg N ha^{-1} as calculated using actual errors rather than the magnitudes reported in Table 4) when corn was the previous crop ($P < 0.01$), with no instances of underfertilization. These findings may be explained in part by a more extensive occurrence of residual manure and a larger input of fertilizer N applied annually to continuous corn, which promotes residue decomposition with microbial production of labile soil N that would reduce fertilizer N response (Shen et al., 1989; Stevens et al., 2005).

Based on Tables 2 to 4, the preceding discussion raises serious questions about the practical value of the PY method for fertilizing individual sites, as does the fact that EOY (data not shown, but readily calculable as yield without sidedressed N plus delta yield) was not related to EONR ($r = 0.08$). This method likewise proved to be inaccurate when fertilizer N recommendations were averaged for the 102 site-years studied, contrary to the usual justification for yield-based N management. A value of 154 kg N ha^{-1} was thereby obtained, as compared with 90 kg N ha^{-1} for the average EONR. The difference was reduced but not eliminated by excluding the 33 nonresponsive site-years, in which case the PY recommendation averaged 38 kg N ha^{-1} higher than did the EONR (131 kg ha^{-1}). The latter strategy has often been employed in reporting N-response trials but cannot be justified, as the PY method provides no a priori basis for identifying nonresponsive site-years.

Evaluation of Soil-based Nitrogen Management

The recurring evidence of serious inaccuracy in fertilizer N recommendations by the PY method has obvious

Table 5. Effectiveness of the Illinois soil N test (ISNT) for differentiating responsive from nonresponsive site-years for N fertilization of corn.

	No. of nonresponsive site-years		No. of responsive site-years	
Soil management†	**Actual**	**Predicted correctly‡**	**Actual**	**Predicted correctly‡**
Manured within 1 yr	**18**	**17**	**4**	**1**
Continuous corn	**7**	**6**	**16**	**13**
Corn after soybean§	**4**	**4**	**45**	**32**
Corn after alfalfa	**4**	**4**	**1**	**1**
Corn after wheat¶	**0**	**0**	**3**	**3**
All site-years	**33**	**31**	**69**	**50**

† Site-years identified by crop rotation had not received manure for at least 1 yr prior to the growing season studied.

‡ A site-year was identified as nonresponsive when the mean ISNT value (Table 2 or 3) exceeded 230 mg kg^{-1}. This value was calculated by averaging data for the lowest testing nonresponsive site-year and the highest testing responsive site-year studied by Khan et al. (2001).

§ Includes two responsive site-years where corn (*Zea mays* L.) followed double-cropped wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L. Merr.).

¶ Includes one site-year where corn followed double-cropped wheat and milo (*Sorghum bicolor maili*).

economic implications for individual farmers, and also raises concern about environmental pollution. Extrapolating from the average error in these recommendations for the site-years studied (\$50 ha^{-1}), the annual cost to Illinois agriculture would exceed \$220 million, which does not include additional expenses associated with excessive N fertilization, such as the loss of Ca^{2+}, Mg^{2+}, and K^{+} that serve as counterions during the leaching of NO_3^-. Such estimates emphasize the need to account for a soil's capacity to supply plant-available N through mineralization, which is the key to improving fertilizer N management in a humid region such as Illinois. The ISNT was developed precisely for this purpose, and is designed to estimate an alkali-1abile fraction of soil N, nominally referred to as amino sugar N, which has been related to net N mineralization (Mulvaney et al., 2001). The same relationship has been observed in several previous investigations to evaluate various alkaline reagents as a chemical index of soil N availability (e.g., Cornfield, 1960; Gianello and Bremner, 1988; Vanotti et al., 1995; Mengel, 1996), whereas soil organic matter measurements are of limited value for the latter purpose (e.g., Schmidt et al., 2002; Walley et al., 2002).

As originated, the ISNT is employed to identify sites where N fertilization is ineffective for increasing corn yield, although an obvious potential also exists for estimation of fertilizer N requirements, in lieu of yield-based N management. Assuming the same critical test value determined by Khan et al. (2001) for 25 site-years in 1990 to 1992 (230 mg kg^{-1}) as a first approximation in evaluating soil N availability without considering management history, the ISNT was 94% effective in identifying site-years characterized in the present project by the lack of an economic yield response to N fertilization. The majority of this group had been manured for the growing season studied, or had received manure within the previous 2 to 5 yr while cropped to continuous corn. As shown by Table 5, all but two such site-years were detected successfully by the ISNT, the only exceptions occurring when yield data were erratic within and among replicate plots, which tended to show a similar pattern of variability in soil test values. Moreover, the ISNT was completely effective in predicting 8 site-years that were nonresponsive to fertilizer N following previous cropping to soybean or alfalfa.

The present project also involved 69 site-years that were responsive to N fertilization. Of these, 50 were correctly identified on the basis of the same critical test value noted previously, while the remaining 19 would have been identified as nonresponsive because this value was exceeded. The latter group raises an apparent concern about the utility of the ISNT for fertilizer N management, but also provides an opportunity to gain valuable insight about interactions that affect crop N requirement, and thereby affect the critical level for interpreting test values. Both topics are addressed by the following discussion, although necessarily through scientific inference concerning factors known to affect crop growth and nutrient requirements, since the work reported was not designed to quantify specifically such effects.

In order for the ISNT to be utilized successfully, conditions must be conducive to soil N mineralization, as well as crop N uptake and utilization. This requirement was not satisfied with four of the 19 site-years incorrectly identified as nonresponsive by the ISNT, owing to serious moisture stress that occurred for most (site-years 101 and 102) or some (site-years 76 and 79) of the growing season. The effect of this stress on interpretation of the ISNT is clearly demonstrated from a comparison of yield data for site-years 22 and 76, which involved the same location with ISNT values above the critical level, but different growing conditions. Rainfall was adequate to promote mineralization throughout the 2001 growing season, whereas a 6-wk period occurred without appreciable rainfall during May and June of 2003, which drastically decreased check-plot yield and led to a dramatic yield response to N fertilization.

Interpretations of ISNT data can also be vitiated if fertilizer N requirement is increased by other factors that reduce soil N availability or crop N utilization, such as weed competition or a soil fertility limitation. This was the case with one responsive site-year (no. 95) where weed competition would have decreased crop uptake of soil and fertilizer N, and with six others for which the critical test value was exceeded with a pH of 5.0 to 5.2 (site-years 57 and 92), Bray-1 P at 14 to 21 mg kg^{-1} (site-years 34, 54, and 57), or exchangeable K at 103 to 132 mg kg^{-1} (site-years 55 and 59). Soil acidity would have impeded mineralization, thereby reducing the availability of labile soil N estimated by the ISNT, whereas a deficiency of P or K would have decreased the physiological efficiency of plant N utilization for grain production. This decrease was clearly reflected in a high EONR (Table 3) that was larger when the limitation involved

Table 6. Interaction of the Illinois soil N test (ISNT) and plant population in affecting crop N response.

	Plant population after thinning (plants ha^{-1})†					
	45 900–60 900			61 000–75 900		
Site-average ISNT value‡	Delta yield§	EONR¶	RRF#	Delta yield§	EONR¶	RRF#
mg kg^{-1}	Mg ha^{-1}	kg ha^{-1}	%	Mg ha^{-1}	kg ha^{-1}	%
<190	3.3	113	45	4.1	150	53
190–229	1.7	101	21	2.6	105	33
>230	0.7	41	8	1.4	58	12

† Values reported as mean data for site-years grouped according to ISNT value and plant population.
‡ As determined for 0–30 cm samples.
§ Calculated as economically optimum yield − yield without sidedressed N, where economically optimum yield was estimated by regression, assuming $\$0.28$ kg^{-1} of fertilizer N and $\$98.42$ Mg^{-1} of corn (*Zea mays* L.) grain.
¶ EONR, economically optimum N rate.
# RRF, relative response to fertilization. Calculated as 100 × delta yield/yield without sidedressed N.

K instead of P. The latter difference may be related to mineralization, which served as a supplemental source of P but not K.

Although often overlooked in fertilizer recommendations promoted during the past three decades, and generally neglected in the scientific literature on soil fertility, plant population has been recognized as a crucial factor in the successful use of soil testing (Bray, 1948; Melsted and Peck, 1973). A fundamental interaction thereby arises, such that a certain critical soil test level could become inadequate if the planting rate were increased. This is exactly what has been observed with the ISNT. In the original work by Khan et al. (2001), a test level of 225 to 235 mg kg^{-1} was completely effective in identifying 12 of 25 site-years as nonresponsive to N fertilization, based on N-response trials conducted between 1990 and 1992 with 47400 to 68900 (60700 on average) plants ha^{-1}. When the same critical ISNT range was applied in the present project, eight failures occurred that are of particular interest because the test value exceeded the critical range, yet a crop N response was obtained with no apparent limitation in growing conditions. Two of these failures involved continuous corn in 1991 or 1992 with a plant population of 60 300 or 64 600 (62400 on average) plants ha^{-1} (site-years 85 and 90), but delta yield was quite limited (0.6 Mg ha^{-1} on average) with a marginal economic return ($\$9$ ha^{-1} on average). The failure rate increased substantially in 2001–2003 with six site-years in a corn–soybean rotation that were planted to a higher density of 66 000 to 77 500 (70 800 on average) plants ha^{-1} (site-years 56, 61, 66, 87, 88, and 98), in which case a six-fold increase also occurred in delta yield (average of 3.7 Mg ha^{-1}). Table 3 provides many examples of greater N response with higher plant populations, for site-years having similar ISNT values, as further evidenced by an ANOVA that showed a significant ($P < 0.05$) increase in EONR with population for responsive site-years. These findings would be expected if fertilizer N requirement is subject to a fundamental interaction between soil N availability and plant demand, as is readily apparent from studies by Lang et al. (1956). A higher planting rate would thereby increase the critical level for interpreting the ISNT.

The interaction of the ISNT with plant population is clearly demonstrated by Table 6, which summarizes the magnitude of crop N response for site-years broadly grouped into two population classes representing only 1990–1992 (<61000 plants ha^{-1}) or largely 2001–2003 (>61000 plants ha^{-1}) site-years, and three ISNT classes consisting of site-years identified as highly responsive (<190 mg kg^{-1}), moderately responsive (190–229 mg kg^{-1}), or nonresponsive (≥230 mg kg^{-1}) to N fertilization. The data in Table 6 leave little doubt about the need for soil-based N management, as fertilizer N requirement decreased with increase in the ISNT, while an increase occurred with plant population, reflecting higher crop N demand. The latter trend adds a new dimension to fertilizer N management with the ISNT, whereby planting rate can be adjusted to fully exploit soil N availability, provided that productivity is not limited by other soil properties (e.g., moisture). Moreover, Table 6 suggests that the ISNT may provide valuable input for optimizing planting rate, although economic factors must also be considered.

Soil testing is inherently more complicated for N than for P or K, due in part to the fact that mineralization and immobilization are highly dependent on the quantity and quality of C available for microbial utilization. This interaction would necessarily affect the predictive value of the ISNT for estimating soil N availability following a recent incorporation of carbonaceous residues, such as bedding-laden manure or a nonleguminous cover crop. The latter explanation applies to one of the ISNT failures observed (site-year 66), in which case rye (*Secale cereale* L.) had been grown as an overwinter catch crop following soybean and would have promoted immobilization after being incorporated by spring tillage.

The same effect of C is implicated for five other site-years under a corn–soybean rotation, which were characterized by a high soil content of organic C (21–27 mg kg^{-1}) when incorrectly identified as nonresponsive by the ISNT in 2001–2003 (site-years 56, 61, 87, 88, and 98). The test values thereby obtained suggest a considerable capacity for mineralization that would have promoted uptake of soil N by the previous soybean crop, thereby reducing the role of symbiotic fixation in meeting the high N requirement of this legume. The resulting decrease in soil N availability, combined with the absence of annual N fertilization, would have impeded decomposition of corn stover, potentially contributing to microbial competition for available N, and hence promoting a crop N response, during the growing season studied. This possibility would be enhanced by the growing trend toward high planting rates for corn and soybean, and is

Table 7. Spatial variability among replicate blocks for site-year 17 in Illinois soil N test (ISNT) values and crop N response.

Block no.	Sample depth, cm†			Yield without sidedressed N	Delta yield‡
	0–15	15–30	30–60		
	—ISNT value, mg kg^{-1}—			——Mg ha^{-1}——	
1	505	473	352	14.6	0
2	380	375	275	13.3	0
3	360	312	156	9.0	3.2
4	383	315	218	12.9	0

† Values reported are the mean of four replicate determinations. Standard deviations did not exceed 3.1 mg kg^{-1}.

‡ Determined as optimum yield – yield without sidedressed N, where optimum yield was estimated by fitting a linear-plateau regression model to unreplicated data.

consistent with previous work by Studdert and Echeverría (2000) showing a longer half-life for soil organic C with a corn–soybean rotation, as compared with continuous corn. When these two rotations were compared by an ANOVA that removed tillage and manure effects, a significant difference was obtained at $P < 0.05$, involving a greater organic C content for site-years where corn followed soybean (22.7 g kg^{-1}), as opposed to corn (17.8 g kg^{-1}). The implication is a higher critical level for the ISNT when corn is grown in rotation with soybean.

As has generally been observed, ISNT values decreased with depth of sampling, for each of the 2001–2003 site-years listed in Tables 2 and 3. The magnitude of this decrease was especially marked for site-years 87 and 88, both of which were located within a field where corn had repeatedly been grown in the past for silage production. The low test values thereby obtained for the 30- to 60-cm depth (data not reported) suggest a limitation in subsoil fertility, which may have contributed to fertilizer N responsiveness that would not have been predicted by testing the surface 30 cm. Any such limitation would have been exacerbated for these site-years because of their high plant populations that would have increased competition for uptake of water and nutrients. The result would have been deeper and more extensive rooting, as observed in several field studies by Pavylochenko (1937).

Utilizing the traditional approach for yield-response trials, the work reported involved replicate field plots in a balanced statistical design, so as to define a site-average relationship between ISNT values and crop N response. The availability of within-site data for 2001–2003 studies revealed that yields were often erratic in comparing different N rates within a block, as well as among blocks. In such cases, ISNT values for different blocks tended to reflect a similar pattern of spatial variation. This association is clearly evident from Table 7, for a site-year identified as nonresponsive from averaged data when one block was actually responsive. The latter response coincided with the lowest ISNT values, particularly for the 30- to 60-cm depth, and test values were generally consistent with block differences in check-plot yield. There is an obvious implication that the effectiveness of the ISNT will depend on sampling scale, which should be adequate to characterize the area sampled for yield measurement. Equally obvious is a potential for site-specific N management.

If the ISNT measures a mineralizable form of soil N, then a positive relationship should exist between test values and grain yield without incremental N fertilization (i.e., check-plot yield). This relationship was confirmed by carrying out an ANOVA, and was found to be highly significant ($P < 0.001$). The same level of significance was observed in differentiating responsive from nonresponsive site-years by the ISNT and in relating test values to delta yield, EONR, and FNUE. The latter effects were negative, as would be expected because crop N response and fertilizer requirement would be reduced by more extensive mineralization. The mineral N thereby generated is ignored in making yield-based fertilizer N recommendations, and as noted previously for the PY method, the result is often overfertilization. The potential value of the ISNT for fertilizer N management was clearly demonstrated by an ANOVA to compare different parameters in accounting for the errors we observed in PY recommendations. Significant effects were observed for only two of the parameters evaluated. Besides the previous crop ($P < 0.05$), the ISNT was the most powerful predictor ($P < 0.001$).

CONCLUSIONS

A yield-based approach for fertilizer N management is inherently flawed by the underlying assumption that soil N provides a constant proportion of crop N uptake, and by the use of fixed credits to estimate the input of N from recent manuring or a previous legume. The usual result is overfertilization, although as demonstrated herein, the PY method can lead to underfertilization with a corn–soybean rotation. The economic and environmental consequences can be alleviated in a humid region by adopting a soil-based approach that quantifies the effect of mineralization on plant N availability.

The ISNT far surpassed the PY method in identifying sites where N fertilization was completely ineffective, and also proved to be sensitive to quantitative differences in soil N availability, suggesting that yield-based N rates can be reduced when test values are high. In order for this test to be utilized successfully, soil sampling must be done on an appropriate scale and to a depth consistent with ISNT calibration, and interpretations must account for crop rotation, planting density, and any occurrence of a soil fertility limitation.

ACKNOWLEDGMENTS

We thank L. C. Gonzini and J. J. Warren for conducting the field-plot research reported, T. J. Smith for assistance with data collection and soil series identifications, Dr. S. Aref for the statistical analyses presented, Dr. C. S. Mulvaney for prayerful support and suggestions, and the farmers whose cooperation provided the site-years studied. Partial support for this research was obtained from the Fertilizer Research and Education Council.

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