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SMAF: A Soil Health Assessment Tool

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The Soil Management Assessment Framework (SMAF) was developed to help quantify soil quality/health effects of tillage, crop rotation, and other soil management practices. Our objective was to determine if the SMAF could detect soil health differences after growing a single winter triticale (*X Triticosecale* Wittmack) crop. Soil samples were collected from 0 to 7.5- and 7.5 to 15-cm depth increments during the 2003 – 2004 and 2004 – 2005 growing seasons near Ames and Lewis, IA, and analyzed for several potential soil quality indicators. The SMAF analysis showed higher soil quality ratings for surface than subsurface samples. It also showed that a single winter grain crop can significantly improve soil quality after either corn (*Zea mays* L.) or soybean (*Glycine max* [L.] Merr.). Finally, in response to increasing interest in soil health assessments, a detailed appendix is attached to provide guidance for future soil health assessments.

INDEX DESCRIPTORS: Soil Management Assessment Framework (SMAF), sustainable soil management, soil health.

Soil quality and soil health are very similar terms, often used by soil scientists and producers, respectively, to characterize current soil conditions. Some may argue for distinguishing between the two terms, but we consider them to be synonymous. Currently, both terms are receiving increased global attention with regard to soil security, as humankind strives to meet food, feed, fiber, and fuel needs for a population expected to exceed nine billion by 2050.

Soil quality assessment strategies were developed during the 1990s to monitor biological, chemical and physical responses to various land uses, farming systems and management practices (Karlen et al., 1997). To help quantify those responses, the Soil Management Assessment Framework (SMAF) was developed by Andrews et al. (2004) and has been shown to be an effective tool for quantifying soil management effects on critical soil functions (Jokela et al., 2009; Karlen et al., 2006; Karlen et al., 2011; Liebig et al., 2006; Stott et al., 2011; Wienhold et al., 2006; Zobeck et al., 2008).

Karlen et al. (2006) used the SMAF to evaluate midwestern crop rotations and concluded that including at least three years of forage resulted in better soil quality than producing only corn and soybean. Total organic carbon (TOC) was the most sensitive indicator, while soil bulk density (BD) was the least sensitive for soils in north central Iowa and southwest Wisconsin. Wienhold et al. (2006) also used the SMAF and concluded that extended crop rotations had positive impacts on soil quality indicators in the Great Plains. Nutrient cycling, TOC content, and productivity improved as the frequency of tillage and fallow periods were reduced and the length of crop rotations was extended.

Similarly, Zobeck et al. (2008) compared the SMAF and the soil conditioning index (SCI) for irrigated cropping systems near

Ft. Collins, CO. The systems included different N fertilizer rates for no-till (NT) and conventionally tilled (CT) corn as well as NT corn grown in rotation with barley (*Hordeum distichon* L.), soybean and dry bean (*Phaseolus vulgaris* L.). Both indexes detected differences between plots receiving very high N from those with no N. However, the SMAF facilitated more detailed differentiation among crop management systems than the SCI. The SMAF separated the cropping systems into three groups and showed a decrease in overall soil quality as tillage intensity increased and surface residues decreased. In Wisconsin, Jokela et al. (2009) used the SMAF to evaluate cover/companion crops incorporated into a silage corn system and concluded that application of animal manure could improve soil quality.

The studies cited above and others have demonstrated the utility of the SMAF as an assessment tool, but further development and evaluation for other soil and crop management systems are needed. The most recent SMAF improvements were the development and incorporation of three new scoring curves for water-filled pore space, soil-test K, and β -glucosidase (Wienhold et al., 2009; Stott et al., 2010). Another need to further improve the SMAF is to acquire temporal data to determine how quickly soil quality changes can be detected. This study was conducted to meet that need by collecting soil samples before and after growing winter triticale (*X Triticosecale* Wittmack) at two Iowa locations during the 2003 – 2004 and 2004 – 2005 cropping seasons.

This SMAF project was imposed on a larger field project (Gibson et al., 2007) that quantified triticale grain and dry matter yield response to four N fertilizer rates and estimated the amount of soil N assimilated by triticale when grown following either corn or soybean. The field study showed that at one site, triticale grain and dry matter yields were greatest when 33 kg N ha⁻¹ was applied, but at the other site, yields were not increased by applying N fertilizer. Total N accumulation by triticale was nearly complete by early May and ranged from 39 to 133 kg N ha⁻¹ with no N fertilizer and from 98 to 192 kg N ha⁻¹ with 99 kg N ha⁻¹.

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Table 1. Mean SMAF indicator and SQI values for two sampling depths collected before and after growing winter triticale near Ames, IA.

Indicator [†]	2003 – 2004 Growing Season				2004 – 2005 Growing Season			
	Pre-plant		Post-harvest		Pre-plant		Post-harvest	
	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm
WSA (g kg ⁻¹)	238	248	289	305	323	319	376	427
pH	6.51	6.48	5.90	5.87	6.53	6.59	7.03	7.13
EC (ds m ⁻¹)	0.11	0.11	0.19	0.13	0.29	0.26	0.21	0.17
TOC (g kg ⁻¹)	20.6	19.6	20.6	18.6	31.2	30.2	30.5	29.6
MBC (mg kg ⁻¹)	329	239	506	519	406	285	585	424
P (mg kg ⁻¹)	55	49	55	29	68	37	52	35
SQI	0.77	0.72	0.85	0.81	0.93	0.88	0.94	0.92

[†]WSA – water stable macro-aggregates; pH – a measure of acidity; EC – electrical conductivity; TOC – total organic carbon; MBC – microbial biomass carbon; P – phosphorus; SQI – soil quality index

In addition, Nance et al. (2007) calculated partial N budgets and found that triticale reduced soil nitrate-nitrogen (NO₃-N) to a depth of 120 cm by 33 to 53 kg N ha⁻¹ at one location and 46 to 53 kg N ha⁻¹ at the other. Their results were supported by other research (e.g., McCracken et al., 1995; Dinnes et al., 2002; Feyereisen et al., 2006; Kaspar et al., 2007) and led to the conclusion that triticale could be grown as a winter cover crop for either grain or bioenergy feedstock with little additional N fertilizer and simultaneously reduce the potential for NO₃-N leaching into surface or subsurface water resources.

Our specific objective was to determine if the SMAF could detect soil quality differences after growing a single winter triticale crop. To do so, the response of various soil quality indicators and changes in an overall SMAF soil quality index (SQI) were evaluated. Finally, to provide complete documentation for future assessments such as these, supplemental information providing detailed methods and results from the soil quality/health evaluation were compiled in an appendix.

MATERIALS AND METHODS

Several biological, chemical, and physical soil quality indicators were evaluated before and after growing a winter triticale crop at two locations near Ames, IA, and two locations near Lewis, IA, during the 2003 – 2004 and 2004 – 2005 growing seasons. The dominant soil series at both Ames locations was Clarion loam (fine-loamy, mixed, mesic Typic Hapludolls), while at Lewis it was Marshall silty clay loam (fine-silty, mixed, mesic Typic Hapludolls) for the 2003 – 2004 site and Exira silty clay loam (fine-silty, mixed, mesic Typic Hapludolls) for the 2004 – 2005 site. Each of the field studies was conducted using a randomized complete block (RCB) design with four replications. Standard soil analytical methods described in the Appendix were used to determine microbial biomass carbon (MBC), water stable aggregation (WSA), pH, electrical conductivity (EC), Mehlich III extractable phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), total organic carbon (TOC), total nitrogen (TN), and diethylenetriamine pentaacetic acid (DTPA)-extractable copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

The SMAF used for this study was developed by Andrews et al. (2004) to assess the impact of management practices on soil functions associated with crop productivity, waste recycling, or environmental protection. Measured values for specific soil

properties or indicators are transformed into unitless scores ranging from 0 to 1 using scoring algorithms. These values provide an indication of how well critical soil functions represented by the indicator are being performed. The nonlinear scoring algorithms take one of three general shapes: more-is-better, less-is-better, or mid-point optimum. For this evaluation, we selected six potential soil quality indicators from those Andrews et al. (2004) used to develop the SMAF. Scores for each indicator were calculated using an Excel spreadsheet version of the SMAF and then combined to obtain an overall SQI for each research site.

RESULTS AND DISCUSSION

Pre-plant and post-harvest mean indicator values for the six soil quality indicators and resultant SQI measured for each sampling depth at the Ames locations are presented in Table 1. Similar data for the Lewis sites are presented in Table 2.

Water stable aggregation (WSA) was chosen as one of the six indicators used to illustrate the SMAF because it reflects several important soil functions. When soil scientists use the term WSA, they are referring to how resistant soil aggregates (combinations of sand, silt, clay, and organic matter) are to being broken apart by physical forces associated with wind, water, and tillage. Soils with higher WSA values will generally have a more crumb-like, granular, or porous surface than soils with low WSA values. Soils with a more porous surface will be able to absorb rainfall more easily and resist the breakdown and formation of soil crusts. If the soil has low WSA values, the soil aggregates are dispersed, and crusts often form after just a small amount of precipitation or irrigation water is applied. If crusting occurs, much of the additional water will simply run off the soil surface, increasing soil erosion and carrying with it valuable soil particles, plant nutrients, and possibly pesticides.

Growing winter triticale on Clarion loam soil at the Ames sites (Table 1) significantly ($P < 0.01$) increased WSA at both sampling depths (0 – 7.5 and 7.5 – 15 cm) each year. Differences between the two depths were also significant ($P \leq 0.05$) following the triticale crop, but not before. At the Lewis sites, (Table 2) which were located on silty clay loam soils, growing triticale significantly increased the WSA values during the 2003 – 2004 growing season, but not during the 2004 – 2005 season. Differences between the two sampling depths were also significant in the first year but not the second. Increased WSA values such as those observed in three of four site-years

Table 2. Mean SMAF indicator and SQI index values for two sampling depths collected before and after growing winter triticale near Lewis, IA.

Indicator [†]	2003 – 2004 Growing Season				2004 – 2005 Growing Season			
	Pre-plant		Post-harvest		Pre-plant		Post-harvest	
	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm
WSA (g kg ⁻¹)	266	225	231	238	266	248	283	280
pH	6.52	5.56	5.70	4.54	6.37	5.64	7.25	6.58
EC (ds m ⁻¹)	0.19	0.13	0.22	0.13	0.28	0.18	0.23	0.19
TOC (g kg ⁻¹)	22.8	22.1	24.0	19.2	20.7	17.3	24.1	16.1
MBC (mg kg ⁻¹)	562	260	501	278	418	155	392	340
P (mg kg ⁻¹)	51	23	36	15	34	20	31	16
SQI	0.81	0.66	0.78	0.61	0.78	0.60	0.77	0.70

[†]WSA – water stable macro-aggregates; pH – a measure of acidity; EC – electrical conductivity; TOC – total organic carbon; MBC – microbial biomass carbon; P – phosphorus; SQI – soil quality index

associated with this study in response to growing winter triticale have subsequently been observed in studies growing winter rye (*Secale cereale* L.) as a cover crop for bioenergy feedstock production studies (Osborne et al., 2014).

Total organic carbon (TOC) content of soils is another indicator included in this SMAF analysis because of the numerous soil quality/health properties and processes that are influenced by soil organic matter. In addition to its impact on WSA as discussed above, TOC influences nutrient cycling, increases soil water retention, and provides an important food source for many soil fauna and micro-organisms. TOC is also the focal point for the Natural Resources Conservation Service (NRCS) soil conditioning index (Zobeck et al., 2008), and as such is a well-recognized indicator of soil quality/health.

Several challenges associated with using only TOC for soil health assessment include the fact that detecting differences due to management practices, especially in soils from the midwestern USA where TOC levels can exceed 40 – 50 g kg⁻¹ (i.e., 4 – 5%) can be very difficult. Also, even though TOC can be quickly lost when switching from perennial cover to row crops or from long-term no-tillage to tilled systems through rapid oxidation (similar to burning logs on a fire), it often takes many years to detect an increase due to improved soil management practices. Therefore, developing tools to detect short-term changes in TOC is an important goal for soil health monitoring.

Measurements of TOC before and after the winter triticale crop showed a significant difference ($P \leq 0.05$) only for the Exira silty-clay loam site (Table 2). This likely reflects the greater slope, more erosion, and lower productivity of Exira soils than either the nearby Marshall soil or the Clarion loam found on the Des Moines Lobe near Ames. Sampling depth comparisons of TOC for the Clarion soil showed a significant difference ($P \leq 0.02$) for the 2003 – 2004 growing season but not for 2004 – 2005, presumably because TOC levels at the second Clarion site were approximately 10 g kg⁻¹ (1.0%) higher than at the first site. For the Lewis sites, TOC differences due to sampling depth were highly significant ($P \leq 0.01$) except for the pre-plant sampling on the Marshall soil.

Soil pH was identified as an important SMAF indicator (Andrews et al., 2004) because of how it affects the availability of several essential plant nutrients. For the Ames sites, pre- and post-harvest soil samplings showed highly significant ($P \leq 0.01$) differences both years (Table 1), although in the first year it reflected lower post-harvest pH values, while in the second it

reflected higher post-harvest pH values. We suggest that spatial soil variability was a more likely cause for this response than growing triticale. At the Lewis sites (Table 2), pre- and post-harvest and sampling depth comparisons both showed highly significant ($P \leq 0.01$) differences. As noted for the Ames sites, post-harvest soil pH values were lower after the 2003 – 2004 growing season and higher after the 2004 – 2005. For the two sampling depths, soil pH for the 7.5 – 15 cm depth increment was significantly lower than for the 0 – 7.5 cm increment both years.

Electrical conductivity (EC) is included in SMAF soil health assessments because it is an effective indicator for saline soils as well as for soils with excess nitrate-nitrogen (NO₃-N) or chloride concentrations. Surface samples from all four sites showed highly significant ($P \leq 0.01$) pre- and post-harvest differences, but as noted for soil pH, the difference was due to an increase the first year and a decrease during the second. For the 7.5 – 15 cm depth, pre- and post-harvest samplings showed highly significant differences except for the Marshall soil during the 2003 – 2004 growing season (Table 2). Sampling depth comparisons showed highly significant differences except for the 2003 – 2004 pre-plant sampling on Clarion soil near Ames (Table 1). Depth differences for the other seven samplings reflected lower EC values within the 7.5 – 15 cm increment.

Microbial biomass carbon (MBC) was selected as a SMAF indicator (Andrews et al., 2004) because it reflects activity of the soil microbiological communities. It also reflects nutrient cycling, but MBC can be difficult to interpret because high values could either reflect a well-functioning soil with active microbial populations or a soil that is literally “burning itself out” due to microbial activity that is consuming more available carbon than is being returned through current management practices.

Pre- and post-harvest samples from the Clarion soils near Ames showed highly significant differences both years, with MBC levels greater following the triticale crop than before (Table 1). Similar comparisons for the Lewis sites showed a significant difference before and after the triticale crop only for the Exira soil at the 7.5 – 15 cm depth. MBC measurements for the other three Lewis sites were all very similar (Table 2). Sampling depth comparisons showed highly significant ($P \leq 0.01$) pre-plant depth differences at all four sites, but post-harvest samples showed significant differences only for the second year near Ames and in the first near Lewis.

The sixth and final SMAF indicator used to evaluate potential soil health effects of growing a winter triticale crop was Mehlich-

extractable or “soil-test” phosphorus (P). The scoring curve associated with this indicator is currently the most complex (Andrews et al., 2004) because for lower P concentrations, the response is determined by the relative availability of P to support plant growth (i.e., increasing score with increasing P values), while at higher soil-test P concentrations (generally $\geq 100 \mu\text{g g}^{-1}$) the score decreases because of increasing potential for surface runoff and off-site water contamination by soluble P. The curves are further complicated because the relative score decreases at a different rate depending upon the slope of the soil.

Pre- and post-harvest soil-test P concentrations showed highly significant differences in five of the eight samplings (Tables 1 and 2). On Clarion soils near Ames, the difference was noted for the 7.5 – 15 cm depth at the 2003 – 2004 site and for the 0 – 7.5 cm depth at 2004 – 2005 site. Both reflected lower post-harvest soil-test P levels. For the Marshall site, pre- and post-harvest soil-test P values showed highly significant differences at both sampling depths, with post-harvest values substantially lower than pre-plant values. For the Exira site there was a slight but statistically non-significant difference in pre- and post-harvest soil-test P values. Sampling depth comparisons showed significant ($P \leq 0.03$) soil-test P differences for all eight samplings, with sub-surface (7.5 – 15 cm) values lower than surface values, as expected.

As suggested by Andrews et al. (2004) soil quality/health indicator scores were added and divided by the number of indicators (i.e., six) to provide an overall soil quality index (SQI) value. The scoring curves used to interpret the indicator measurements reflect published and/or expert opinion for each specific soil (Andrews et al., 2004); therefore, individual indicator scores or the composite index should be used only to evaluate relative soil performance (i.e., health or quality) for a specific soil at a specific site over a given time period. Comparisons of different soils or soils at different sites are not valid and can actually be misleading. Furthermore, it is not essential to try to identify any specific SQI reference point such as a fence row or undisturbed cemetery plot, as suggested by some, simply because it is the magnitude and direction of change (i.e., aggrading, degrading, or stable) for a specific soil at a specific location that provides the critical measures for soil health assessment and response to different soil and crop management practices.

This study showed that with the exception of surface (0 – 7.5 cm) pre- and post-harvest SQI comparisons for the 2004 – 2005 Clarion soil near Ames and the 2004 – 2005 Exira soil near Lewis, SQI comparisons generally showed highly significant differences (Tables 1 and 2) in response to growing winter triticale. Sampling depth comparisons for all four sites also showed lower SQI ratings for the 7.5 – 15 cm sampling depth.

Finally, although this study demonstrates use of the SMAF for soil quality/health assessments using just six indicators, scoring curves have been developed for another seven indicators, and many others could easily be added to the framework (Wienhold et al., 2009). For those interested in pursuing such an activity, the rigorous field sampling, background management treatments, soil analytical techniques, and subsequent statistical analyses used to compile the mean values discussed above are presented in an appendix. That information may be useful for guiding similar soil health assessment studies to quantify effects of other soil and crop management practices.

SUMMARY AND CONCLUSIONS

Inclusion of meadow crops and small grains into extended crop rotations has previously been shown to improve soil quality

(Karlen et al., 2006; Wienhold et al., 2006; Jokela et al., 2009). This assessment shows that even a single growing season with winter triticale following either a silage corn or soybean crop can have measurable effects on several soil quality indicators and the overall SMAF index. It also supports more recent studies (e.g., Osborne et al., 2014) showing that winter cover crops can significantly improve soil resources even when a portion of the crop residue is harvested for bioenergy or bioproduct feedstock.

REFERENCES

- ANDREWS, S. S., D. L. KARLEN, and C. A. CAMBARDELLA. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. *Soil Science Society of America Journal* 68:1945–1962.
- DINNES, D. L., D. L. KARLEN, J. B. JAYNES, T. C. KASPAR, J. L. HATFIELD, T. S. COLVIN, and C. A. CAMBARDELLA. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agronomy Journal* 94:153–171.
- FEYEREISEN, G. W., B. N. WILSON, G. R. SANDS, J. S. STROCK, and P. M. PORTER. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. *Agronomy Journal* 98:1416–1426.
- GIBSON, L. R., C. D. NANCE, and D. L. KARLEN. 2007. Winter triticale response to nitrogen fertilization when grown after corn or soybean. *Agronomy Journal* 99:49–58.
- JOKELA, W. E., J. H. GRABBER, D. L. KARLEN, T. C. BALSER, and D. E. PALMQUIST. 2009. Cover crop and liquid manure effects on soil quality indicators in a corn silage system. *Agronomy Journal* 101:727–737.
- KARLEN, D. L., M. J. MAUSBACH, J. W. DORAN, R. G. CLINE, R. F. HARRIS, and G. E. SCHUMAN. 1997. Soil quality: A concept, definition, and framework for evaluation. *Soil Science Society of America Journal* 61:4–10.
- KARLEN, D. L., E. G. HURLEY, S. S. ANDREWS, C. A. CAMBARDELLA, D. W. MEEK, M. D. DUFFY, and A. P. MALLARINO. 2006. Crop rotation effects on soil quality at three northern corn/soybean belt locations. *Agronomy Journal* 98:484–495.
- KARLEN, D. L., G. E. VARVEL, J. M. F. JOHNSON, J. M. BAKER, S. L. OSBORNE, J. M. NOVAK, P. R. ADLER, G. W. ROTH, and S. J. BIRRELL. 2011. Monitoring soil quality to assess the sustainability of harvesting corn stover. *Agronomy Journal* 103:288–295.
- KASPAR, T. C., D. B. JAYNES, T. B. PARKIN, and T. B. MOORMAN. 2007. Rye cover crop and gamagrass strip effects on NO_3 concentration and load in tile drainage. *Journal of Environmental Quality* 36:1503–1511.
- LIEBIG, M., L. CARPENTER-BOGGS, J. M. F. JOHNSON, S. WRIGHT, and N. BARBOUR. 2006. Cropping system effects on soil biological characteristics in the Great Plains. *Renewable Agriculture and Food Systems* 21:36–48.
- MCCRACKEN, D. V., J. E. BOX, JR., W. L. HARGROVE, M. L. CABRERA, J. W. JOHNSON, P. L. RAYMER, A. D. JOHNSON, and G. W. HARBERS. 1995. Tillage and cover crop effects on nitrate leaching in the Southern Piedmont. Pages 135–138. *In* clean water, clean environment, 21st century: Team agriculture, working to protect water resources. Conf. Proc., Vol. II. Kansas City, MO. 5–8 Mar. 1995. American Society of Agricultural Engineers, St. Joseph, MI.
- NANCE, C. D., L. R. GIBSON, and D. L. KARLEN. 2007. Soil profile nitrate response to nitrogen fertilization of winter triticale. *Soil Science Society of America Journal* 71:1343–1351.
- OSBORNE, S. L., J. M. F. JOHNSON, V. L. JIN, G. E. VARVEL, and T. E. SCHUMACHER. 2014. The impact of corn residue removal on soil aggregates and particulate organic matter. *BioEnergy Research* 7:559–567.
- STOTT, D. E., S. S. ANDREWS, M. A. LIEBIG, B. J. WIENHOLD, and D. L. KARLEN. 2010. Evaluation of β -glucosidase activity as a soil quality indicator for the soil management assessment framework (SMAF). *Soil Science Society of America Journal* 74:107–119.

- STOTT, D. E., C. A. CAMBARDELLA, M. D. TOMER, D. L. KARLEN, and R. WOLF. 2011. A soil quality assessment within the Iowa River south fork watershed. *Soil Science Society of America Journal* 75:2271–2282.
- WIENHOLD, B. J., J. L. PIKUL, JR., M. A. LIEBIG, M. M. MIKHA, G. E. VARVEL, J. W. DORAN, and S. S. ANDREWS. 2006. Cropping system effects on soil quality in the Great Plains: Synthesis from a regional project. *Renewable Agriculture and Food Systems* 21:49–59.
- WIENHOLD, B. J., D. L. KARLEN, S. S. ANDREWS, and D. E. STOTT. 2009. Protocol for indicator scoring in the soil management assessment framework (SMAF). *Renewable Agriculture and Food Systems* 24:260–266.
- ZOBECK, T. M., A. D. HALVORSON, B. WIENHOLD, V. ACOSTA MARTINEZ, and D. L. KARLEN. 2008. Comparison of two soil quality indexes to evaluate cropping systems in northern Colorado. *Journal of Soil and Water Conservation* 63:329–338.

APPENDIX

Interest in soil quality/health assessment has increased substantially in the decade since the field study providing data for the accompanying manuscript was conducted. Because the SMAF project generated an abundance of data and provided insight into temporal soil health changes that may be of interest to those implementing soil health assessment strategies, information that was too detailed for the primary *Journal of the Iowa Academy of Science* article has been compiled for this appendix.

METHODS AND MATERIALS

The field study evaluating effects of winter triticale on various soil quality/health indicators was conducted at two Iowa locations during the 2003 – 2004 and 2004 – 2005 growing seasons. The trials were conducted on two sites at the Iowa State University (ISU) Brunner Farm (42.0° N, –93.6° W) near Ames, and on two sites at the ISU Armstrong Research and Demonstration Farm (41.2° N, –95.1° W) near Lewis. Elevations at the two sites are approximately 291 and 370 m above mean sea level, respectively.

The Ames sites were both located within major land resource area (MLRA) 103: Central Iowa and Minnesota Till Prairies. Soils in this MLRA are derived from till material deposited when the Des Moines Lobe of the Wisconsin Glacier retreated about 12,000 yrs ago. Most soils within this MLRA have low phosphorus (P) and potassium (K) subsoil fertility levels. The Lewis sites were located within MLRA 107B, the Iowa and Missouri Deep Loess Hills. The Exira and Marshall soils in this MLRA have a loess mantle underlain by glacial till from the Kansan glaciation. The Marshall series typically has high subsoil P and K, whereas, the Exira series is generally found on more sloping, eroded areas and has low subsoil P and high subsoil K.

Field Study Protocol

New plots were selected for corn and soybean planting at both sites each year. Near Ames, pre-plant tillage was completed using one pass of a field cultivator, but there was no pre-plant tillage at the Lewis sites. Corn and soybean were planted in alternating 196 m² strips (12 rows spaced 0.76 m apart [9.2 m wide] and 21.3 m long). Early maturing soybean cultivars (DeKalb DKB17-51 RR which has a relative maturity of 1.7, was used at Ames and Pioneer 92B05 RR which has a relative maturity of 1.9 was used at Lewis) were grown to ensure an optimum triticale planting date (Schwarte et al., 2005) following grain harvest. The corn crop (DeKalb DKC64-11 RR, 114-d relative maturity and Channel 7699C, 109-d relative maturity [2003] or Nutrient C 1153 ND, 115-d relative maturity [2004]) was harvested as silage at physiologic maturity to allow timely triticale planting. All non-harvested crop residues were left in the field.

Prior to establishing the field studies, soil-test data were obtained for each site. The October 2001 sampling for the

2003 – 2004 Ames site showed the surface (0 – 15 cm) soil had an average of 40 mg kg⁻¹ P, 250 mg kg⁻¹ K and a water pH of 6.5. An October 2004 soil test at the second Ames site showed 27 mg kg⁻¹ P, 160 mg kg⁻¹ K and a pH of 6.9 for the surface soil. Soil tests for the top 15 cm at the Lewis sites averaged 23 mg kg⁻¹ P, 207 mg kg⁻¹ K and a pH of 6.5 at site 1 in October 2003, and 25 mg kg⁻¹ P, 167 mg kg⁻¹ K and a pH of 7.3 at site 2 in October 2004.

Corn and soybean were planted at the Ames sites 20 May 2003 and 5 May 2004. The same corn hybrid and soybean cultivars were planted each year. Nitrogen fertilizer was applied to corn at 134 kg ha⁻¹ using urea on 9 June 2003 and as injected 32% (320 g kg⁻¹) urea-ammonium-nitrate (UAN) solution on 16 June 2004. The corn was cultivated between the rows on 9 June 2003 for weed control and to incorporate the N fertilizer. At the Lewis sites, corn was planted on 27 April 2003 and soybean on 13 May 2003. In 2004, corn was planted on 19 April and soybean on 23 April. The same planting densities were used both years. No inter-row cultivation occurred in 2003. Mechanical weed management in 2004 consisted of an inter-row cultivation of corn on 15 June. Additional agronomic and seasonal weather information for this experiment is available in Gibson et al. (2007) and Nance et al. (2007).

Winter triticale (DANKO Presto in 2003 and NE426GT in 2004) was seeded at 320 seeds m⁻² with a Tye[®]1 model 2007 no-till drill (AGCO Corp., Lockney, TX) at a row spacing of 20 cm. No tillage was performed between corn or soybean harvest and triticale planting at either site. Triticale planting dates for Ames were 26 September 2003 and 28 September 2004, and 24 September 2003 and 25 September 2004 at Lewis. Grain harvest occurred on 15 July 2003 and 11 July 2004 at Ames and on 14 July 2003 and 13 July 2004 at Lewis.

Four N fertilizer rates (0, 33, 66, or 99 kg N ha⁻¹) were randomly assigned to each pair of triticale plots growing on the harvested corn silage and soybean strips. Applications of N fertilizer in Ames were made on 23 March 2003 and 21 March 2004, and on 23 March 2003 and 17 March 2004 at Lewis. The N fertilizer was applied at Ames using a Gandy model 1010T-TBM (Gandy Co., Owatonna, MN) spreader with a 3 m width, and at Lewis with a Gandy model 6500 spreader with a 1.5 m width. Ammonium nitrate (NH₄NO₃) was used as the N fertilizer source at both locations.

Soil Quality Assessment Study

The SMAF study utilized the field plots to provide data for several potential soil quality indicators, thus expanding the evolving knowledge base for evaluating effects of soil and crop management practices (e.g. Jokela et al., 2009; Karlen et al., 2006; Karlen et al., 2011; Liebig et al., 2006; Stott et al., 2010; Wienhold et al., 2006, 2009; Zobeck et al., 2008). It is

¹ Mention of trademark, proprietary product, or vendor is for information only and does not constitute a guarantee or warranty of the product by the USDA or Iowa State University or imply its approval to the exclusion of other products or vendors that may also be suitable.

Table A1. Soil Management Assessment Framework (SMAF) indicators, their type, statistical transformation used to normalize data for analysis, and processes/properties affected.

	Notation	Type	Statistical Power Transformation [‡]	Affected Soil Process or Property
Measured indicators [†]				
Water stable aggregates (g kg ⁻¹)	WSA	Physical	-0.50	Infiltration, runoff, erosion
Mean-weight diameter (mm)	MWD	Physical	-0.50	Infiltration, runoff, erosion
Acidity/alkalinity	pH	Chemical	None	Nutrient availability
Electrical conductivity (ds m ⁻¹)	EC	Chemical	0.25	Salinity and/or NO ₃ -N levels
Total organic carbon (g kg ⁻¹)	TOC	Biological	None	Structure, nutrient cycling, microbial activity
Total nitrogen (g kg ⁻¹)	TN	Chemical	0.75	Plant growth
Microbial biomass carbon (mg kg ⁻¹)	MBC	Biological	0.25	Biological activity
Phosphorus (mg kg ⁻¹)	P	Chemical	0.50	Plant growth
Potassium (mg kg ⁻¹)	K	Chemical	Log [y + 1]	Plant growth
Calcium (mg kg ⁻¹)	Ca	Chemical	Log [y + 1]	Plant growth
Magnesium (mg kg ⁻¹)	Mg	Chemical	-0.75	Plant growth
Copper (mg kg ⁻¹)	Cu	Chemical	-0.25	Plant growth
Iron (mg kg ⁻¹)	Fe	Chemical	0.50	Plant growth
Manganese (mg kg ⁻¹)	Mn	Chemical	0.25	Plant growth
Zinc (mg kg ⁻¹)	Zn	Chemical	Log [y + 1]	Plant growth
Scored indicators [†]				
TOC score	TOC	Biological	0.75	—
WSA score	WSA	Physical	None	—
MBC score	MBC	Biological	1.75	—
pH score	pH	Chemical	3.00	—
P score	P	Chemical	3.00	—
Soil Quality Index [§]	SQI	Comprehensive	3.00	—

[†]Measured indicators are the soil properties that were actually measured for each of the soil samples, while Scored indicators were those computed by applying the SMAF scoring curves to the measured data

[‡]The statistical transformation required to normalize the data for statistical analyses

[§]The SQI is computed by summing each of the scored SMAF indicators noted in the tables as Notation_{score} and then dividing by the number of indicators used

important to note that this assessment study was not designed to measure any sequential soil quality effects of growing triticale or multi-year effects of either a corn silage-triticale-soybean or soybean-triticale-corn silage rotation. The goal was to collect temporal data that can be used to verify and/or refine current and future scoring curves for a variety of SMAF indicators.

For each site-year the soil quality assessment study had an identical treatment structure consisting of four N fertilizer rates, two prior crops, two sampling depths, and two sampling times. Nitrogen fertilizer rate was the main (whole plot) factor. Prior crop strips (silage corn or soybean) were split within each N fertilizer treatment. Soils for the indicator assessment were sampled at two sequential depth intervals of 0 – 7.5 cm and 7.5 – 15 cm. The sampling times were non-random, targeted to be within one week prior to planting triticale and again within one week after harvest.

For each sampling date, 20 soil cores were taken at random locations to a depth of 15 cm within each designated plot using a soil probe with a 31.75 mm (1¹/₄ in) sampling tip. Each soil core was separated into two depth increments: 0 – 7.5 cm, and 7.5 – 15 cm. The multiple samples were mixed and composited into a single sample for each depth within each plot.

Field-moist samples were weighed before further processing. After hand-mixing, a sub-sample (100 g) was removed and immediately frozen until it could be analyzed for microbial

biomass. The remainder of the field-moist soil sample was passed through an 8-mm screen and dried. A subsample was retained to measure water-stable aggregation and the remainder was ground to pass a 2 mm screen and analyzed for pH using a 1:1 soil-to-water ratio (Watson and Brown, 1998), electrical conductivity (EC) (Whitney, 1998a), as well as Mehlich III extractable P, K, calcium (Ca), and magnesium (Mg) (Mehlich, 1984). Total organic carbon (TOC) and total nitrogen (TN) were determined by dry combustion with a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). Extractable P, K, Ca, and Mg concentrations were determined using an inductively coupled plasma-atomic emission spectrograph (ICP-AES). Analyses for copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were made using diethylenetriaminepentaacetic acid (DTPA) extraction procedure as described by Whitney (1998b).

Microbial biomass carbon (MBC) was determined using the fumigation-extraction procedure (Vance et al., 1987) with a K-value of 0.39 for conversion of extracted C to biomass. The quantity of water-stable macro-aggregates (WSA) was calculated after determining aggregate stability for a 100-g air-dry subsample using the wet-sieve method (Cambardella and Elliott, 1993) with five sieves that separated water stable aggregates into size classes of: 4.0 – 8.0 mm, 2.0 – 4.0 mm, 1.0 – 2.0 mm, 0.5 – 1.0 mm, and 0.25 – 0.50 mm. Weights for the individual size classes were combined to create three water-stable macro-

Table A2. Probability of significant replication, N fertilizer rate or preceding crop effects on transformed soil quality indicator data for each site-year.

Indicator [†]	Site-year											
	Ames 2003–2004 <i>P(F)</i> [‡]			Ames 2004–2005 <i>P(F)</i>			Lewis 2003–2004 <i>P(F)</i>			Lewis 2004–2005 <i>P(F)</i>		
	Rep	N Rate	Prior Crop	Rep	N Rate	Prior Crop	Rep	N Rate	Prior Crop	Rep	N Rate	Prior Crop
WSA	<0.01	0.87	0.37	0.33	0.02	0.75	0.48	0.43	0.23	0.64	0.74	0.01
MWD	0.01	0.39	0.23	0.16	0.09	0.93	0.51	0.37	0.04	0.28	0.29	<0.01
pH	0.92	0.80	0.80	0.13	0.78	0.80	0.02	0.89	0.36	0.12	0.13	0.74
EC	0.62	0.98	0.72	<0.01	0.55	0.04	0.02	0.16	0.61	0.57	0.07	<0.01
TOC	0.46	0.30	0.97	0.70	0.28	0.94	0.63	0.13	0.23	0.09	0.55	0.35
TN	0.18	0.36	0.64	0.39	0.46	0.32	0.60	0.38	0.11	0.04	0.37	0.57
MBC	0.44	0.70	0.69	0.07	0.13	0.38	0.92	0.65	0.12	0.10	0.26	0.45
P	0.05	0.11	0.85	0.49	0.44	0.01	0.19	0.66	0.13	0.50	0.46	0.70
K	0.02	0.06	<0.01	0.46	0.36	0.04	0.74	0.87	0.08	0.06	0.21	0.26
Ca	0.67	0.38	0.15	0.17	0.42	0.55	0.01	0.70	0.59	0.23	0.08	0.12
Mg	0.45	0.21	0.87	0.08	0.24	0.25	0.04	0.92	0.84	0.11	0.57	0.79
Cu	0.82	0.92	0.01	0.62	0.68	0.46	0.02	0.75	0.54	0.53	0.89	0.11
Fe	0.46	0.83	0.83	0.01	0.65	0.94	0.01	0.58	0.32	0.29	0.53	0.09
Mn	0.66	0.73	0.70	0.31	0.59	0.58	0.06	0.62	0.76	0.02	0.16	0.41
Zn	0.50	0.84	0.01	0.61	0.44	0.38	0.29	0.76	0.87	0.40	0.61	0.34
TOC	0.45	0.29	0.96	0.66	0.45	0.71	0.63	0.13	0.23	0.10	0.52	0.31
AGG	<0.01	0.90	0.41	0.36	0.03	0.64	0.43	0.31	0.18	0.42	0.76	0.05
MBC	0.84	0.66	0.67	0.11	0.18	0.20	0.80	0.74	0.26	0.21	0.65	0.26
pH	0.88	0.81	0.90	0.37	0.95	0.76	0.04	0.74	0.22	0.15	0.81	0.57
P	0.08	0.19	0.78	0.63	0.62	0.07	0.11	0.85	0.57	0.18	0.55	0.55
EC	0.75	0.85	0.22	<0.01	0.74	0.79	0.12	0.94	0.34	0.80	0.36	<0.01
SQI	0.26	0.51	0.55	0.72	0.30	0.95	0.67	0.52	0.07	0.18	0.81	0.44

[†]See Table A1 for soil health indicator definitions and units of measurement

[‡] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

aggregate categories – All (0.25 – 8.0 mm), Small (0.25 – 2.0 mm), and Large (2.0 – 8.0 mm), each expressed as a fraction of total soil mass (g kg⁻¹). To characterize stable aggregate size distribution, we calculated the mean weight diameter (MWD), a single-number index equal to the sum of the fraction of total soil mass in each aggregate size class (including <0.25 mm), weighted by the mean diameter of each size class (Vansteenberg et al., 1991). Our general classifications of these soil quality/health indicators and key functions of each are presented in Table A1.

The SMAF Framework

Six potential soil quality indicators – TOC, WSA, MBC, pH, soil test P, and EC – were used to quantify effects of growing winter triticale on overall soil quality/health. The indicators used were based upon availability of laboratory resources with a requirement that there was at least one indicator reflecting biological, chemical, and physical properties (Table A1).

Statistical Analysis

Due to inherent differences in soil biogeochemical properties and weather patterns for the four site years, the statistical analyses were designed to determine if it was necessary to treat each site-year as a single trial. Pre-planned comparisons included pre-plant vs. post-harvest soil sampling dates and surface (0.0 – 7.5 cm) vs. sub-surface (7.5 – 15.0 cm) sampling depths. Given that pre-plant

and post-harvest samples were collected twice at similar depth intervals, the samples were considered as repeated measures.

Exploratory data analyses (e.g. mean, standard deviation, normality tests, etc.) were used for all variables across all site-years. Considerable heterogeneity of variance and outliers existed for all but a few parameters within the datasets. Outliers beyond three standard deviations were removed and treated as missing data. Variance stabilizing transformations for each response variable were made using the Box-Cox Test (British Columbia Ministry of Forest Research Program, 2005) within the SAS Trans-Regression Procedure (SAS Inst., Inc., Cary, NC). An analysis of variance (ANOVA) was run for each variable dataset with power transformations as recommended by the Box-Cox Test and site-year added as a factor. The site-year and site-year-by-factor terms were examined as both fixed and random effects. However, for practicality and recognizing that the SMAF was designed to simply provide an overall soil quality index showing how various indicators responded in comparison to literature and/or experiential knowledge values (Andrews et al., 2004), our analyses were made separately for each site-year.

Each analysis began with an ANOVA using the General Linear Models (GLM) Procedure (SAS Inst., Inc., Cary, NC). Power transformations recommended by the Box-Cox Test were used to normalize the data for each variable. A fixed effects model that treated sampling depth and time of sampling as split-plot factors within a split-split-split plot ANOVA was used. Appropriate error terms were specified in the statistical programs to accurately assess the main and interaction effects. Least Squares Means (LSmeans)

Table A3. Probability of significant depth and time of sampling effects using transformed soil quality indicator data for each site-year.

Indicator [‡]	Site-year							
	Ames 2003–2004 $P(F)$ [†]		Ames 2004–2005 $P(F)$		Lewis 2003–2004 $P(F)$		Lewis 2004–2005 $P(F)$	
	Depth	Time	Depth	Time	Depth	Time	Depth	Time
WSA	0.04	<0.01	0.09	<0.01	0.03	0.14	0.32	0.01
MWD	0.03	<0.01	0.20	<0.01	<0.01	<0.01	<0.01	<0.01
pH	0.38	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01
EC	<0.01	<0.01	<0.01	<0.01	<0.01	0.07	<0.01	0.03
TOC	<0.01	0.10	0.07	0.20	<0.01	0.05	<0.01	0.06
TN	0.07	<0.01	0.54	0.81	<0.01	0.06	<0.01	0.04
MBC	<0.01	<0.01	<0.01	<0.01	<0.01	0.59	<0.01	<0.01
P	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.27
K	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ca	0.02	0.06	<0.01	0.11	<0.01	<0.01	<0.01	0.38
Mg	0.05	0.36	<0.01	<0.01	<0.01	0.33	0.01	0.12
Cu	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe	<0.01	0.97	<0.01	<0.01	<0.01	0.27	<0.01	<0.01
Mn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	0.49	<0.01	0.21	<0.01	<0.01	0.28	<0.01	<0.01
TOC	<0.01	0.07	0.10	0.54	<0.01	0.06	<0.01	0.05
AGG	0.04	<0.01	0.09	<0.01	0.03	0.15	0.74	<0.01
MBC	<0.01	<0.01	<0.01	<0.01	<0.01	0.91	<0.01	<0.01
pH	0.51	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.77
P	<0.01	<0.01	0.04	0.90	<0.01	<0.01	<0.01	0.80
EC	<0.01	<0.01	<0.01	<0.01	<0.01	0.53	<0.01	0.36
SQI	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table A1 for soil health indicator definitions and units of measurement

and all pre-planned comparisons were performed for all significant factors (i.e., p-values for F tests ≤ 0.10). This approach is consistent with other environmental assessments such as paired watershed investigations, where replication is restricted by site characteristics (Murtaugh, P. A., 2000; Meals, 2001; Meals and Hopkins, 2001).

RESULTS AND DISCUSSION

To stabilize variance before conducting statistical analyses, power transformations were applied to each indicator (Table A1). An ANOVA, conducted across all four site-years on the transformed variables, showed that variability among sites was

generally greater than within a site-year (i.e., random effects were significant at $P < 0.10$ for 10 of the 22 measured variables and fixed effects were significant at $P < 0.01$ for all indicators [data not shown]). The statistical complexity of this response is extensive and well beyond the intended goal of evaluating soil quality indicator data collected before and after a triticale crop. However, simply stated, the frequent significance of site-year and site-year by other factor (e.g., N rate, prior crop, sampling depth, etc.) interactions confirmed that separate analyses by site-year were appropriate for the study goals.

For those interested in the statistical response of each soil quality indicator to replicate N rate, prior crop, sampling depth,

Table A4. Mean soil quality indicator values and probability levels for significant differences (using transformed values) among N fertilizer rates for the various site-years.

Site-year	Indicator [‡]	N Fertilizer Rate (kg ha ⁻¹)				LSMeans Effects $Pr > t $ Value [†]					
		0	33	66	99	0 vs. 33	0 vs. 66	0 vs. 99	33 vs. 66	33 vs. 99	66 vs. 99
Ames 2003–2004	K	168	171	155	147	0.69	0.17	0.04	0.09	0.02	0.37
Ames 2004–2005	WSA	350	334	396	354	0.38	0.02	0.70	<0.01	0.21	0.04
	MWD	18.9	18.3	22.0	18.7	0.67	0.05	0.94	0.02	0.73	0.04
	AGG score	0.82	0.80	0.88	0.83	0.40	0.02	0.77	<0.01	0.26	0.03
Lewis 2004–2005	EC	0.19	0.23	0.23	0.22	0.02	0.03	0.12	0.96	0.36	0.35
	Ca	3405	3855	3645	3526	0.02	0.14	0.43	0.22	0.06	0.45

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

Table A5. Mean soil quality indicator values and probability levels for showing significant differences (using transformed values) due to prior crop for each site-year.

Site-year	Indicator [‡]	Prior Crop		Pr > t Value [†]
		Corn	Soybean	
Ames 2003–2004	K	149	171	<0.01
	Cu	3.1	3.5	<0.01
	Zn	1.6	1.9	<0.01
Ames 2004–2005	EC	0.22	0.24	0.04
	P	43	52	0.01
	K	148	165	0.04
	P	0.99	1.00	0.07
Lewis 2003–2004	MWD	10.6	11.8	0.04
	K	269	262	0.08
	SQI	0.72	0.73	0.07
Lewis 2004–2005	WSA	283	255	<0.01
	MWD	16.7	13.5	<0.01
	EC	0.20	0.24	<0.01
	Fe	35	31	0.09
	WSA	0.62	0.56	0.05
	EC	0.95	0.99	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

Table A6. Soil quality indicator means and selected contrast comparisons for time and depth of sampling at the Ames 2003 – 2004 site.

Indicator [‡]	Mean Values (Statistical Contrast Group)				Contrasts $P(F)$ [†]			
	Pre-plant		Post-harvest		Sampling Time		Sampling Depth	
	0–7.5 cm (AC)	7.5–15 cm (AD)	0–7.5 cm (BC)	7.5–15 cm (BD)	AC vs. BC	AD vs. BD	AC vs. AD	BC vs. BD
WSA	238	248	289	305	<0.01	<0.01	0.12	0.05
MWD	12.6	11.7	15.4	13.6	<0.01	<0.01	0.10	0.01
pH	6.51	6.48	5.90	5.87	<0.01	<0.01	0.57	0.56
EC	0.11	0.11	0.19	0.13	<0.01	<0.01	0.62	<0.01
TOC	20.6	19.6	20.6	18.6	0.98	0.02	0.02	<0.01
TN	1.54	1.56	1.50	1.35	0.25	<0.01	0.76	<0.01
MBC	329	239	506	519	<0.01	<0.01	<0.01	0.59
P	55	49	55	29	0.97	<0.01	0.03	<0.01
K	186	175	189	106	0.75	<0.01	0.29	<0.01
Ca	2948	3121	2951	3014	0.92	0.01	<0.01	0.11
Mg	296	327	296	327	0.57	0.46	0.12	0.08
Cu	2.6	3.1	3.5	4.2	<0.01	<0.01	0.05	0.08
Fe	58	63	53	68	0.10	0.11	0.10	<0.01
Mn	29.1	25.4	18.6	13.6	<0.01	<0.01	0.02	<0.01
Zn	1.5	1.6	2.0	2.1	<0.01	<0.01	0.60	0.64
TOC	0.47	0.42	0.46	0.38	0.83	0.02	0.02	<0.01
AGG	0.62	0.64	0.72	0.75	<0.01	<0.01	0.12	0.04
MBC	0.86	0.61	0.98	0.99	<0.01	<0.01	<0.01	0.90
pH	0.99	0.99	0.95	0.94	<0.01	<0.01	0.91	0.47
P	1.00	1.00	1.00	0.99	0.77	<0.01	0.99	<0.01
EC	0.70	0.66	0.97	0.82	<0.01	<0.01	0.46	<0.01
SQI	0.77	0.72	0.85	0.81	<0.01	<0.01	<0.01	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

Table A7. Mean soil quality indicator values and selected contrast comparisons for time and depth of sampling at the Ames 2004 – 2005 site.

Indicator [‡]	Mean Values (Statistical Contrast Group)				Contrasts $P(F)$ [†]			
	Pre-plant		Post-harvest		Sampling Time		Sampling Depth	
	0–7.5 cm (AC)	7.5–15 cm (AD)	0–7.5 cm (BC)	7.5–15 cm (BD)	AC vs. BC	AD vs. BD	AC vs. AD	BC vs. BD
WSA	323	319	376	427	<0.01	<0.01	0.92	0.03
MWD	16.5	16.7	21.4	24.5	<0.01	<0.01	0.94	0.12
pH	6.53	6.59	7.03	7.13	<0.01	<0.01	0.26	0.08
EC	0.29	0.26	0.21	0.17	<0.01	<0.01	<0.01	<0.01
TOC	31.2	30.2	30.5	29.6	0.35	0.39	0.19	0.16
TN	2.36	2.33	2.38	2.35	0.85	0.87	0.79	0.77
MBC	406	285	585	424	<0.01	<0.01	<0.01	<0.01
P	68	37	52	35	<0.01	0.32	<0.01	<0.01
K	213	130	179	121	<0.01	0.17	<0.01	<0.01
Ca	4407	4551	4425	4680	0.78	0.05	0.02	<0.01
Mg	470	534	446	464	<0.01	<0.01	<0.01	<0.01
Cu	1.1	1.3	3.6	4.2	<0.01	<0.01	0.01	0.07
Fe	21	29	31	37	<0.01	<0.01	<0.01	<0.01
Mn	11.2	9.3	27.6	25.7	<0.01	<0.01	0.01	0.18
Zn	1.0	0.9	1.7	1.7	<0.01	<0.01	0.36	0.71
TOC	0.83	0.80	0.82	0.79	0.67	0.66	0.25	0.19
AGG	0.78	0.78	0.86	0.92	<0.01	<0.01	0.92	0.03
MBC	0.94	0.76	0.99	0.96	0.02	<0.01	<0.01	0.07
pH	0.99	0.98	0.95	0.94	<0.01	<0.01	0.17	0.32
P	1.00	0.98	1.00	0.98	0.51	0.63	<0.01	<0.01
EC	1.00	1.00	0.99	0.92	0.56	<0.01	0.74	<0.01
SQI	0.93	0.88	0.94	0.92	0.05	<0.01	<0.01	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

or sampling time, probability tests for each main effect are presented in Appendix Tables A2 and A3 for each site-year. Using $P < 0.10$ as our benchmark for statistical significance across the 88 indicator-by-site-year tests, the number of times main effects were significant was: 24 for replication, 6 for N fertilizer rate, 16 for prior crop, 80 for depth of sampling, and 67 for time of sampling. It is important to interpret these results not as an “either-or” when considering significance, but to recognize that soil quality indicator effects are often expressed over a range of values rather than as distinct step functions. Thus, among the five main factors there were 21 additional occurrences of “near-significance” in the range of $P > 0.10$ but < 0.15 . Prior crop type accounted for 6 of the 21, half of which occurred at the Lewis site in 2003–2004. The rest were most often associated with N rates. Fertilizer N rate had five and time-of-sampling three near-significant results, but neither factor showed any clear trends regarding indicators for which they occurred.

For the six instances where N fertilizer rate was significant, the only discernible trend was for the Ames 2003 – 2004 site-year, when the 66 and 99 kg N ha⁻¹ rates decreased soil-test K (Table A4). This may have been caused by greater uptake (data not presented) or possibly displacement of exchangeable K by the ammonium portion of the NH₄NO₃ fertilizer. Other differences for N fertilizer rate, though statistically significant, were not considered to be important or meaningful from a practical perspective (i.e., fertilizer recommendation or soil management).

Among the 16 instances when prior crop showed a significant effect on a soil quality indicator, only the three associated with soil-test P and K at Ames are important from a soil and crop management perspective (Table A5). For both site-years, soil-test K following corn silage was significantly lower than following soybean. This has implications not only for corn silage production (Jokela et al., 2009) but also for producers who are considering opportunities to harvest corn stover as a feedstock for bioenergy production (Karlen and Kovar, 2006; Karlen et al., 2009). Simply stated, harvesting corn grain removes less K than harvesting both grain and stover.

At the Lewis site, MWD was the only indicator showing significant differences both years, but there was no consistency due to prior crop. The other prior crop differences, though statistically significant, were not large enough to suggest any specific cause or management response.

Sampling time (prior to planting triticale or after triticale harvest) and depth of sampling (0 – 7.5 cm or 7.5 – 15 cm) showed the largest number of statistically significant soil quality indicator differences in our dataset. These factors are presented by site-year in Tables A6 to A9. For the Ames 2003 – 2004 site (Table A6), 9 of 15 indicators showed significant differences due to sampling time (comparison AC vs. BC) in the 0–7.5 cm depth increment. Three indicators (WSA, MWD, and MBC) showed highly significant increases between the pre-triticale and post-triticale sampling. Two processes – freeze-thaw effects during the

Table A8. Mean soil quality indicator values and selected contrast comparisons for time and depth of sampling at the Lewis 2003 – 2004 site.

Indicator [‡]	Mean Values (Statistical Contrast Group)				Contrasts $P(F)^{\dagger}$			
	Pre-plant		Post-harvest		Sampling Time		Sampling Depth	
	0–7.5 cm (AC)	7.5–15 cm (AD)	0–7.5 cm (BC)	7.5–15 cm (BD)	AC vs. BC	AD vs. BD	AC vs. AD	BC vs. BD
WSA	266	225	231	238	<0.01	0.18	<0.01	0.45
MWD	14.9	11.4	11.2	8.5	<0.01	<0.01	<0.01	<0.01
pH	6.52	5.56	5.70	4.54	<0.01	<0.01	<0.01	<0.01
EC	0.19	0.13	0.22	0.13	<0.01	0.07	<0.01	<0.01
TOC	22.8	22.1	24.0	19.2	0.07	<0.01	0.23	<0.01
TN	2.08	1.95	2.16	1.72	0.16	<0.01	0.03	<0.01
MBC	562	260	501	278	0.14	0.48	<0.01	<0.01
P	51	23	36	15	<0.01	<0.01	<0.01	<0.01
K	428	220	327	161	<0.01	<0.01	<0.01	<0.01
Ca	2766	2695	2858	2244	0.22	<0.01	0.34	<0.01
Mg	368	324	352	325	0.10	0.78	<0.01	<0.01
Cu	3.0	3.4	4.0	5.7	<0.01	<0.01	0.10	<0.01
Fe	60	110	49	116	<0.01	0.26	<0.01	<0.01
Mn	51.4	58.9	31.3	45.6	<0.01	<0.01	0.01	<0.01
Zn	2.1	1.8	2.0	1.7	0.33	0.58	0.04	0.10
TOC	0.41	0.38	0.45	0.28	0.07	<0.01	0.23	<0.01
AGG	0.56	0.46	0.48	0.50	<0.01	0.15	<0.01	0.35
MBC	0.96	0.45	0.87	0.59	0.02	0.01	<0.01	<0.01
pH	0.99	0.90	0.92	0.63	<0.01	<0.01	<0.01	<0.01
P	1.00	0.98	1.00	0.93	0.74	<0.01	<0.01	<0.01
EC	0.97	0.82	1.00	0.75	0.04	<0.01	<0.01	<0.01
SQI	0.81	0.66	0.78	0.61	<0.01	<0.01	<0.01	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

winter and the abundance of fine roots produced by the triticale – presumably contributed to that change. The significant increase in EC and decrease in pH were probably associated with application and mineralization of the NH_4NO_3 fertilizer. Differences in the micronutrient (Cu, Fe, Mn, and Zn) concentrations, though significant, showed no consistent identifiable trends and were attributed more to sample variation than any predictable management effect.

Within the 7.5 – 15 cm increment (comparison AD vs. BD), 13 of 15 indicators showed statistically significant differences, with WSA, MWD, and MBC again increasing between the pre- and post-triticale sampling. The EC also increased significantly in the 7.5 – 15 cm increment, but soil pH and soil-test P, K, and Ca all decreased. Three of the four micronutrient concentrations showed significant differences, but once again the changes were neither large nor clearly related to any management practice.

With regard to sampling depth at the Ames 2003 – 2004 site, 8 of 15 indicators showed significant differences for the 0 – 7.5 cm increment, and 11 of 15 indicators showed significant differences at the 7.5 – 15 cm depth (Table A6). The AC vs. AD comparison shows that prior to planting, MWD, TOC, MBC and soil-test P values were significantly lower in the 7.5 – 15 cm increment than in the surface increment. Statistically, Ca, Cu, and Fe concentrations were significantly higher, while Mn concentrations were lower in the 7.5 – 15 cm increment than in the surface increment, but with regard to management the

differences were not important. For the post-triticale sampling, 11 of the 15 indicators were again statistically significant (comparison BC vs. BD) with higher WSA, MWD, EC, Mg, Cu, and Fe and lower pH, TOC, TN, P, K, Ca, and Mn.

Indicator values that could be scored using the original SMAF framework (Andrews et al., 2004) showed significant differences for 4 of 6 (0 – 7.5 cm) and 6 of 6 (7.5 – 15 cm) time-of-sampling assessments. With regard to sampling depth, 2 of 6 (0 – 7.5 cm) and 4 of 6 (7.5 – 15 cm) scored values showed significant differences (Table A6). When evaluated as an overall SQI, the index increased significantly at both sampling depths following triticale (AC vs. BC and AD vs. BD). The SQI was also significantly higher for the surface 7.5 cm than in the 7.5 – 15 cm increment (AC vs. AD and BC vs. BD).

The second site-year at Ames (2004 – 2005) showed 12 of 15 significant indicators when comparing the pre- and post-triticale samplings within the 0 – 7.5 cm depth increment (AC vs. BC) (Table A7). Those increasing were WSA, MWD, MBC, pH, Cu, Fe, Mn, and Zn, while EC, P, K, and Mg decreased significantly. For the 7.5 – 15 cm increment (AD vs. BD), 11 of 15 indicators showed significant differences between sampling dates, with WSA, MWD, MBC, pH, Ca, Cu, Fe, Mn, and Zn increasing and EC and Mg decreasing.

With regard to sampling depth, 9 of 15 indicators showed significant differences between the 0 – 7.5 cm and 7.5 – 15 cm increment prior to growing triticale (AC vs. AD), and 10 of 15 were significant following triticale (BC vs. BD); however, they

Table A9. Mean soil quality indicator values and selected contrast comparisons for time and depth of sampling at the Lewis 2004 – 2005 site.

Indicator [‡]	Mean Values (Statistical Contrast Group)				Contrasts $P(F)$ [†]			
	Pre-plant		Post-harvest		Sampling Time		Sampling Depth	
	0–7.5 cm (AC)	7.5–15 cm (AD)	0–7.5 cm (BC)	7.5–15 cm (BD)	AC vs. BC	AD vs. BD	AC vs. AD	BC vs. BD
WSA	266	248	283	280	0.24	0.01	0.10	0.86
MWD	16.3	11.4	18.4	15.3	0.06	<0.01	<0.01	0.01
pH	6.37	5.64	7.25	6.58	<0.01	<0.01	<0.01	<0.01
EC	0.28	0.18	0.23	0.19	<0.01	0.64	<0.01	<0.01
TOC	20.7	17.3	24.1	16.1	<0.01	0.15	<0.01	<0.01
TN	1.82	1.52	2.18	1.43	<0.01	0.29	<0.01	<0.01
MBC	418	155	392	340	0.50	<0.01	<0.01	0.14
P	34	20	31	16	0.51	0.36	<0.01	<0.01
K	184	150	171	101	0.33	<0.01	0.01	<0.01
Ca	3797	3488	4032	3159	0.06	<0.01	<0.01	<0.01
Mg	483	477	477	446	0.54	0.11	0.26	0.03
Cu	1.7	2.0	2.8	3.2	<0.01	<0.01	0.01	0.03
Fe	15	43	30	50	<0.01	0.06	<0.01	<0.01
Mn	19.9	25.0	52.7	60.2	<0.01	<0.01	0.04	0.15
Zn	2.0	0.8	2.2	1.1	0.24	<0.01	<0.01	<0.01
TOC	0.34	0.24	0.45	0.21	<0.01	0.17	<0.01	<0.01
AGG	0.57	0.54	0.62	0.63	0.07	<0.01	0.35	0.74
MBC	0.82	0.18	0.74	0.68	0.12	<0.01	<0.01	0.29
pH	0.99	0.90	0.93	0.96	<0.01	<0.01	<0.01	0.04
P	0.94	0.88	0.94	0.87	0.94	0.78	0.04	0.02
EC	1.00	0.95	0.98	0.95	0.21	0.98	<0.01	0.06
SQI	0.78	0.60	0.77	0.70	0.38	<0.01	<0.01	<0.01

[†] $P(F) \leq 0.10$ was selected as the benchmark to indicate statistical significance

[‡]See Table 1 for soil health indicator definitions and units of measurement

were not exactly the same indicators. The pre-triticale sampling had lower EC, MBC, P, K, and Mn values and higher Ca, Mg, Cu, and Fe, while post-triticale had lower EC, MBC, P, and K and higher WSA, pH, Ca, Mg, Cu, and Fe. Based on the SMAF, the soil quality index was higher following triticale at both depth increments and was also higher in the surface 7.5 cm than in the 7.5 – 15 cm increment.

For the Lewis 2003 – 2004 site, 11 of 15 indicators in the surface 7.5 cm (AC vs. BC) and 10 of 15 indicators (AD vs. BD) in the 7.5 – 15 cm increment were significantly different between the two sampling dates (Table A8). In contrast to the Ames site, WSA and MWD decreased significantly in the surface 7.5 cm and MWD decreased significantly in the 7.5 – 15 cm increment between the two sampling dates. This site difference may have reflected differences in soil texture (silty clay loam at Lewis vs. loam at Ames) or triticale growth, since grain yields were lower at Lewis than Ames following either corn silage or soybean (Gibson et al., 2007). For the other indicators showing significant differences between the two sampling dates, EC, TOC, and Cu increased while pH, P, K, Mg, Fe, and Mn decreased in the surface 7.5 cm. For the 7.5 – 15 cm increment, pH, EC, TOC, P, K, Ca, and Mn decreased, while TN and Cu increased significantly between sampling dates.

With regard to sampling depth, 13 of 15 indicators showed significant differences within the 0 – 7.5 cm increment (AC vs. AD) and 14 of 15 showed significant differences at the 7.5 – 15 cm depth (BC vs. BD) when pre-plant and post-harvest

samples were compared (Table A8). Prior to planting triticale, Cu, Fe, and Mn concentrations were significantly higher in the 7.5 – 15 cm depth than in the surface 7.5 cm, but AGG, MWD, MBC, pH, EC, TN, P, K, Mg, and Zn were significantly lower. Following triticale, MWD, MBC, pH, EC, TOC, TN, P, K, Ca, Mg, and Zn were significantly lower, but Cu, Fe, and Mn concentrations remained significantly higher in the 7.5 – 15 cm increment.

Among the scored indicator values, 5 of 6 values were significantly different between sampling dates and depth increments, but again they were not always the same ones (Table A8). At this site, TOC and EC scores increased in the surface 7.5 cm between sampling dates but AGG, MBC, and pH scores decreased. Within the 7.5 – 15 cm depth, the MBC score increased significantly but TOC, pH, P, and EC scores decreased significantly between sampling dates. Between depth increments, the 7.5 – 15 cm samples always had lower scores than surface samples, but prior to the triticale crop, differences were significant for WSA, MBC, pH, P, and EC scores, while the post-triticale sampling showed significant differences for the TOC, MBC, pH, P, and EC scores. Also in contrast to the Ames site, overall soil quality was lower at both depth increments following the triticale crop than before. Based on individual indicator scores, this appears to primarily be due to changes in EC and pH. Differences between depth increments were similar, with surface ratings (7.5 cm) higher than at the 7.5 – 15 cm increment.

Sampling at the second Lewis site (2004 – 2005) showed that 9 of 15 and 10 of 15 indicators were significantly different at the 0 – 7.5 cm and 7.5 – 15 cm depth increments, respectively (Table A9). Within the surface 7.5 cm, MWD, TOC, TN, pH, Ca, Cu, Fe, and Mn were significantly higher following triticale than before, while EC was lower. For the 7.5 – 15 cm increment, WSA, MWD, MBC, pH, Cu, Fe, Mn, and Zn were significantly greater, while K and Ca concentrations were lower following triticale than before. For the two depth increments, 14 of 15 indicators showed significant differences in the surface 7.5 cm, and 12 of 15 were significantly different within the 7.5 – 15 cm increment. With the exception of Cu, Fe, and Mn, which were greater at the 7.5 – 15 cm depth, the other indicators (WSA, MWD, MBC, TOC, TN, pH, EC, P, K, Ca, and Zn) were significantly lower prior to planting triticale. Post-harvest, Cu and Fe were still higher in the 7.5 – 15 cm increment, while MWD, TOC, TN, pH, EC, P, K, Ca, Mg, and Zn were all greater in the surface 7.5 cm. In contrast to the first site-year at Lewis, the overall soil quality rating for the 7.5 – 15 cm increment was increased by growing triticale, but there was no significant difference for the surface 7.5 cm. Once again, the overall soil quality rating for the surface 7.5 cm was significantly greater than for the 7.5 – 15 cm increment on both sampling dates.

For all four site-years, the SMAF soil quality rating was higher for the surface 7.5 cm than for the 7.5 – 15 cm increment. This reflects higher TOC, soil-test P, and soil-test K levels, and emphasizes the importance of protecting the surface soil from erosion. Differences in response between the Ames and Lewis sites reinforced the importance of accounting for soil texture when assessing soil quality indicators. This is a factor that has been incorporated into the SMAF assessment framework and supports conclusions published by Liebig et al. (2006).

SUMMARY AND CONCLUSIONS

Detailed methods and an in-depth discussion of how the various soil and crop management factors affected several soil quality/health indicators are presented. It also provides applied soil chemistry and environmental response information needed to support a growing database for assessing effects of management practices on soil quality indicators with tools such as the SMAF.

ADDITIONAL REFERENCES

- BRITISH COLUMBIA MINISTRY OF FOREST RESEARCH PROGRAM. 2005. The Box-Cox transformations. Pamphlet No. 62.
- CAMBARDELLA, C. A. and E. T. ELLIOTT. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Science Society of America Journal* 57:1071–1076.
- KARLEN, D. L. and J. L. KOVAR. 2006. Is potassium limiting no-till corn yields? Pages 206–211. *In* Schlegel, A. J. (ed.). *Proc. Great Plains Soil Fertility Conf.*, 6 – 7 March 2006, Denver, Colorado.
- KARLEN, D. L., S. J. BIRRELL, L. M. WENDT, and J. R. HESS. 2009. Strategies for sustainable corn stover feedstock production. (CD-ROM). *In* *Proc. 18th International Soil Tillage Research Organization (ISTRO)*, 15 – 19 June 2009. Izmir, Turkey.
- MEALS, D. W. 2001. Water quality response to riparian restoration in an agricultural watershed in Vermont, USA. *Water Science and Technology* 43(5): 175–182.
- MEALS, D. W. and R. B. HOPKINS. 2001. Phosphorus reductions following riparian restoration in two agricultural watersheds in Vermont, USA. *Water Science and Technology* 45(9): 51–60.
- MEHLICH, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis* 15:1409–1416.
- MURTAUGH, P. A. 2000. Paired intervention analysis in ecology. *Journal of Agricultural Biological and Environmental Statistics* 5(3): 280–292.
- SCHWARTE, A. J., L. R. GIBSON, D. L. KARLEN, M. LIEBMAN, and J. L. JANNINK. 2005. Planting date effects on winter triticale dry matter and nitrogen accumulation. *Agronomy Journal* 97:1333–1341.
- VANCE, E. C., P. C. BROOKES, and D. S. JENKINSON. 1987. An extraction method for measuring microbial biomass C. *Soil Biology and Biochemistry* 19:703–707.
- VANSTEENBERGEN, M., C. A. CAMBARDELLA, E. T. ELLIOTT, and R. MERCKX. 1991. 2 simple indexes for distributions of soil components among size classes. *Agriculture Ecosystems & Environment* 34:335–340.
- WATSON, M. E. and J. R. BROWN. 1998. pH and lime requirement. Pages 13–16. *In* Brown, J. R. (ed.). *Recommended chemical soil test procedures for the North Central region*, NCR Publ. 221 (rev.) Missouri Agric. Expt. Stn., Columbia, Missouri.
- WHITNEY, D. A. 1998a. Soil salinity. Pages 59–60. *In* Brown, J. R. (ed.). *Recommended chemical soil test procedures for the North Central region*, NCR Publ. 221 (rev.) Missouri Agric. Expt. Stn., Columbia, Missouri.
- WHITNEY, D. A. 1998b. Micronutrients: Zinc, iron, manganese and copper. Pages 41–44. *In* Brown, J. R. (ed.). *Recommended chemical soil test procedures for the North Central region*, NCR Publ. 221 (rev.) Missouri Agric. Expt. Stn., Columbia, Missouri.