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Cropping system effects on soil quality in the Great Plains: Synthesis from a regional project

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Abstract

Soils perform a number of essential functions affecting management goals. Soil functions were assessed by measuring physical, chemical, and biological properties in a regional assessment of conventional (CON) and alternative (ALT) management practices at eight sites within the Great Plains. The results, reported in accompanying papers, provide excellent data for assessing how management practices collectively affect agronomic and environmental soil functions that benefit both farmers and society. Our objective was to use the regional data as an input for two new assessment tools to evaluate their potential and sensitivity for detecting differences (aggradation or degradation) in management systems. The soil management assessment framework (SMAF) and the agro-ecosystem performance assessment tool (AEPAT) were used to score individual soil properties at each location relative to expected conditions based on inherent soil-forming factors and to compute index values that provide an overall assessment of the agronomic and environmental impact of the CON and ALT practices. SMAF index values were positively correlated with grain yield (an agronomic function) and total organic matter (an agronomic and environmental function). They were negatively correlated with soil nitrate concentration at harvest (an indicator of environmental function). There was general agreement between the two assessment tools when used to compare management practices. Users can measure a small number of soil properties and use one of these tools to easily assess the effectiveness of soil management practices. A higher score in either tool identifies more environmentally and agronomically sustainable management. Temporal variability in measured indicators makes dynamic assessments of management practices essential. Water-filled pore space, aggregate stability, particulate organic matter, and microbial biomass were sensitive to management and should be included in studies aimed at improving soil management. Reductions in both tillage and fallow combined with crop rotation has resulted in improved soil function (e.g., nutrient cycling, organic C content, and productivity) throughout the Great Plains.

Key words: cropping systems, soil quality, crop rotation, tillage management, assessment tools

Introduction

Soils perform numerous functions in support of agroecosystems. They provide a substrate for supporting plant growth, a reservoir for many nutrients essential for plant growth, a filter maintaining air quality through interactions with the atmosphere, a storage and purification medium for water as it passes through the soil, and a site for biological activity involved in the decomposition and recycling of

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SMAF is an additive, non-linear indexing tool for assessing soil function[12]. Soil indicator values for the 0–7.5 cm and 7.5–15 cm depths were averaged and converted to index values using scoring curves that relate soil indicators to essential functions performed by soils. Scoring curves take the general forms of less is better (e.g., bulk density), more is better (e.g., organic C), or a local optimum (e.g., pH). The tool changes the scoring curves' inflection points and thresholds to account for differences in expected ranges due to inherent soil properties, climate, and crops. Scoring curves available in the most recent version of SMAF and measured at all sites in this study included physical (macro-aggregate percentage and bulk density), chemical [total organic C, electrical conductivity (EC), and pH], and biological [microbial biomass C, microbial quotient (relationship between microbial biomass C and mineralizable C), and potentially mineralizable N] soil properties. These soil properties are indicators of soil functions (e.g., nutrient reservoir and substrate for plant growth) related to agronomic production. Indicator scores were summed to generate an index value. Increasing index values denote increasing levels of soil function. We hypothesized that greater index values were associated with increased agronomic yield.

The CON and alternative (ALT) management systems at each location were compared using the calculated SMAF index values for each replication of both treatments at each sampling date. Analysis of variance was used to detect treatment, sampling time, and treatment × sampling time effects on index values. Effects were considered significant at $P < 0.10$. Correlation between SMAF index values and agronomic (grain yield) and environmental goals (nitrate concentration and organic matter content) were also calculated to determine the utility of using this index to assess management goals.

AEPAT is a performance-based assessment tool that utilizes user-selected scoring curves and weights to generate index values[13]. Measured indicators are assigned to agro-ecosystem functions. Weights are given to individual indicators based on the user's perception of the influence that indicator has on the assigned agro-ecosystem function. Weighted indicator scores are combined to generate an agro-ecosystem function score. Weights are also given to the agro-ecosystem functions based on the user's perception of the influence the functions have on agro-ecosystem sustainability. Weighted agro-ecosystem function scores are combined to generate a score for comparing management practices. To compare CON to ALT management at each site, food production and nutrient cycling functions were used to generate an AEPAT score:

$$\text{AEPAT score} = (\text{food production} \times W_{fp}) + (\text{nutrient cycling} \times W_{nc}) \quad (1)$$

For the AEPAT assessment, the food production function was assigned a weight (W_{fp}) of 75% and the nutrient cycling function a weight (W_{nc}) of 25% to reflect the importance of productivity and uncertainty of nutrient cycling to most land managers. Soil pH and spring nitrate-N concentration were the indicators assigned to the food production function. Soil pH was assigned a weight of 40% and spring nitrate-N a weight of 60%. Spring nitrate-N was assigned a slightly higher weight since N is the fertilizer nutrient most commonly limiting crop production in the Great Plains. Soil pH was included in the scoring function because pH serves as a sensitive indicator for inefficient N fertilizer use and pH values outside the optimum range strongly influence plant availability of several essential nutrients. A threshold value sigmoidal scoring curve was selected for the soil pH indicator with an optimal value of 6.5 in wheat (*Triticum aestivum* L.)-based systems and 6.3 in corn (*Zea mays* L.)-based systems. A higher is better logistic scoring curve was selected for the spring nitrate-N scoring curve with an optimal value of 200 kg ha^{-1} and a lower bound of 1 kg ha^{-1}.

Fall nitrate-N and organic C were selected as indicators for the nutrient cycling function to reflect the environmental importance of nitrate-N leaching losses and the agronomic importance of organic matter in nutrient cycling and soil structure in these systems. Fall nitrate-N and organic C were weighted equally at 50% for assessments at Fargo, Brookings, and Mead. Equal weights were assigned due to the need to maintain organic C and to minimize fall nitrate-N concentration to reduce the potential for leaching losses at these sites. Fall nitrate-N was assigned a weight of 25% at the other locations because of the reduced potential for leaching at these semi-arid sites. Organic C was assigned a weight of 75% to reflect the importance of organic matter in nutrient cycling and soil structure in these systems. A lower is better exponential scoring curve with an optimal value of 1 kg ha^{-1} and an upper bound of 200 kg ha^{-1} was selected for the soil fall nitrate-N indicator. A higher is better logistic curve with an optimal value of 110 Mg ha^{-1} and a lower bound of 20 Mg ha^{-1} was selected for the organic C scoring curve.

Comparisons of food production function, nutrient cycling function, and AEPAT scores for contrasting management practices at each location were performed using scores calculated for each year and each replication. Analysis of variance was used to determine differences among index values between treatments and among years for each location. Differences were considered significant at $P < 0.10$.

Results and Discussion

SMAF index values

Differences between treatments for SMAF index values were observed at Fargo, Mandan, Mead, and Swift Current (Table 2). At these four locations, SMAF index values (Fig. 1) for the ALT treatment were greater than those for the CON treatment. At Fargo, Mandan, Mead, and Sidney,

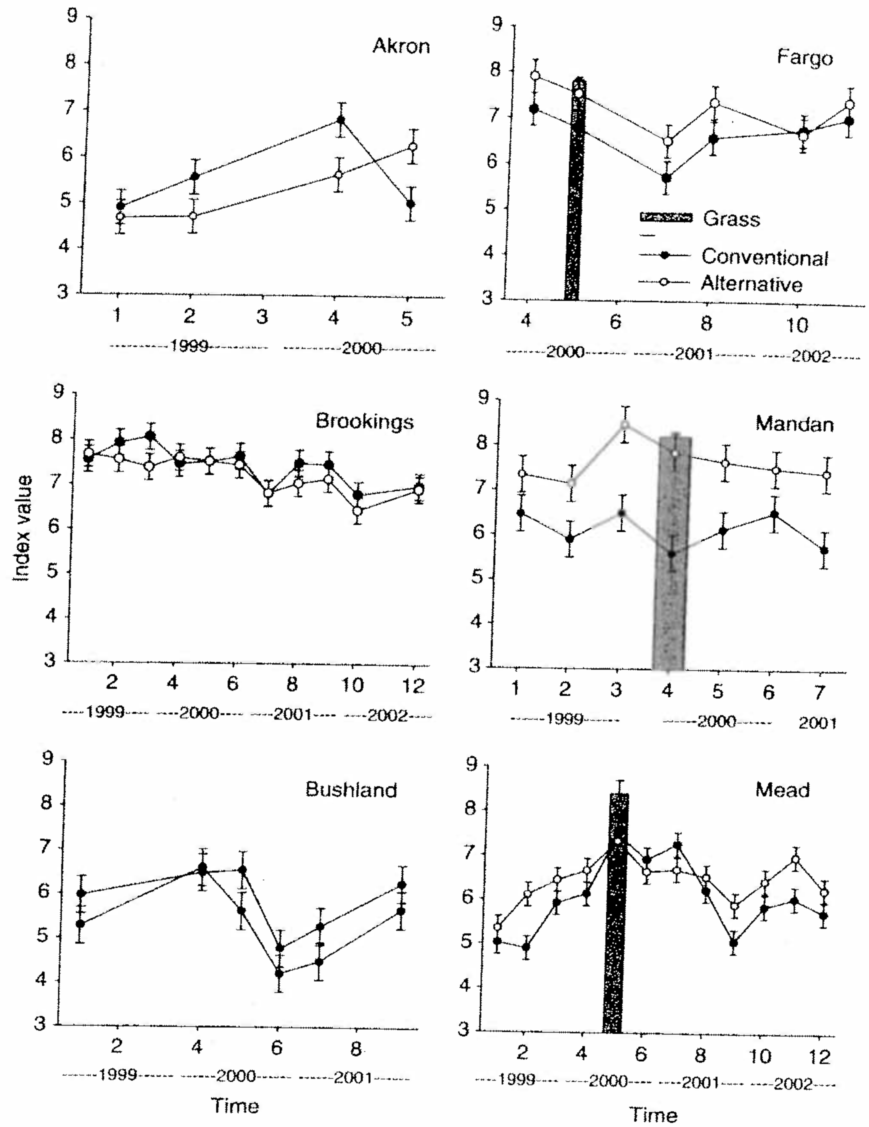

Figure 2. Soil management assessment framework (SMAF) index values as a function of time for six locations in the Great Plains. Error bars represent ±1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; post-harvest = 3, 6, 9, and 12.

Table 3. Correlation between soil management assessment framework (SMAF) index values and indicators of agronomic and environmental soil functions.

Location	Yield[1]	Nitrate-N[2]	Total Organic C[3]
Akron, CO	0.21 (0.687)[4]	0.15 (0.775)	−0.14 (0.793)
Brookings, SD	−0.63 (0.179)	0.85 (0.033)	0.01 (0.985)
Bushland, TX	n.d.	−0.94 (0.005)	−0.10 (0.853)
Fargo, ND	0.32 (0.533)	−0.61 (0.082)	0.70 (0.035)
Mandan, ND	0.89 (0.017)	−0.24 (0.537)	0.97 (< 0.001)
Mead, NE	−0.27 (0.607)	−0.89 (0.002)	0.86 (0.003)
Sidney, MT	−0.41 (0.421)	−0.91 (0.001)	0.07 (0.862)
Swift Current, SK	0.79 (0.061)	−0.28 (0.595)	0.74 (0.091)

[1] Correlation between index values averaged across sample times within a year and annual yield.
[2] Correlation between index value and nitrate-N concentration at planting.
[3] Correlation between index values and total organic C content averaged across sampling times within a year.
[4] Values in parenthesis are P-levels for the correlation analysis.

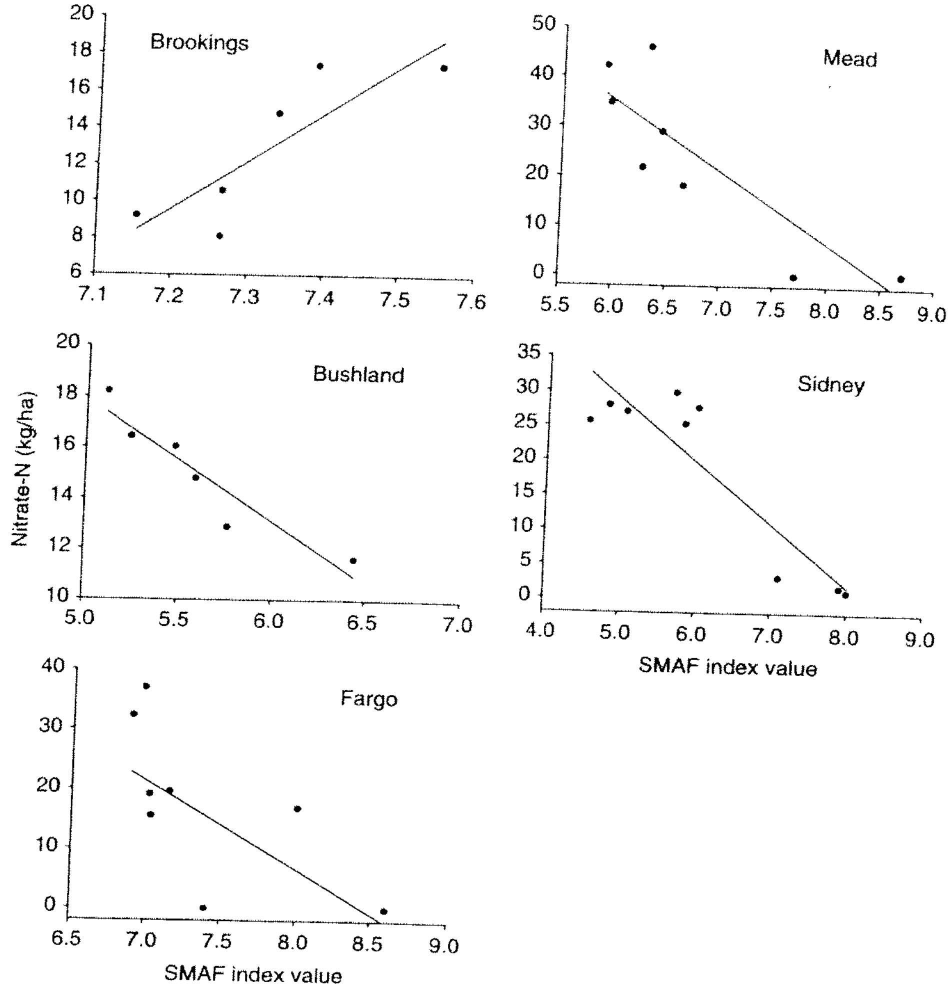

Figure 4. Correlation of soil management assessment framework (SMAF) index values and soil nitrate content at harvest for five sites in the Great Plains. See Table 3 for correlation coefficients.

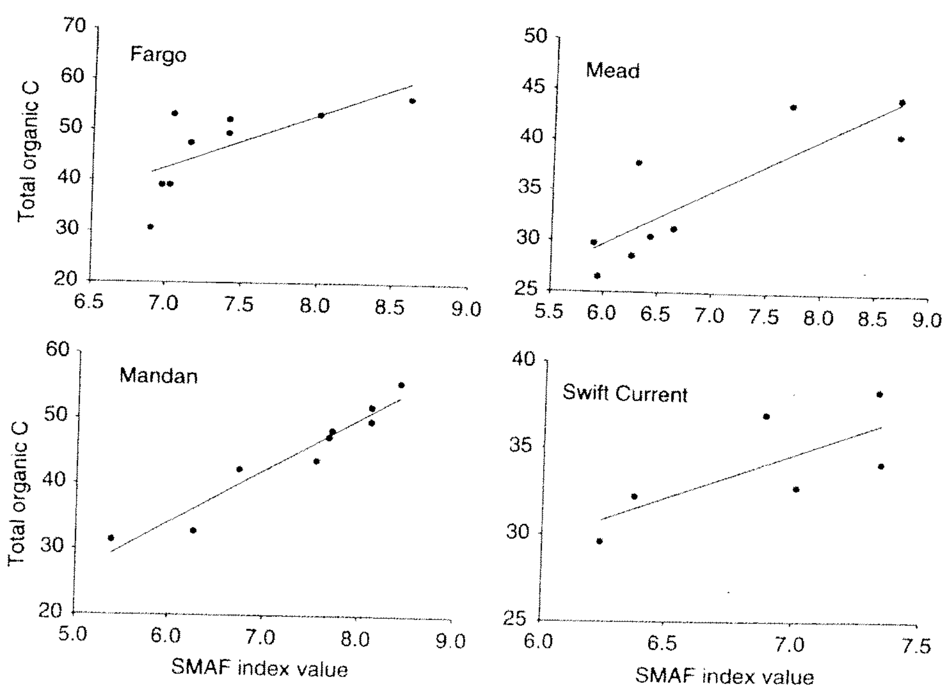

Figure 5. Correlation of soil management assessment framework (SMAF) index values and soil organic C content for four sites in the Great Plains. See Table 3 for correlation coefficients.

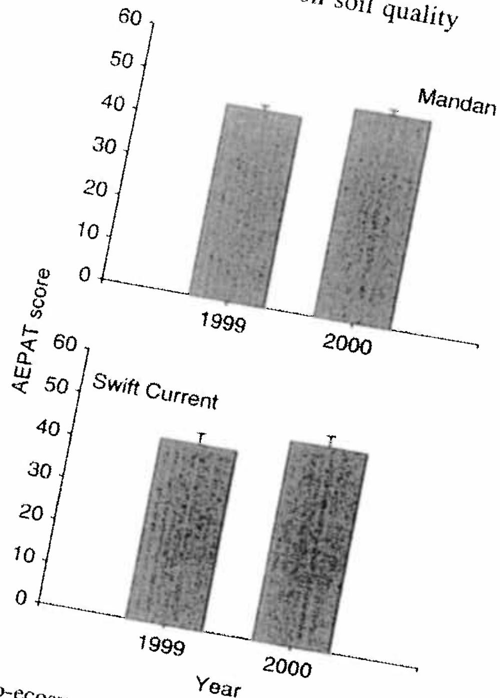

Figure 7. Agro-ecosystem performance assessment tool (AEPAT) scores as a function of year for two locations in the Great Plains. Error bars represent 1 SEM.

here, that were not included in the original objectives[8]. These research sites, with their well-documented management, sampling, and analytical procedures, are a resource for local producers and a network for the study of regional (e.g., cropping systems), national (e.g., soil erosion), and global problems (e.g., greenhouse gas emissions). Methods for interpreting large data sets are needed. Statistical methods are useful for determining differences and trends in the data, but assessment tools that interpret how these differences and trends relate to essential system functions are needed to complement statistical approaches. Two assessment tools were implemented in this study.

Assessment tools

Both of the assessment tools used in this study are readily available but are also undergoing continuing development[12,14]. The SMAF is intended for use by land managers and their advisors for use in assessing ongoing management practices[12]. The scoring curves in SMAF require only ndicator data along with crop and soils information. The rop and soils information is used by the program to adjust scoring curves for the effect of inherent soil properties, mate, and crop response. Users of the SMAF do not need ensive knowledge of the relationship between soil cators and management goals to utilize the framework. ing curves for 11 indicators are available in the current on of the SMAF and these scoring curves use indicator or the 0–15 cm depth[12]. Therefore, the use of SMAF es that samples are collected from the 0–15 cm depth ly the currently included indicators can be utilized.

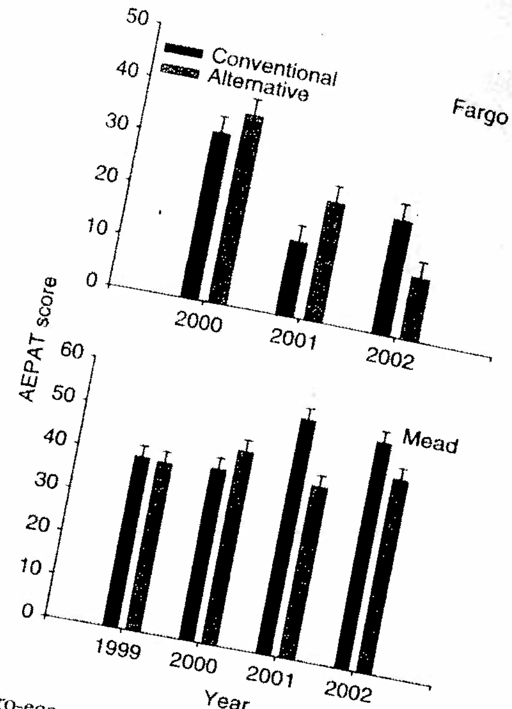

Figure 8. Agro-ecosystem performance assessment tool (AEPAT) scores as a function of management treatment and year for two locations in the Great Plains. Error bars represent 1 SEM.

The AEPAT is designed for agricultural researchers working with long-term agro-ecosystem experiments[14]. The AEPAT allows the user to select whatever indicators are thought to be important for evaluating a particular function. The user must also select the type of curve (e.g., sigmoid curve for pH) and threshold values (e.g., pH optimum of 6.5 for wheat and 6.3 for corn) for each indicator. The user also provides weights for indicators and functions to reflect their relative importance to the management goal. The input demands of AEPAT require that the user have a thorough understanding of how indicators relate to management goals. The AEPAT allows for more flexibility in terms of indicators (e.g., any indicator that affects the management goal and has a known relationship to that management goal) and sampling requirements (samples are not limited to the 0–15 cm depth increment).

Since the input requirements and intended uses of the SMAF and AEPAT are different, it is unrealistic to expect a high degree of correlation between the two indices, and inappropriate to make direct comparisons between them. However, since both programs are intended as tools for assessing the impact of management practices on essential agronomic and environmental functions, there should be a general agreement. The reason for using both assessment tools in this study relates to our third objective of assessing recently developed tools and methods.

Soil indicators

Pikul et al.[9] pointed out that spatial variation exhibited by point measurements of physical properties

7 Karlen, D.L. and Stott, D.E. 1994. A framework for evaluating physical and chemical indicators of soil quality. In J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (eds). Defining Soil Quality for A Sustainable Environment. Science Society of America Special Publication no. 35. Soil Science Society of America, Madison, WI. p. 53–72.

8 Varvel, G., Reidell, W., Deibert, E., McConkey, B., Tanaka, D., Vigil, M., and Schwartz, R. 2006. Great Plains cropping system studies for soil quality assessment. Renewable Agriculture and Food Systems 21:3–14.

9 Pikul, J.L. Jr, Schwartz, R.C., Benjamin, J.G., Baumhardt, R.L., and Merrill, S. 2006. Cropping system influences on soil physical properties in the Great Plains. Renewable Agriculture and Food Systems 21:15–25.

10 Mikha, M.M., Vigil, M.F., Liebig, M., Bowman, R., McConkey, B., Deibert, E., and Pikul, J. Jr 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renewable Agriculture and Food Systems 21:26–35.

11 Liebig, M., Carpenter-Boggs, L., Johnson, J.M.F., Wright, S., and Barbour, N. 2006. Cropping system effects on soil biological characteristics in the Great Plains. Renewable Agriculture and Food Systems 21:36–48.

12 Andrews, S.S., Karlen, D.L., and Cambardella, C.A. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal 68:1945–1962.

13 Liebig, M.A., Miller, M.E., Varvel, G.E., Doran, J.W., and Hanson, J.D. 2004. AEPAT: a computer program to assess agronomic and environmental performance of management practices in long-term agroecosystem experiments. Agronomy Journal 96:109–115.

14 Liebig, M.A. and Varvel, G.E. 2003. Effects of western Corn Belt cropping systems on agroecosystem functions. Agronomy Journal 95:316–322.

15 Bauer, A. and Black, A.L. 1994. A quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal 58:185–193.

16 Wienhold, B.J. and Halvorson, A.D. 1998. Cropping system influences on several soil quality attributes in the northern Great Plains. Journal of Soil and Water Conservation 53: 254–258.

17 Campbell, C.A. and Zentner, R.P. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Science Society of America Journal 57:1034–1040.

18 Jones, O.R. and Popham, T.W. 1997. Cropping and tillage systems for dryland grain production in the Southern High Plains. Agronomy Journal 89:222–232.

19 Lal, R., Kimble, J.M., Follett, R.F., and Cole, C.V. 1999. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL, USA.

20 Varvel, G.E. 1994. Rotation and nitrogen fertilization effects on changes in soil carbon and nitrogen. Agronomy Journal 86:319–325.

21 Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Science Society of America Journal 44:765–771.

22 Cambardella, C.A., Gijda, A.M., Doran, J.W., Wienhold, B.J., and Kettler, T.A. 2001. Estimation of particulate and total organic matter by weight loss-on-ignition. In R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (eds). Assessment Methods for Soil Carbon. Lewis Publishers, Boca Raton, FL, USA. p. 349–359.

23 Smith, J.L. and Doran, J.W. 1996. Measurement and use of pH and electrical conductivity for soil quality analysis. In J.W. Doran and A.J. Jones (eds). Methods for Assessing Soil Quality. Science Society of America Special Publication no. 49. Soil Science Society of America, Madison, WI, USA. p. 169–185.

24 Wright, S.F. and Upadhyaya, A. 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. Plant and Soil 198:97–107.

25 Islam, K.R. and Weil, R.R. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biology and Fertility of Soils 27:408–416.