*Renewable Agriculture and Food Systems: 22(4); 271–281* doi:10.1017/S1742170507001834

# Farmer perceptions of soil quality and their relationship to management-sensitive soil parameters

J.B. Gruver[1,2,*] and R.R. Weil[1]

[1]Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, USA.
[2]Department of Agriculture, Western Illinois University, Macomb, IL 61455-1390, USA.
*Corresponding author: jgruv@hotmail.com

**Accepted 24 July 2006** **Research Paper**

## Abstract

A critical step in the quantification of soil quality (SQ) is the selection of SQ benchmarks. The benchmarks used in this study were SQ ratings made by 32 farmer collaborators representing a range of farming systems, scales of operation and geographic locations in the Mid-Atlantic region of USA. Soils from 45 pairs of sites identified by their farmers as having good and poor SQ were sampled over three seasons and analyzed for 19 soil parameters. Farmer judgments of SQ were based on many factors, most commonly soil organic matter, crop performance, soil water availability and erosion history. Selected individual soil parameters were normalized and integrated into an additive SQ index (SQI). Three additional indices were developed using discriminant analysis. The level of agreement between individual parameters, SQIs and farmer SQ ratings was evaluated using paired *t*-tests and mean percent difference values. The additive SQI was found to have the highest level of agreement with farmer SQ ratings ($P < 0.0001$), demonstrating that a linear combination of soil parameters can be assembled that is more in agreement with holistic SQ criteria, such as farmer SQ ratings, than individual soil parameters. Extractable C from microwave (MW) sterilized soil (a measure of microbial biomass) was the individual parameter that best agreed with farmer SQ ratings ($P < 0.0001$). Five additional soil C parameters, as well as aggregate stability, also agreed well with farmer SQ ratings (all $P$ values $< 0.0005$). The three parameters with the highest ratio of mean percent difference to coefficient of variation (an indication of parameter reliability) were extractable C from MW sterilized soil, anthrone reactive C and macroaggregate stability (14.2, 7.7 and 3.7, respectively). Mineral fertility parameters (pH, Ca, Ca : Mg ratio, P and K) were not significantly related to farmer SQ ratings ($P$ values $>0.05$). The strong relationships observed between soil C parameters, soil structural parameters and farmer SQ ratings suggest that efforts to improve SQ in the study region should focus on monitoring and enhancement of soil C and soil structure.

**Key words:** soil quality index, farmer perceptions, soil structure, soil aggregation, extractable soil C, microbial biomass

## Introduction

A basic assumption underlying the concept of land stewardship popularized by Aldo Leopold[1] is that local knowledge of soil and other natural resources is the foundation of sustainable land management. A logical extension of this view is that farmer knowledge is a valuable resource that can contribute to the scientific investigation of soil quality (SQ). Several recent studies[2,3] have proposed that farmer assessments of SQ are a useful antecedent to more technical investigations. Other studies[4,5], however, have identified poor agreement between farmer perceptions and technical descriptions of soil and cautioned that misunderstanding of scientific principles impedes problem solving by farmers. Integration of experiential knowledge (e.g., farmer understanding of soil) with scientific methods is clearly challenging, but may be essential for understanding holistic concepts such as SQ.

Understanding how farmer perceptions of soil relate to objective soil properties is key to using farmer knowledge as a resource in the scientific investigation of soil. Ethnopedologists have identified strong relationships between indigenous soil classification systems and chemical and physical soil parameters[6]. Perhaps even more importantly, however, indigenous soil classification systems distinguish the soil characteristics that guide local management[7]. Often constraints and opportunities can be identified when local perceptions of soil contrast with scientific assessments[8].

Several recent studies[2,4] have indicated that farmers in the US have limited understanding of the technical characteristics of the soils they manage. A survey of 745 farmers in Wisconsin found a low level of agreement between farmer responses and profile characteristics of the solum at Natural Resource Inventory sampling points in their fields[4]. This is not surprising, however, as farmers interact primarily with surface soil and rarely use the esoteric soil science terminology included in the survey. In eastern Nebraska, Liebig and Doran[2] evaluated the accuracy of SQ assessments by 24 farmers of paired sites ('good' and 'poor' soils) with respect to field descriptive, field analytical and laboratory-analytical assays of soil. Farmer assessments were 'correct' or 'near correct' greater than 75% of the time for most soil parameters, but were less accurate for 'poor' soils than 'good' soils and particularly inaccurate for intangible soil properties such as available N and P.

Several regional SQ research initiatives[9,10] have used farmer perceptions of soil as a central resource. The Wisconsin Soil Health Program (WSHP) was initiated in 1990 and involved more than 100 Wisconsin farmers in a collaborative effort to gather, analyze and utilize farmer perceptions of soil[9]. One WSHP activity used a series of structured questions to identify how a select group of 28 farmers recognize healthy soil[11]. Another WSHP activity was the development of the Wisconsin Soil Health Scorecard, a checklist of soil health indicators accompanied by distinct scoring criteria[12]. The Illinois Soil Quality Initiative (ISQI) was established in 1990 and monitored physical, chemical and biological soil characteristics under different cropping systems and environmental conditions[10]. Collaborating farmers participated in evaluating soil data, developing new directions for SQ research and communicating SQ concepts to a wider audience[10]. These programs and others that have involved farmers in SQ research recognize that farmers implement the practices that improve, maintain or diminish agricultural SQ[13].

The terms 'soil quality' and 'soil health' have often been used synonymously[14] to describe the concept of 'soil fitness to perform important soil functions'[15]. While some semantic distinctions between the two terms have been presented in the literature[16,17], we offer the following differentiation to encourage greater linguistic precision in future discussions. *Soil quality* is a utilitarian term that describes compatibility between a soil's properties and valued services performed by soil. These soil properties include both inherent[18] *alias* use-invariant[19] and static[20] properties (e.g., texture, mineralogy, landscape position) and management-sensitive *alias* use-dependent[19] and dynamic[18] properties (e.g., organic matter content, biological activity, aggregate stability). In contrast, *soil health* is an ecological term that describes the extent to which a soil fulfils key criteria of biological integrity (e.g., self regulation through feedback processes and freedom from distress symptoms)[21,22]. Thus, *soil quality*, with its utilitarian orientation, is the appropriate term when discussing farmer perceptions of soil performance in agricultural production systems.

Some studies have quantified SQ using single soil parameters with broad ecological impact, such as microbial biomass[23] and active organic matter[24]. Other studies have quantified SQ using mathematical functions that vary with respect to techniques for selection (e.g., key functions[25], best-fit regression[26], power analysis[27]), weighting (e.g., threshold values[25], data set maximums[26], scoring functions[25]) and integration (e.g., additive[25,26], multiplicative[28]) of multiple parameters. Most integrative models are subjective (i.e., dependent on the priorities and judgments of investigators).

A critical step in the assessment of SQ is the identification of SQ benchmarks. Within the traditional 'soil productivity equals SQ' paradigm, high yields are a benchmark of SQ. More holistic concepts of SQ attach importance to environmental quality and soil fitness for uses other than agriculture[3]. Some studies[29–31] have used soil conditions under native vegetation as SQ benchmarks. Harris and Bezdicek[16] proposed that farmer observations and judgments of SQ could serve as the foundation for a SQ index (SQI). The present study used farmer ratings of SQ as benchmarks for evaluating the relationship between management-sensitive soil parameters and SQ. Unlike studies[2,4,5] which evaluated the accuracy of farmer perceptions, this study started with the premise that SQ ratings by recognized land stewards encapsulate valuable experiential knowledge.

The primary objective of the study was to identify management-sensitive soil parameters and SQI models that agree well with farmer SQ ratings. A secondary objective was to document field indicators of SQ used by farmers and farmer perspectives regarding best management practices for SQ.

## Materials and Methods

### *Selection of farmers*

Between the summer of 1996 and the fall of 1997, 75 Mid-Atlantic farmers recognized for their interest in soil conservation were identified as potential farmer collaborators by county extension agents, Natural Resources Conservation Service (NRCS) conservationists or the authors. During short informal telephone interviews, perspective farmer collaborators were asked to identify paired sites on their farms or adjacent land that they perceived to have the same soil type but contrasting SQ. SQ was briefly defined as 'fitness to perform important soil functions'. It was stipulated that paired sites should be mapped as the same (or very similar) soil series, so as to reduce the likelihood that differences in inherent properties (e.g., texture, slope and drainage) would obscure relationships between management-sensitive soil properties and

**Table 1.** Location, mapped soil series, main contrasting feature and season sampled for all paired SQ contrast sites.

| Farm no. | Mapped soils | Pair no. | Main contrasting SQ characteristic | Season sampled | | |
|---|---|---|---|---|---|---|
| | | | | f96 | s97 | f97 |
| 1 | Glenelg | 1 | Alfalfa versus NT[1] corn | ◆ | ◆ | ◆ |
| 2 | Sassafrass | 2 | Higher yield versus lower yield | ◆ | | |
| 3 | Penn | 3 | Higher yield versus lower yield | | ◆ | ◆ |
| 4 | Urbana | 4 | More pest damage versus less pest damage | | ◆ | ◆ |
| 5 | Glenelg | 5 | Timothy for 6 years versus timothy for 1 year | | | ◆ |
| 6 | Fauquier | 6 | 42 years of NT versus neighbor's field | ◆ | ◆ | ◆ |
| 7 | Matapeake | 7 | Fescue sod versus CT[2] row crops | | ◆ | ◆ |
| | Matapeake | 8 | Drought stressed corn versus healthy corn | | | ◆ |
| 8 | Collington | 9 | Grazed pasture versus hay field | | | ◆ |
| 9 | Urbana | 10 | Rye cover crop versus no cover crop | ◆ | | |
| 10 | Chester | 11 | NT with cover crop versus CT w/o cover crop | | ◆ | ◆ |
| | Meadowville | 12 | >30 years NT versus 15 years NT | | ◆ | ◆ |
| | Chester/Glenville | 13 | History of CT versus >30 years NT | | ◆ | ◆ |
| 11 | Sassafrass | 14 | Good tilth versus poor tilth | | | ◆ |
| 12 | Westphalia | 15 | Poor pasture versus good pasture | ◆ | ◆ | ◆ |
| 13 | Myersville/Fauqu. | 16 | Poor pasture versus good pasture | | | ◆ |
| 14 | Manor | 17 | Eroded strawberries versus sodded lane | | ◆ | ◆ |
| 15 | Fauquier | 18 | Higher yield versus lower yield | ◆ | ◆ | ◆ |
| | Myersville/Fauqu. | 19 | Higher yield versus lower yield | ◆ | ◆ | ◆ |
| 16 | Nolichucky | 20 | Permanent pasture versus NT corn | ◆ | ◆ | ◆ |
| 17 | Nolichucky | 21 | Poor pasture versus good pasture | ◆ | ◆ | ◆ |
| 18 | Chester | 22 | NT corn silage versus CT flowers | | ◆ | ◆ |
| | Chester | 23 | Full rate manure versus low rate manure | ◆ | | |
| 19 | Hagerstown | 24 | Cover crop versus no cover crop | ◆ | | |
| 20 | Mt Airy | 25 | Hay versus NT corn rotation | | | ◆ |
| | Mt Airy | 26 | Hay versus NT corn rotation | | | ◆ |
| 21 | Glenelg | 27 | Higher manure rate versus lower rate | ◆ | ◆ | |
| 22 | Mt Airy | 28 | History of orchard versus strawberries | | | |
| 23 | Chester | 29 | Good tilth versus poor tilth | ◆ | ◆ | |
| | Chester | 30 | CT org.[3] vegetables versus chisel corn/soy | ◆ | | ◆ |
| 24 | Sassafrass | 31 | Higher yield versus lower yield | ◆ | | |
| 25 | Woodstown | 32 | Alfalfa versus row crops | ◆ | | |
| 26 | Pocomoke | 33 | Poor yield versus good yield | | | ◆ |
| 27 | Chester | 34 | Eroded vegetables versus field crops | ◆ | | |
| | Glenelg | 35 | Poor pumpkins versus old Xmas tree sod | ◆ | | |
| | Glenelg | 36 | Higher yield versus lower yield | ◆ | | |
| 28 | Sassafras | 37 | Alfalfa grass sod versus small grain/soy | ◆ | ◆ | |
| | Fallsington | 38 | Irrigated crops versus non-irrigated crops | ◆ | | |
| | Sassafras | 39 | Higher yield versus lower yield | ◆ | ◆ | |
| 29 | Matapeake compl. | 40 | Agronomic versus spinach | | ◆ | |
| | Matepeake compl. | 41 | Agronomic versus spinach | | ◆ | |
| 30 | Hagerstown | 42 | Compost versus no compost | ◆ | ◆ | ◆ |
| 31 | Penn | 43 | Corn/orchard grass versus alfalfa/NT corn | ◆ | | |
| | Penn | 44 | Digestor liquids versus digestor solids | ◆ | ◆ | ◆ |
| 32 | Bucks | 45 | Good yield versus poor yield | | ◆ | |

[1] NT = no-till.
[2] CT = conventional tillage.
[3] org. = certified organic.
f96, fall 1996; s97, spring 1997; f97, fall 1997.

farmer SQ ratings. Forty-five paired sites on 32 farms were selected for inclusion in the study (Table 1) based on farmer interest and ability to identify contrasting sites and our goal of including soils from farms with a range of enterprises and scales of operation (Table 2) across the Mid-Atlantic.

During initial farm visits, farmers showed the investigators the paired sites that they perceived to have contrasting SQ (Table 2). Some of the contrasting sites were adjacent fields while others were distinct areas within the same field. Farmers were interviewed at the sites about (1) the management history of each site, (2) evidence

**Table 2.** Type and scale of enterprises associated with the participating farms.

| Enterprise | No. of farms | Scale of crop enterprise | | Scale of animal enterprise | |
|---|---|---|---|---|---|
| | | min | max | min | max |
| | | ------------------ha------------------ | | -----------animal units------------ | |
| Cash grains | 21 | 20 | 2800 | – | – |
| Vegetables | 9 | 4 | 140 | – | – |
| Cash hay | 6 | <20 | 400 | – | – |
| Fruits | 3 | 0.4 | 24 | – | – |
| Dairy | 9 | – | – | 70 | 2260 |
| Beef | 6 | – | – | 50 | 150 |
| Hogs | 1 | – | – | na | 100 |
| Poultry | 1 | – | – | na | 1000 |

of SQ differences between paired sites and (3) best management practices for improving SQ. Interviews were informal and responses were transcribed in the field. All paired sites included in the study were of similar landscape position. All but three paired sites were mapped as the same series with the remaining three mapped as different but similar soil series (e.g., Chester and Glenville silt loams).

## Soil sampling and processing

Soil samples were collected from 45 pairs of sites on 32 farms located in five mid-Atlantic states (26 in Maryland, 1 in Delaware, 2 in Pennsylvania, 2 in Virginia and 1 in West Virginia). The farms were located in three physiographic provinces: 8 in the mid-Atlantic Coastal plain, 15 in the Piedmont and 9 in the Ridge and Valley province. According to NRCS county soil survey maps, 22 different soil series were sampled (Table 1).

Soil samples were collected one, two or three times from paired sites, depending on the initial sampling season. Samples were collected prior to spring tillage or planting and after harvest but before tillage in the fall, so as to avoid periods of recent physical disturbance. At the time of each sampling, 12–14 cores (0–7.5 cm, total composite volume = 380 $cm^3$) were collected from each site using a fully enclosed zero contamination JMC soil probe (Clements Associates, Inc., Newton, IA). When row crops were sampled, an equal number of row and inter-row soil cores were collected. Samples were sealed in plastic-lined bags and transported on ice to a cold storage facility where they were stored at 5°C until processed.

The fresh weight of each soil sample was recorded and the gravimetric moisture content was determined by mass loss after drying approximately 10 $cm^3$ of soil to constant mass in a microwave (MW) oven. The remaining soil was gently crumbled through a sieve with 4 mm openings. Approximately 100 g of soil were returned to the original plastic-lined bag and reserved for analysis of macroaggregate stability. The remaining soil was passed through a sieve with 2 mm openings, analyzed for gravimetric moisture content (method described above) and then transferred to a new plastic-lined bag. Both bags of soil were stored at 5°C until needed for analysis.

## Soil analyses

Within two weeks of sampling, moist soil (<2 mm) was analyzed for the following labile C parameters: 0.5 M $K_2SO_4$ extractable C from MW sterilized soil ($C_{MW}$)[32], 0.5 M $K_2SO_4$ extractable C from unmicrowaved soil ($C_{NMW}$)[32], anthrone reactive C ($C_{AR}$)[33] in 0.5 M $K_2SO_4$ extracts of MW sterilized soil ($C_{AR}$) and substrate induced respiration ($C_{SIR}$)[34].

Total C in the $K_2SO_4$ extracts was determined using the Islam and Weil MW digestion method[35]. Microbial biomass C ($C_{MB}$) was calculated by subtracting $C_{NMW}$ from $C_{MW}$ and multiplying by an efficiency coefficient of $k = 0.21$ determined by Islam and Weil[32]. $C_{AR}$ (a measure of reducing sugars) was determined by reacting 0.1% anthrone with 0.5 M $K_2SO_4$ extracts of MW sterilized field moist soil ($C_{AR}$) at 80°C in concentrated sulfuric acid[33] followed by spectrophotometric analysis of the resulting color complex. $C_{SIR}$ was calculated as the difference in $CO_2$ evolution during a 6 h incubation of amended (glucose and nutrients) and unamended soil samples[34].

Soil (<2 mm) that had been dried overnight at 105°C was analyzed for (1) total C and N content using a dry combustion analyzer (LECO Corp., Warrendale, PA) and (2) particle size distribution using a modified pipette method[36].

Air dry soil (<2 mm) was analyzed for pH and Mehlich I extractable Mg, Ca, P and K using methods outlined by the Northeast Coordinating Committee on Soil Testing[37].

Air dry soil (1–4 mm) was analyzed for macroaggregate stability (AGSTAB) using a modified Kemper and Rosenau method[38]. AGSTAB was calculated as the mass fraction of <0.73 mm soil retained on a micro-sieve (50 mm diameter, 0.73 mm mesh openings) after rapid submergence in deionized water and 2 min of orbital shaking at 100 revolutions per minute.

The porosity of each soil was calculated assuming that all composite soil samples had a total volume of $380\,cm^3$ and a particle density of $2.65\,g\,cm^{-3}$.

Finally, two quotient parameters were calculated using the following functions:

$$qC_{MB} = C_{MB} * C_T^{-1} * 100 \quad (1)$$

$$qC_{NMW} = C_{NMW} * C_{MW}^{-1} * 100 \quad (2)$$

where $C_{MB}$ is microbial biomass carbon, $C_T$ is total C, $C_{NMW}$ is extractable C from unmicrowaved soil and $C_{MW}$ is extractable C from MW sterilized soil.

The parameters described above were determined for all soil samples with the exception of the routine soil test parameters (pH and Mehlich I extractable Ca, Mg, K and P) that were only measured for the first samples collected from each site and $C_{SIR}$ that was only determined for samples collected during the spring and fall of 1997. Higher parameter values were assumed to indicate superior SQ for all parameters other than $qC_{NMW}$ and clay content.

### Calculating a SQI and three soil discrimination indices

A SQI was calculated by averaging normalized values of the five individual SQ parameters that best agreed with farmer SQ ratings. The component parameters were normalized around a mean value of 50 and a standard deviation of 10, using a Z score approach[39]. The following function was used to calculate the SQI:

$$SQI = \sum [(10 * \Delta p * p_{std}^{-1}) + 50] * n^{-1} \quad (3)$$

where $\Delta p$ is the difference between the value of an individual component parameter and its data set mean, $p_{std}$ is the data set standard deviation of the component parameter, and $n$ is the total number of parameters integrated.

Discriminant analysis (DA) was used to generate three additional indices: (1) $SDI_{TILL}$ with optimized discrimination between soils receiving conventional tillage management and no-till management, (2) $SDI_{SOD}$ with optimized discrimination between soils under long-term sod and soils with no sod in rotation, and (3) $SDI_{FR}$ with optimized discrimination between soils rated good and poor by farmers. DA was chosen over other multivariate statistical tools (e.g., principal component analysis) that are also useful for data reduction because DA is specifically designed for identifying minimum sets of variables that best discriminate between contrasting groups[39].

Parameters that best discriminated between the contrasting soil classes were identified using procedure PROC STEPDISC[39] with the stay criteria set at $p(F) < 0.05$. Paired classification functions of best discriminator parameters were calculated using procedure PROC DISCRIM[39]. The discrimination power of the calculated classification functions was tested using the resubstitution option in PROC DISCRIM[39].

### Creating indices out of classification functions

The paired classification functions associated with the best discriminator parameters for each soil categorical contrast were combined by subtraction, forming single linear functions. The conventional tillage function was subtracted from the no-till function, the no-sod function from the long-term sod function and the poor rated soil function from the good rated soil function. Parameter values from the data sets were plugged back into the linear functions and SAS procedure PROC MEANS[39] was used to calculate data set means and standard deviations for the linear functions. The following function was used to calculate three indices ($SDI_{TILL}$, $SDI_{SOD}$ and $SDI_{FR}$):

$$SDI = 10 * [f(x) - f(x)_{mean}] * f(x)_{std}^{-1} + 50 \quad (4)$$

where $f(x)$ is the linear function and $f(x)_{mean}$ and $f(x)_{std}$ are the mean and standard deviation of the linear function.

### Evaluating the relationship between farmer SQ ratings and individual soil parameters

The relationship between individual soil parameters and farmer SQ ratings was evaluated using data associated with all samplings of all sites (75 soil SQ contrast pairs) and data associated with the first sampling of all sites (45 SQ contrast pairs). Paired *t*-tests (PROC MEANS[39]) were performed on $\Delta p$ values ($\Delta p = \text{parameter}_{\text{good rated soil}} - \text{parameter}_{\text{poor rated soil}}$) to test the likelihood of parameters having $\Delta p$ values greater than zero. Parameters with positive *t*-scores and $p(H_0) < 0.05$ were interpreted to be significantly in agreement with farmer SQ ratings. Mean percent parameter difference values were calculated for paired good and poor rated soils using the following function:

$$\text{mean percent parameter difference} = 100 * \sum (\Delta p * p_{mean}^{-1}) * n^{-1} \quad (5)$$

where $\Delta p$ is the difference between the good and poor soil parameter values, $p_{mean}$ is the mean parameter value for a pair of good and poor rated soils and $n$ is the number of SQ contrast pairs. Parameters with greater mean percent difference values were interpreted to be more sensitive to farmer SQ ratings.

### Evaluating the relationship between soil indices, index component parameters and farmer SQ ratings

Data associated with 48 paired sites sampled in spring and fall 1997 that had no missing values for component parameters, were selected for evaluating the relationship between the four calculated indices, individual component parameters and farmer SQ ratings. Paired *t*-tests (PROC MEANS[39]) were used to evaluate the relationship.

**Table 3.** SQ diagnostic indicators, best management practices for improving SQ, and the number of farmers that mentioned each ($n = 32$).

| SQ indicators | Farmers | Management practice | Farmers |
|---|---|---|---|
| Soil organic matter content | 28 | Conservation tillage | 26 |
| Crop yield and appearance | 22 | Long-term no-till | 16 |
| Soil water availability | 19 | Sod in rotation | 14 |
| Minimum erosion/clear run-off | 16 | Manure/compost | 11 |
| Soil mineral fertility | 14 | Cover crops | 9 |
| Ease of tillage/soil density | 10 | Minimization of field traffic | 6 |
| Soil biological activity | 9 | Adequate liming | 4 |

## Results and Discussion

### *Diagnostic indicators of SQ mentioned by farmers*

The indicators of SQ discussed by farmers during field interviews were ranked with respect to the number of farmers that mentioned each indicator (Table 3). Soil organic matter (SOM) was the indicator of SQ mentioned by the most farmers (88%). This high level of recognition of SOM as a SQ indicator concurs with Granatstein and Bezdicek[3] who stated that SOM is the most universally accepted indicator of SQ. Crop condition (e.g., yield, drought tolerance, pest damage and root appearance) was the next most frequently mentioned SQ indicator (69%). Farmers tend to have much more visual contact with their crops than their soils, and thus it is logical that many look to crop characteristics as SQ indicators. SOM and crop condition, the SQ indicators mentioned most frequently in this study, were also the top two indicators of SQ/soil health identified by Wisconsin farmers[11].

SQ indicators related to soil hydrologic function were mentioned by 59% of farmers. Four farmers commented that they consider soil water-holding capacity to be the most distinguishing feature between good and poor quality soils. Evidence of soil erosion was mentioned by 50% of farmers. Most of the farmers using minimum tillage practices mentioned that they have observed much less erosion on their farm as compared to their neighbors who use more intensive tillage practices or as compared to when they previously used more intensive tillage practices. The fact that a majority of farmers (63%) did *not* mention soil mineral fertility as a SQ indicator suggests many farmers perceive their soil productivity is currently not limited by soil mineral fertility. The relatively small fraction (31%) of farmers that mentioned ease of tillage is related to most (81%) of the participating farmers using minimum tillage or no-till systems. Soil biological indicators, such as the presence of earthworms and their middens, fungal fruiting bodies, rate of residue decay, etc., were mentioned relatively infrequently (28%) by farmers. This small percentage suggests a need for identification of practical biological indicators of SQ and training programs for mid-Atlantic farmers related to the importance of soil biology in mediating soil functions.

The percentages of farmers that described a relationship between SQ and specific soil and crop characteristics should not be interpreted as a direct measure of farmer valuation of the soil and crop characteristics as SQ indicators. Romig et al.[11] ranked SQ indicators based on a three part scoring system that assigned value based on when the indicator was mentioned in the interview, how frequently it was mentioned, and how many farmers mentioned the indicator. The less structured interviewing process used in this study necessitated a simpler and less inferential technique for quantifying interview responses. Direct insights into farmer valuation of specific SQ indicators can only be drawn from the individual farmer comments. Indicators described as most important by individual farmers included crop yield, soil water-holding capacity, crop root appearance, clarity of run-off, lack of soil compaction and ease of seed bed preparation.

### *Farmer perceptions of best management practices for SQ*

Farmer remarks concerning the effects of specific management practices on SQ are summarized in Table 3. SQ benefits from minimizing tillage were described by 81% of the farmers. Among collaborating farmers, half have eliminated all tillage. This is congruent with the Conservation Tillage Information Center's[40] statistics for Maryland (50% of all crop acres were planted no-till in 1999). Many of the collaborating farmers that used no-till had not tilled for over 10 years and were convinced of the SQ benefits of long-term no-till. SQ benefits from including sod in crop rotations were described by 44% of the farmers. SQ benefits from the use of organic soil amendments (e.g., manure, compost) and cover crops were mentioned by approximately one-third of the farmers (34 and 28%, respectively); however, the farmers that mentioned these practices were very convinced of their positive impact on SQ. In addition to describing positive management effects on SQ, many farmers, particularly those using continuous no-till, described the negative impacts of excessive field traffic, any traffic over wet soils, inadequate liming and application of pesticides that are toxic to earthworms.

**Table 4.** Significant relationships between farmer SQ ratings and soil parameters associated with all samplings of paired SQ contrast sites.

| Parameter[1] | *n* | Units | Good rated soil mean | Poor rated soil mean | Mean percent difference | Paired *t*-test: $p(H_0)$ |
|---|---|---|---|---|---|---|
| $C_T$ | 74 | $mg\,g^{-1}$ | 18.6 | 15.2 | 14.1 | <0.0001 |
| $C_{MB}$ | 75 | $mg\,g^{-1}$ | 0.563 | 0.398 | 29.4 | <0.0001 |
| $C_{MW}$ | 75 | $mg\,g^{-1}$ | 0.203 | 0.151 | 21.3 | <0.0001 |
| $C_{NMW}$ | 75 | $mg\,g^{-1}$ | 0.085 | 0.068 | 14.8 | 0.0005 |
| $C_{AR}$ | 75 | $mg\,g^{-1}$ | 0.088 | 0.067 | 19.9 | <0.0001 |
| $qC_{MB}$ | 74 | % | 3.06 | 2.57 | 15.7 | 0.0071 |
| $qC_{NMW}$ | 75 | % | 43.3 | 48.4 | −6.4 | 0.0058 |
| AGSTAB | 70 | % | 51.4 | 38.3 | 26.3 | <0.0001 |
| Porosity | 75 | % | 51.2 | 49.4 | 2.6 | 0.0003 |
| $\theta_m$ | 75 | % | 26.1 | 23.7 | 6.1 | 0.0344 |

[1] $C_T$ = total C, $C_{MB}$ = microbial biomass C, $C_{MW}$ = C in 0.5 M $K_2SO_4$ extract of MW irradiated soil, $C_{NMW}$ = C in 0.5 M $K_2SO_4$ extract of non-irradiated soil, $C_{AR}$ = anthrone reactive C in 0.5 M $K_2SO_4$ extract of MW irradiated soil, $C_{SIR}$ = substrate induced respiration rate, $qC_{MB} = C_{MB}\,C_T^{-1}$, $qC_{NMW} = C_{NMW}\,C_{MW}^{-1}$, AGSTAB = % macroaggregate stability, $\theta_m$ = gravimetric moisture content at sampling.

**Table 5.** The relationship between farmer SQ ratings and soil parameters associated with the first sampling of paired SQ contrast sites.

| Parameter[1] | *n* | Units | Good rated soil mean | Poor rated soil mean | Paired *t*-test: $p(H_0)$ |
|---|---|---|---|---|---|
| $C_T$ | 44 | $mg\,g^{-1}$ | 17.6 | 14.6 | 0.0075 |
| $C_{MB}$ | 45 | $mg\,g^{-1}$ | 0.486 | 0.342 | 0.0002 |
| $C_{MW}$ | 45 | $mg\,g^{-1}$ | 0.189 | 0.141 | < 0.0001 |
| $C_{NMW}$ | 45 | $mg\,g^{-1}$ | 0.087 | 0.070 | 0.0230 |
| $C_{AR}$ | 45 | $mg\,g^{-1}$ | 0.078 | 0.059 | 0.0002 |
| AGSTAB | 41 | % | 52.4 | 38.2 | 0.0015 |
| Porosity | 45 | % | 46.7 | 44.3 | 0.0010 |
| pH | 41 | −log(H) | 6.5 | 6.3 | 0.0570 |
| Ca | 40 | $mg\,kg^{-1}$ | 1182 | 989 | 0.0630 |
| Mg | 36 | $mg\,kg^{-1}$ | 152 | 140 | 0.0280 |
| Ca : Mg ratio | 36 | na | 4.9 | 4.2 | 0.1340 |
| K | 39 | $mg\,kg^{-1}$ | 190 | 182 | 0.6390 |
| P | 41 | $mg\,kg^{-1}$ | 184 | 154 | 0.0910 |
| Sand | 35 | % | 45.0 | 42.4 | 0.0460 |
| Clay | 35 | % | 10.5 | 12.1 | 0.0158 |

[1] Ca = Mehlich I extractable calcium, Mg = Mehlich I extractable magnesium, Ca : Mg ratio = equivalents Mehlich I extractable Ca * (equivalents Mehlich I extractable Mg)$^{-1}$, K = Mehlich I extractable $K_2O$, P = Mehlich I extractable $P_2O_5$, sand = % sand, clay = % clay; see Table 4 for additional parameter abbreviation interpretations.

### *SQ parameters*

SQ parameter statistics for all samplings are presented in Table 4. Statistics for just the first sampling of each site are presented in Table 5. Select statistics for samples collected in the spring and fall of 1997 are presented in Table 8.

Soil C parameters ($C_T$, $C_{MB}$, $C_{MW}$, $C_{AR}$ and $C_{SIR}$) and soil structure parameters (porosity and AGSTAB) were found to agree well with farmer SQ ratings ($P < 0.0005$). Quotient parameters $qC_{MB}$ and $qC_{NMW}$ also had a highly significant level of agreement with farmer SQ ratings ($P < 0.007$). Sparling[41] suggested that active C:total C quotients have greater meaning than absolute active C levels when comparing soils with differences in texture, drainage, or climate, and therefore different inherent capacities to retain SOM. When comparing soils with similar inherent properties, such as in this study, quotient parameters would not be expected to have an advantage.

For a parameter to be useful as a SQ indicator, the parameter should consistently (i.e., with a high probability) differ between good and poor quality soils and the difference should be relatively large in magnitude so as to be readily detectable. Many authors[23,24,42] have reported that soils with contrasting management have greater relative differences between biologically active C parameters as compared to total C. This study found that soil C parameters associated with MW sterilized soil ($C_{MB}$, $C_{MW}$, $C_{AR}$) had mean percent differences (29.4, 21.3 and 19.9%, respectively) that were larger than those associated with $C_T$ and $C_{NMW}$ (14.1 and 14.8%, respectively) (Table 4).

**Table 6.** Soil parameters identified using SAS procedure PROC STEPDISC as the best discriminators between tillage, presence of sod and farmer rating soil categories

| Contrast | Parameters[1] | Partial $R^2$ | p(F) |
|---|---|---|---|
| Tillage intensity | AGSTAB | 27.5 | 0.0001 |
| | $qC_{NMW}$ | 10.9 | 0.0007 |
| | Porosity | 7.07 | 0.0072 |
| Presence of sod | $C_{MB}$ | 26.11 | 0.0001 |
| | AGSTAB | 13.65 | 0.0001 |
| Farmer soil rating | $C_{NMW}$ | 6.2 | 0.0082 |
| | $C_{SIR}$ | 4.9 | 0.0199 |

[1] See Table 4 for parameter abbreviation interpretations.

Experimental error is unlikely to obscure the relationship between a particular parameter and farmer SQ ratings if the differences in parameter values between good and poor rated soils are many times greater than the coefficient of variation (CV) for the analytical method. Among the parameters measured in this study, the ratio of mean percent difference to CV was greatest for $C_{MW}$, $C_{AR}$ and AGSTAB (14.2, 7.7 and 3.7, respectively), indicating that these three parameters may be most reliable in distinguishing between soils with contrasting SQ. Islam and Weil[43] found these parameters to be among the best discriminators between soils managed with and without conservation practices.

At the first sampling of each pair of SQ contrast sites, soils were analyzed for all the soil parameters just discussed as well as particle size distribution and standard mineral fertility parameters (Table 5). AGSTAB and all the soil C parameters agreed well ($P \ll 0.05$) with farmer SQ ratings. Mehlich I extractable Mg was the only mineral fertility that differed significantly ($P < 0.05$) between good and poor rated soils. The Ca : Mg ratio, a relationship considered important by proponents of the base cation saturation ratio (BCSR) approach to soil fertility management[44], was not significantly related to farmer SQ ratings.

Both sand and clay showed small but statistically significant ($P < 0.05$) differences between paired sites. Good rated soils had $16\,mg\,g^{-1}$ less clay and $26\,mg\,g^{-1}$ more sand than poor rated soils. This difference in texture, for soils mapped as the same or very similar soil series, is likely to relate to differences in erosion. Compared to less eroded sites, more eroded sites would have clay-enriched argillic horizons closer to the surface and more likely to be incorporated into the Ap horizon by tillage. In addition, erosion tends to enrich surface soil with clay by preferentially removing fine sand and silt-size particles[45]. It is also possible that some of the measured textural differences were related to incomplete dispersion of micro-aggregates during particle size analysis[46].

## *Development of indices from linear classification functions*

The parameters identified as the best discriminators (by stepwise DA) between tillage classes, presence of sod classes and farmer SQ rating classes are presented in Table 6. Parameters AGSTAB and $C_{MB}$ were associated with greater than 25% of the variability between tillage and presence of sod classes, respectively. None of the individual parameters were strong discriminators between the unpaired good and poor rated soil populations (Table 6). The normalized linear combinations of best discriminator parameters used to calculate $SDI_{TILL}$, $SDI_{SOD}$ and $SDI_{FR}$ were as follows:

$$SDI_{TILL} = 0.310 * AGSTAB - 0.357 * qC_{NMW} - 0.695 * \text{porosity} + 91.15$$

$$SDI_{SOD} = 18.22 * C_{MB} + 0.197 * \text{AGSTAB} + 33.9$$

$$SDI_{FR} = 263.9 * C_{NMW} + 11.03 * C_{SIR} + 23.39$$

Using the resubstitution option in SAS procedure PROC DISCRIM[36], we compared the discrimination power of a linear function of all measured parameters with a function of the best discrimination parameters. The respective classification success rates for these two types of functions were: 85.3 versus 82.4% for conventional tillage: 83.1 versus 83.1% for no-till, 86.5 versus 86.5% for no-sod, 83.3 versus 75.0% for sod, 65.5 versus 62.1% for good rated soils and 87.0 versus 66.7% for poor rated soils. Thus, functions comprised of only two or three best discriminator parameters were nearly as good at discriminating between the contrasting soil categories as functions containing all measured parameters.

## *Relationships between SQ ratings by farmers and indices and index component parameters*

Means and standard deviations of the component parameters are presented in Table 7. Paired *t*-test, *t*-scores, and $p(H_0)$ values associated with indices and index component parameters are presented in Table 8. Unlike Tables 4 and 5, all the parameters presented in Table 8 are associated with the same number of SQ contrast pairs ($n = 48$). As a result, it is meaningful to compare *t*-scores in addition to $p(H_0)$ values.

The SQI that integrated the five best individual parameters (based on data from all samples) had a *t*-score of 7.52. The five best individual parameters ($C_T$, $C_{MW}$, $C_{MB}$, $C_{AR}$, AGSTAB) had *t*-scores ranging from 4.63 to 6.71. This demonstrates that linear combinations of SQ parameters can be assembled which are more in agreement with holistic SQ criteria such as farmer SQ ratings than individual SQ parameters. The process of averaging multiple parameters, which was used in creating the SQI, reduced the impact of individual parameter variability. We speculate that this statistical process is analogous to the process by which farmers make their judgments of SQ. For example, single observations of erosion, drought stress or pest damage are unlikely to cause a farmer to rate a site as having poor SQ if the farmer's overall recollection of soil performance at the site is favorable.

DA using appropriate class contrasts produced linear combinations of soil parameters that were strongly related

**Table 7.** Data set parameter means and standard deviations used in the calculation of the soil indices: SQI, $SDI_{TILL}$, $SDI_{SOD}$ and $SDI_{FR}$.

| Index | Parameter | Category | *n* | Mean | Standard deviation |
|---|---|---|---|---|---|
| SQI[1] | $C_T$ | – | 256 | 16.2 | 7.1 |
| SQI | $C_{MB}$ | – | 285 | 0.405 | 0.27 |
| SQI | $C_{MW}$ | – | 287 | 0.146 | 0.078 |
| SQI | $C_{AR}$ | – | 281 | 0.070 | 0.051 |
| SQI | AGSTAB | – | 263 | 45.3 | 26.7 |
| $SDI_{TILL}$ | AGSTAB | NT | 71 | 49.0 | 26.0 |
| $SDI_{TILL}$ | AGSTAB | CT[2] | 34 | 18.7 | 16.7 |
| $SDI_{TILL}$ | $qC_{NMW}$ | NT | 71 | 44.5 | 15.7 |
| $SDI_{TILL}$ | $qC_{NMW}$ | CT | 34 | 55.8 | 19.6 |
| $SDI_{TILL}$ | Porosity | NT | 71 | 51.9 | 5.8 |
| $SDI_{TILL}$ | Porosity | CT | 34 | 52.1 | 6.1 |
| $SDI_{SOD}$ | $C_{MB}$ | LS | 24 | 0.790 | 0.541 |
| $SDI_{SOD}$ | $C_{MB}$ | NS | 111 | 0.336 | 0.209 |
| $SDI_{SOD}$ | AGSTAB | LS | 24 | 74.1 | 24.9 |
| $SDI_{SOD}$ | AGSTAB | NS | 111 | 36.5 | 25.5 |
| $SDI_{FR}$ | $C_{NMW}$ | RG | 58 | 0.069 | 0.031 |
| $SDI_{FR}$ | $C_{NMW}$ | RP | 54 | 0.054 | 0.025 |
| $SDI_{FR}$ | $C_{SIR}$[3] | RG | 58 | 1.060 | 0.643 |
| $SDI_{FR}$ | $C_{SIR}$ | RP | 54 | 0.810 | 0.502 |

[1] SQI = *f*($C_T$, $C_{MW}$, $C_{MB}$, $C_{AR}$, AGSTAB), $SDI_{TILL}$ = *f*(AGSTAB, $qC_{NMW}$, porosity), $SDI_{SOD}$ = *f*($C_{MB}$, AGSTAB), $SDI_{FR}$ = *f*($C_{NMW}$, $C_{SIR}$).
[2] CT = conventional tillage, NT = no-till, LS = long-term sod, NS = no sod in rotation, RG = rated good quality by farmer, RP = rated poor quality by farmer.
[3] $C_{SIR}$ = substrate induced respiration rate in µmol $CO_2$ (g soil)$^{-1}$ h$^{-1}$. This parameter was not included in previous tables because it was not analyzed during the initial sampling season. See Tables 4 and 5 for all other parameter abbreviation interpretations and units.

to farmer SQ ratings. The index derived from contrasting long-term sod and no sod in rotation ($SDI_{SOD}$) had the strongest level of agreement with farmer SQ ratings of the three indices. This is not surprising as the positive impact of sod on SQ has been described by many authors[47–49].

The index based on farmer ratings ($SDI_{FR}$) was calculated as a linear function of two parameters, $C_{NMW}$ and $C_{SIR}$, which were selected because they optimized discrimination between *unpaired* good and poor rated soils. Individual parameters ($C_T$, $C_{MW}$, $C_{NMW}$, $C_{MB}$, $C_{AR}$, $C_{SIR}$ and AGSTAB) that were analyzed for within-pair differences were more in agreement with farmer SQ ratings than $SDI_{FR}$, as indicated by lower $p(H_0)$ values. The greater level of agreement associated with paired analysis as compared to unpaired analysis demonstrates a major SQ research challenge. Many soil parameters that are good discriminators between sites that have received contrasting management but have similar inherent soil properties do not appear to have absolute threshold values that would allow SQ assessment across soils that differ widely in their inherent properties.

**Table 8.** Results of paired *t*-tests between contrasting SQ sites for soil indices and individual component parameters ($n = 48$ pairs).

| Parameter[1] | *t*-score | $p(H_0)$ |
|---|---|---|
| $C_T$ | 5.84 | < 0.0001 |
| $C_{MW}$ | 6.71 | < 0.0001 |
| $C_{NMW}$ | 4.94 | < 0.0001 |
| $C_{MB}$ | 5.61 | < 0.0001 |
| $C_{AR}$ | 5.56 | < 0.0001 |
| $C_{SIR}$ | 3.94 | 0.0003 |
| $qC_{NMW}$ | − 2.11 | 0.0399 |
| AGSTAB | 4.63 | < 0.0001 |
| Porosity | 2.14 | 0.0379 |
| SQI | 7.52 | < 0.0001 |
| $SDI_{TILL}$ | 3.45 | 0.0012 |
| $SDI_{SOD}$ | 6.76 | < 0.0001 |
| $SDI_{FR}$ | 6.08 | < 0.0001 |

[1] See Tables 4 and 7 for parameter abbreviations.

The index based on contrasting tillage regimes ($SDI_{TILL}$) had the weakest relationship with farmer SQ ratings of the three soil discrimination indices. This is not surprising as only six of the 48 SQ contrast pairs consisted of a good rated soil receiving less intensive tillage management than its poor rated pair. In fact, both the good and poor rated soils in 15 out the 48 SQ contrast pairs were under NT management. The inclusion in the index database of 15 soils under no-till management that had been described as poor quality by their farmers, reduced the strength of relationship between $SDI_{TILL}$ and farmer SQ ratings.

## Conclusions

Farmer knowledge of SQ as encapsulated in contrasting SQ ratings assigned to paired sites provided a useful benchmark for evaluating the relationship between management-sensitive soil parameters and SQ. Among the individual SQ parameters measured, $C_{MW}$ had the highest level of agreement with farmer SQ ratings as indicated by low $p(H_0)$ and high mean percent difference values. This parameter is closely related to microbial biomass, and several authors[50,51] have suggested that biomass C can be estimated without subtracting a control ($C_{NMW}$ in this study). AGSTAB and soil C parameters ($C_T$, $C_{MB}$, $C_{AR}$, $C_{SIR}$) also agreed well with farmer SQ ratings. Some of the quotient parameters investigated ($qC_{MB}$ and $qC_{NMW}$) did not agree as well with farmer SQ ratings as their component parameters.

The calculated SQI had the highest *t*-score of all measured and calculated parameters (associated with samples collected in the spring and fall of 1997 that had no missing values) demonstrating that linear combinations of SQ parameters can be assembled which are more in agreement with holistic SQ criteria such as farmer SQ ratings than individual SQ parameters. DA was an effective approach for selecting and integrating minimum data sets of SQ parameters into discrimination indices that are related to farmer perceptions of SQ. This objective method of data reduction based on ability to discriminate between soils with contrasting management merits more investigation.

The lack of differences in pH and available nutrients between soils rated by farmers as having contrasting SQ, suggests that these mid-Atlantic farmers have largely resolved mineral fertility constraints on SQ. In contrast, parameters related to soil structure and C were found to be strongly related to SQ ratings by these mid-Atlantic farmers. This suggests that efforts to improve SQ in the Mid-Atlantic region should focus on monitoring and enhancement of soil C and soil structure.

The integration of on-farm data as collected in this study with data from appropriate replicated experiments may allow the identification of threshold values for select SQ parameters and thus move SQ interpretation beyond relative comparisons of soils with similar inherent properties.

**Acknowledgements.** We thank the participating farmers for their insights and cooperation, and K.R. Islam for his assistance with the laboratory analyses. This work was partially supported by the USDA Sustainable Agriculture Research and Education grant 960119-7073. This article is a contribution of the Maryland Agricultural Experiment Station.

## References

1 Leopold, A. 1939. The farmer as conservationist. In J.B. Callicott and E.T. Freyfogle (eds) 1999. Aldo Leopold: For the Health of the Land. (Previously unpublished essays and other writings.) Island Press/Shearwater Books, Washington, DC. p. 161–175.

2 Liebig, M. and Doran, J.W. 1999. Evaluation of farmer's perceptions of soil quality indicators. American Journal of Alternative Agriculture 14:11–21.

3 Granatstein, D. and Bezdicek, D.F. 1992. The need for a soil quality index: local and regional perspectives. American Journal of Alternative Agriculture 7:12–16.

4 McCallister, R. and Nowak, P. 1999. Whole soil knowledge and management: a foundation of soil quality. In R. Lal (ed.). Soil Quality and Soil Erosion. Soil Water Conservation Society, Ankeny, IA. p. 173–193.

5 Bentley, J.W. 1989. What farmers don't know can't help them: the strengths and weakness of indigenous technical knowledge in Honduras. Agriculture and Human Values 6:25–31.

6 Queiroz, J.S.D. and Norton, B.E. 1992. An assessment of an indigenous soil classification used in the Caatinga region of Caera State, Northeast Brazil. Agricultural Systems 39: 289–305.

7 Krasilnikov, P.V. and Tabor, J.A. 2003. Perspectives on utilitarian ethnopedology. Geoderma 111:197–215.

8 Tabor, J.A. and Hutchinson, C.F. 1994. Using indigenous knowledge, remote sensing and GIS for sustainable development. Indigenous Knowledge and Development Monitor 2(1): 2–6. Available at Web site: http://www.nuffic.nl/ciran/ikdm/2-1/articles/tabor.html

9 Garlynd, M.J., Kurakov, A.V., Romig, D.E., and Harris, R.F. 1994. Descriptive and analytical characterization of soil quality/health. In J.W. Doran, D.C. Coleman, D.F. Bezdicek and B.A. Stewart (eds). Defining Soil Quality for a Sustainable Environment. Special Publication 35. Soil Science Society of America, Madison, WI. p. 159–168.

10 Walter, G., Wander, M., and Bollero, G. 1997. A farmer-centered approach to developing information for soil resource management: the Illinois soil quality initiative. American Journal of Alternative Agriculture 12:64–72.

11 Romig, D.E., Garlynd, M.J., Harris, R.F., and McSweeney, K. 1995. How farmers assess soil health and quality. Journal of Soil and Water Conservation 50:229–236.

12 Romig, D.E., Garlynd, M.J., and Harris, R.F. 1995. Farmer based assessment of soil quality: a soil health scorecard. In J.W. Doran and A.J. Jones (eds). Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI. p. 39–60.

13 Wander, M.M. and Drinkwater, L.E. 2000. Fostering soil stewardship through soil quality assessment. Applied Soil Ecology 15:61–73.

14 Doran, J.W. and Safley, M. 1997. Defining and assessing soil health and sustainable productivity. In C.E. Pankhurst, B.M. Doube, and V.V.S.R. Gupta (eds). Biological Indicators of Soil Health. CAB International, New York. p. 1–28.

15 Larson, W.E. and Pierce, F.J. 1994. The dynamics of soil quality as a measure of sustainable management. In J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (eds). Defining Soil Quality for a Sustainable Environment. Special Publication 35. Soil Science Society of America, Madison, WI. p. 37–51.

16 Harris, R.F. and Bezdicek, D.F. 1994. Descriptive aspects of soil quality/health. In J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (eds). Defining Soil Quality for a Sustainable Environment. Special Publication 35. Soil Science Society of America, Madison, WI. p. 23–35.

17 Pankhurst, C.E. 1997. Biodiversity of soil organisms as an indicator of soil health. In C.E. Pankhurst, B.M. Doube, and V.V.S.R. Gupta (ed.). Biological Indicators of Soil Health. CAB International, New York. p. 297–324.

18 Wander, M.M., Walter, G.L., Nissen, T.M., Bollero, G.A., Andrews, S.S., and Cavanaugh-Grant, D. 2002. Soil quality: science and process. Agronomy Journal 94:23–32.

19 Grossman, R.B., Harms, D.S., Seybold, C.A., and Herrick, J.E. 2001. Coupling use-dependent and use-invariant data for soil quality evaluation in the United States. Journal of Soil and Water Conservation 56(1):63–68.

20 Wagenet, R.J. and Hutson, J.L. 1997. Soil quality and its dependence on dynamic physical processes. Journal of Environmental Quality 26:41–48.

21 Okey, B.W. 1996. System approaches and properties and agroecosystem health. Journal of Environmental Management 48:87–199.

22 Rapport, D.J., McCullum, J., and Miller, M.H. 1997. Soil health: its relationship to ecosystem health. In C.E. Pankhurst, B.M. Doube, and V.V.S.R. Gupta (eds). Biological Indicators of Soil Health. CAB International, New York. p. 29–47.

23 Carter, M.R. 1986. Microbial biomass as in index for tillage-induced changes in soil biological properties. Soil and Tillage Research 7:9–40.

24 Weil, R.R., Islam, K.R., Stine, M.A., Gruver, J.B., and Samson-Liebig, S.E. 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. American Journal of Alternative Agriculture 18(1): 3–17.

25 Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., and Jordahl, J.L. 1994. Crop residue effects on soil quality following 10 years of no-till corn. Soil and Tillage Research 31:149–167.

26 Islam, K.R. and Weil, R.R. 1997. Stability of soil quality indices across seasons and regions. Agronomy Abstracts. Annual Meetings of the American Society of Agronomy, Anaheim, CA. p. 215.

27 Nui, M., Murphy, D., Braimbridge, M., Osler, G., Jasper, D., and Abbott, L. 2002. Using power analysis to identify soil quality indicators. 17th World Congress of Soil Science, Bangkok, Thailand, August 14–21 Symposium no. 32. Paper no. 557. Available at Web site: http://www.ldd.go.th/Wcss2002/papers/0557.pdf

28 Singh, K.K., Colvin, T.S., Erbach, D.C., and Mughal, A.Q. 1992. Tilth index: an approach to quantifying tilth. Transactions of the American Society of Agricultural Engineers 35: 1777–1785.

29 Buyanovsky, G.A., Kucera, C.L., and Wagner, G.H. 1987. Comparative analyses of carbon dynamics in native and cultivated ecosystems. Ecology 68:2023–2031.

30 Davidson, E.A. and Ackerman, I.L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20:161–193.

31 Skidmore, E.L., Carestenson, W.A., and Banbury, E.E. 1975. Soil changes resulting from cropping and tillage. Soil Science Society of America Proceedings 39:964–967.

32 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.

33 Brink, R.H., Dubach, P., and Lynch, D.L. 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Science 89:157–166.

34 Van de Werf, H. and Verstrate, W. 1987. Estimation of active soil microbial biomass by mathematical analysis of respiration curves: calibration of the test procedure. Soil Biology and Biochemistry 19:261–266.

35 Day P.R. 1965. Particle fractionation and particle-size analysis. In C.A. Black (ed.). Methods of Soil Analysis, Part 2, 2nd ed. American Society of Agronomy, Madison, WI. p. 545–567.

36 Islam, K.R. and Weil, R.R. 1998. A rapid microwave digestion method for colorimetric measurement of soil organic carbon. Communications in Soil Science and Plant Analysis 29:2269–2284.

37 Northeast Coordinating Committee on Soil Testing. 1995. Recommended soil testing procedures for the Northeastern United States. 2nd ed. Northeast Regional Publication. No. 493. Agricultural Experiment Station, University of Delaware, Newark, NJ.

38 Kemper, W.D. and Rosenau, R.C. 1986. Aggregate stability and size distribution. In Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods: Agronomy Monograph no. 9. 2nd ed. Agronomy Society of America—Soil Science Society of America, Madison, WI. p. 425–442.

39 SAS Institute, Inc. 1985. SAS Users Guide: Statistics. Version 5 edition. SAS Institute, Inc., Cary, NC.

40 Conservation Tillage Information Center. 1999. Maryland Tillage Statistics. Available at Web site: http://ingis.acn.ces.purdue.edu:9999/ctic/ctic.html.old

41 Sparling, G.P. 1997. Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In C.E. Pankhurst, B.M. Doube, and V.V.S.R. Gupta (eds). Biological Indicators of Soil Health. CAB International, New York. p. 97–119.

42 Powlson, D.S. and Jenkinson, D.S. 1981. A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct-drilled soils. Journal of Agricultural Science 97:713–721.

43 Islam, K.R. and Weil, R.R. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation 55: 69–78.

44 Eckert, D.J. 1987. Soil test interpretations: basic cation saturation ratios and sufficiency levels. In J.R. Brown (ed.). Soil Testing: Sampling, Correlation, Calibration and Interpretation. Special Publication 21. Soil Science Society of America, Madison, WI. p. 53–64.

45 Rhoton, F.E. 2000. Influence of time on soil response to no-till practices. Soil Science Society of America Journal 64: 700–709.

46 Tisdall, J.M. and Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33: 141–164.

47 Low, A.J. 1955. Improvements in the structural state of soils under leys. Journal of Soil Science 6:180–199.

48 Deluca, T.H. and Keeney, D.R. 1993. Soluble anthrone-reactive carbon in soils: effect of carbon and nitrogen amendments. Soil Science Society of America Journal 57: 1296–1300.

49 Weil, R.R., Lowell, K.A., and Shade, H.M. 1993. Effects of intensity of agronomic practices on a soil ecosystem. American Journal of Alternative Agriculture 8:5–14.

50 Wardle, D.A. and Ghani, A. 1995. Why is the strength of relationships between pairs of methods for estimating soil microbial biomass often so variable. Soil Biology and Biochemistry 27(6):821–828.

51 Franzluebbers, A.J., Haney, R.L., Hons, F.M., and Zuberer, D.A. 1999. Assessing biological soil quality with chloroform fumigation-incubation: why subtract a control? Canadian Journal of Soil Science 79:521–528.