Soil & Tillage Research 174 (2017) 147–155

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Multivariate assessment of soil quality indicators for crop rotation and tillage in Illinois

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ARTICLE INFO

Keywords:
Soil quality
Crop rotation
Tillage

ABSTRACT

The long-term implementation of crop rotation and tillage influences the soil environment through inputs and disturbance of the soil, which in turn, impact soil quality (SQ). A vital component of developing sustainable agronomic practices is to evaluate their effect on SQ. The objective of this study is to address the first step in this process by identifying soil parameters that are sensitive to changes in the soil and indicative of soil functions. Soil samples were collected from two Illinois sites with cropping systems and tillage treatments in place for more than 16 years. Crop rotation and tillage were evaluated with separate principal component analyses (PCA) of 20 soil parameters. Six principal components accounted for 74% of variability among rotations. The soil parameters loaded within these components highlighted the strong influence on carbon and nitrogen cycling indicated by greater soil organic carbon, total nitrogen, microbial biomass, and aggregate stability under crop rotations with high C:N residues and biomass production. Other strongly loaded parameters, such as soil pH and nutrient contents, are likely related to the use of nitrogenous fertilizers in grass species. Rotations with only a single contrasting crop were able to be differentiated readily while the multi-species crop rotations were only marginally able to be separated. The PCA for tillage explained 73% of variability with six principal components; of those, three were able to separate no-till from conventional tillage. As with rotation, the choice of tillage practice can have a large influence on the cycling of carbon and nitrogen, as decomposition of residues and soil organic matter are accelerated by tillage. No-till was also associated with stratification of pH and other nutrients. Soil parameters relating to carbon and nitrogen cycling have the greatest potential as SQ indicators while other measures relating to nitrogen fertilization, such as shifts in soil pH and nutrient contents, can also prove useful in comparing SQ under crop rotation and tillage in Illinois.

1. Introduction

Maintaining or improving soil fertility and productivity is central to developing sustainable agricultural practices. Soil quality is defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health (Doran and Parkin, 1994). Soil physical, chemical and biological properties all provide information about different aspects of the soil as a system. Many researchers have developed soil quality indices (SQI) that allow incorporation of many different soil properties into a single value with the purpose of comparing agronomic practices in relation to the productivity of those soils (Karlen et al., 2006; Jokela et al., 2011; Aziz et al., 2013).

The first step in evaluating SQ as an index is to determine the small set of soil properties that will be utilized as soil quality indicators for a given region (Andrews et al., 2004). A suitable indicator should be sensitive to management and should convey information about the soil functions and processes occurring within the soil (Doran and Zeiss, 2000). While several of the SQIs in the literature have utilized soil chemical and physical properties, the sensitivity of biological properties to changing management has increased their use in SQIs (Aziz et al., 2013). Management practices as well as soil type, climate and other environmental characteristics should also be taken into consideration during indicator selection as an individual indicator is not equally useful or sensitive in all locations or situations (Cardoso et al., 2013).

There have been a variety of contrasting methods for the selection of sensitive indicators since the concept of SQ arose. As a first approach, Karlen et al. (1994) used expert opinion to weight scores representing different functions of the soil. Later on, quantitative methods to select indicators were based on multivariate analysis of soil properties (Brejda et al., 2000; Shukla et al., 2006; Nosrati, 2013). For example, Wander and Bollero (1999) utilized principal component analysis (PCA) to evaluate the effect of tillage on SQ in Illinois. To use a PCA as a selection tool, only those variables that are strongly loaded into the PCs

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http://dx.doi.org/10.1016/j.still.2017.07.007
Received 20 December 2016; Received in revised form 12 June 2017; Accepted 10 July 2017
Available online 19 July 2017

are kept to be indicators in a SQI. Wander and Bollero (1999) selected bulk density (BD), aggregate stability, penetration resistance, organic C, total N (TN), K, soil pH, particulate organic matter, basal respiration, and microbial biomass carbon (MBC) as the indicators to separate tillage practices. Andrews et al. (2002) compared several methods of developing an SQI, specifically expert opinion based indicators versus indicators selected using PCA. While both methods provided similar representative SQIs as related to the measurement of environmental and production goals, the strength of a quantitative approach is the avoidance of subjectivity. However, statistical methods of indicator selection require a large data set and may prove more difficult to interpret than using expert opinion to select indicators (Bastida et al., 2008).

While each SQI uses a different set of indicators, certain soil parameters are frequently selected when evaluating agricultural systems. Soil organic carbon (SOC) has often been considered a reliable indicator of SQ as it is so closely related to other soil properties, including soil structure, nutrient availability, water holding capacity, and erosion resistance (Doran and Parkin, 1994; Islam and Weil, 2000; West and Post, 2002) as well as influencing microbial activity (Schimel and Schaeffer, 2012). Other chemical properties commonly selected as indicators include soil pH, cation exchange capacity (CEC), and nutrient availability, connected to the ability of a soil to provide adequate nutrients and support plant growth (Bastida et al., 2008; Cardoso et al., 2013). Physical soil properties such BD, porosity and aggregate stability are often included as they are simple, inexpensive measurements that are related to the aeration of the soil, infiltration capacity as well as the ability to resist erosion processes (Schoenholtz et al., 2000). Properties that are inherent to the soil, such as texture, might not work as indicators. While soil texture impacts many other facets of the soil environment from water holding capacity to CEC, it is a relatively stable measurement that is unlikely to change as a result of agricultural practices so is not particularly useful as an indicator to differentiate between management practices (Cardoso et al., 2013). Biological properties are receiving increasing attention in SQIs as these properties are more sensitive to alterations in the soil environment than physical and chemical soil properties (Jimenez et al., 2002; Nannipieri et al., 2003). In some cases, SQIs have been developed that only include the biological component based on the assumption that changes in chemical and physical properties will be related to the changes in the microbial community (Puglisi et al., 2006; Romaniuk et al., 2011). Biological properties often included as indicators are microbial biomass, metabolic quotient, and enzyme activities (Gil-Sotres et al., 2005; Cardoso et al., 2013). While these properties are more sensitive to changes in agronomic practices than properties such as SOC, they often are highly variable measures with significant temporal fluctuations and spatial variability that need to be considered when using them as indicators in an SQI (Bastida et al., 2008; Cardoso et al., 2013; Zuber and Villamil, 2016).

The goal of the SQI and the agronomic practices that we wish to assess will also influence which indicators are most suitable. If the goal is to reduce environmental impact, the indicators selected may be different from those selected when trying to maximize a soil's productivity. In creating a SQI evaluating different crop rotations, indicators selected may vary from those included in a SQI for tillage practices. Crop rotations influence the soil environment and microbial communities primarily through differences in the quantity and quality of crop residues returned to the soil (McDaniel et al., 2014a). Tillage increases the rate of decomposition of those residues by breaking up the tissues, thus increasing microbial access to the substrates and mixing them into the soil. The soil environment also changes as a mulch layer develops in no-till soils, retaining moisture and lowering the temperature compared to conventionally tilled soils (Johnson and Hoyt, 1999). Crop rotations that include high C:N residue producing crops like corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) combined with the use of no-till have been found to lead to higher SOC, TN, and aggregate stability (Benjamin et al., 2010; Zuber et al., 2015). The sensitivity of these measures to agronomic practices demonstrates their potential as SQI indicators. Karlen et al. (2006) used bulk density, soil pH, aggregate stability, SOC, TN, microbial biomass C, extractable P and K, and penetration resistance in a SQI to assess crop rotations in Iowa and Wisconsin; SOC was found to be the most sensitive indicator to the effects of rotation. Similar SQI indicators in the analysis by Jokela et al. (2011) included aggregate stability, BD, SOC, potentially mineralizable N, MBC, pH and soil P to compare grain rotations with forage and pasture systems. The indicators of Aziz et al. (2013) were MBC, basal respiration, metabolic quotient, SOC, TN, active C, aggregate stability, porosity, and particulate organic matter as components of the SQI to compare three crop rotations under both no-till and conventional tillage. However, these studies included indicators based on available measures and methodologies rather than using a multivariate approach to select indicators. Shukla et al. (2006) identified SOC as the most sensitive measurement for SQ for comparing five different tillage and crop rotation cropping systems through factor analysis. Fuentes et al. (2009) also reported SOC as a significant indicator for different tillage practices with monoculture and rotations; in addition TN, aggregate stability, penetration resistance, pH, and electrical conductivity were selected as indicators using PCA.

The high productivity of corn and soybean (*Glycine max* [L.] Merr.) in Illinois is directly related to the fertility and quality of the soils. The determination of suitable SQ indicators for this region will help to maintain those high productivity levels as it is vital to protect this key factor in the productivity of the state. We expect that for differentiating among crop rotations soil properties closely related to the crop residue quantity and quality, such as SOC and aggregate stability will be more sensitive indicators. For tillage, those properties will also be important, as will the physical properties related to the structure and compaction of the soil. Within this study, the objective is to determine which soil properties are most sensitive to crop rotations and tillage practices after long-term management at two Illinois sites with contrasting soils as well as to evaluate how the interaction of crop rotation and tillage practice affects soil quality and potential indicators.

2. Materials and methods

2.1. Experimental sites

Experimental sites were initiated in 1996 at the Northwestern Illinois Agricultural Research and Demonstration Center (40°55′50″ N, 90°43′38″ W), approximately 8 km northwest of Monmouth, Illinois and at the Orr Agricultural Research and Demonstration Center (39°48′4″ N, 90°49′16″ W), approximately 8 km northwest of Perry, Illinois. The experimental layout at both sites was a split-plot arrangement of rotation (four levels) and tillage (two levels), in a randomized complete block design with four replications. Rotation was assigned to the main plot and consisted of continuous corn (CCC), corn-soybean (CS), corn-soybean-wheat (CSW), and continuous soybean (SSS) with all phases of each rotation present each year (seven main plots). Each rotation main plot was split into two levels of tillage: no-till (NT) and chisel tillage (CT). The tillage at both sites consisted of fall tillage to a depth of 20–25 cm with a chisel plow and secondary tillage in the spring with a field cultivator prior to planting. Each main plot was 22 m long by 12 m wide, and sub-plots were 22 m long by 6 m wide. Nitrogen rates at Perry were 224 kg N ha^{-1} regardless of rotation; however, at Monmouth, rates for corn differed by rotation with corn following soybean or wheat receiving 202 kg N ha^{-1} compared to 246 kg N ha^{-1} for corn following corn. Nitrogen fertilizer for wheat was applied as split application at planting and as spring topdress with rates of 49 and 90 kg N ha^{-1}, respectively, at Perry and of 34 and 56 kg N ha^{-1}, respectively, at Monmouth. No N fertilizer was applied to soybean. For P and K, fertilizer applications were applied to the entire experimental area and did not differ based on crop rotation. Agronomic