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Identification of soil quality indicators for assessing the effect of different tillage practices through a soil quality index in a semi-arid environment

Fayez Raiesi*, Vida Kabiri

Department of Soil Science and Engineering, Faculty of Agriculture, Shahrekord University, P.O. Box 115, Shahrekord, Iran

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ABSTRACT

Tillage is known to potentially affect soil quality in various ways. In this study, a soil quality index (SQI) was developed by quantifying several soil attributes either sensitive or insensitive to physical disturbance, using factor analysis as a dimension reduction technique, in order to discriminate different tillage systems. Soil properties including physical (MWD), chemical (pH, organic C, total N, available P and POM contents) and microbial (MBC, MBN, PCM, PNM and three enzymes) parameters were measured to establish a minimum data set (MDS) for the assessment of overall SQI. The soil attributes were determined on samples (0–20 cm depth) collected under moldboard (MP) and disk (DP) plows as conventional tillage (CT), and rotary (RP) and chisel (CP) plows as reduced tillage (RT) systems with a similar plant C input rate and cover crop over a period of six years (2005–2011) in a semi-arid calcareous soil (Calcixerepts) from Central Iran. Results indicated a clear difference in soil quality among the tillage systems with a significant increase of SQI under RT over time, particularly under CP practices. Although RT improved most soil microbial attributes, not all attributes contributed to SQI because of their close interrelationship. The final SQI consisted only of geometric mean of microbial activity (GMA, the square root of the product of PCM and PNM) and geometric mean of enzyme activity (GME, the cube root of the product of enzyme activities). Soil GME and GMA were found to be as key indicators contributing 55% and 36% to SQI, respectively. Therefore, the GME and GMA were the most important indicators effectively discriminating tillage systems, and could be used to monitor the enhancement of soil quality under RT in this semiarid environment. The influence of tillage year on SQI was greater than that of tillage practices. In conclusion, RT systems were characterized by a higher value of SQI, suggesting a good recovery of soil capacity and functions after abandoning CT in the studied area. Smallholder farmers should therefore be aware of the potential for high soil quality in future as a result of continuing RT systems, especially with surface tillage using CP practices.

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1. Introduction

Removal of crop residues and continuing soil disturbance by intensive tillage practices can often accelerate soil erosion primarily by reducing soil organic matter (SOM) and aggregate stability, subsequently resulting in a decline of soil productivity and quality (Bradford and Huang, 1994; Karlen et al., 1994; Hussain et al., 1999). Degradation of soil quality with excessive or conventional tillage (CT) is particularly important in low-input agroecosystems located in arid and semiarid environments (Mrabet et al., 2001; Moreno et al., 2006; Álvaro-Fuentes et al., 2008). Factors contributing to low SOM include a minimal amount of organic input from plant biomass due to low rainfall and water availability and SOM losses that are stimulated by high air temperatures (Moreno et al., 2006; Madejón et al., 2007). Over the last decades, there has been increasing attention to use conservation tillage systems to minimize soil erosion, improve soil quality, sustain or increase plant production, and maintain environmental quality in agricultural systems (Karlen et al., 1994; Hussain et al., 1999; Wander and Bollero,

Abbreviations: SOM, soil organic matter; C, organic carbon; N, total nitrogen; POM, particulate organic matter; MWD, mean weight diameter; MBC, microbial biomass C; MBN, microbial biomass N; PCM, potential C mineralization; PNM, potential N mineralization; qCO_2, metabolic quotient; URE, urease; ALP, alkaline phosphatase; CAT, catalase; GMB, geometric mean of microbial biomass; GME, geometric mean of enzyme activity; GMA, geometric mean of microbial activity; MP, moldboard plow; DP, disk plow; RP, rotary plow; CP, chisel plow; RT, reduced tillage; CT, conventional tillage; MDS, minimum data set; SQI, soil quality index.

* Corresponding author.
E-mail addresses: f_raiesi@yahoo.com, fayez.raiesi@gmail.com (F. Raiesi).

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1999; Liebig et al., 2004). Agricultural management practices using conservation tillage systems have been proposed as a means to maintain or even enhance SOM storage and soil quality, to sustain crop production and to lower energy (fuel) consumption in arid and semiarid regions (Mrabet et al., 2001; Álvaro-Fuentes et al., 2008; Tabatabaeefar et al., 2009; Imaz et al., 2010; Abdullah, 2014). Reduced tillage (RT), a type of conservation tillage system, with less physical disturbance and soil inversion are often thought to improve soil quality by increasing SOM and soil structure, and subsequently the functioning of soil microbial community important for the transformation and mineralization of organic compounds and nutrients in soil ecosystem (Karlen et al., 1994; Laudicina et al., 2011).

Soil quality, an indicator of sustainable soil management (Hussain et al., 1999; Herrick, 2000), can be assessed most effectively using a combination of physical, chemical and microbiological properties that reflect management-induced changes in soil conditions following tillage or land use changes (Karlen et al., 1994; Doran and Parkin, 1996; Hussain et al., 1999; Gregorich et al., 1997; Bastida et al., 2006). Although individual attributes are often interdependent, they may respond differently to management practices, thus confounding interpretation of their influence (Griffiths et al., 2010) or sensitivity to management and agricultural practices (Simard et al., 1994; Yakovchenko et al., 1996). Attempting to balance several different soil characteristics may make the interpretation and synthesis of results quite complicated. Hence, combining soil properties into an overall single index may make the assessment more meaningful and practical (Andrews et al., 2002a; Andrews et al., 2004; Erkossa et al., 2007; Armenise et al., 2013).

Soil microbiological and biochemical properties, including microbial biomass and activities (*i.e.*, potential C and N mineralization), and enzyme activities involved in nutrient cycling, are generally regarded as potentially useful indicators of soil quality, because of their close link to SOM dynamics and nutrient cycling (Gregorich et al., 1997; Bastida et al., 2006; Bastida et al., 2008) as well as their sensitivity to soil disturbance and changes induced by tillage (Simard et al., 1994; Gregorich et al., 1997; Wander and Bollero, 1999; Balota et al., 2004; Franchini et al., 2007). Several studies have proposed C and N mineralization as sensitive and potential indicators of soil quality (Andrews et al., 2002b; Schloter et al., 2003; Andrews et al., 2004; Liebig et al., 2004; Gil-Sotres et al., 2005; Canali and Benedetti, 2006). Ecologically-related biological parameters such as C and N mineralization are of crucial importance in biogeochemical cycling in the soil as both represent the microbial activity (Gregorich et al., 1997; Filip 2002). Soil microbial activity leads to the release of nutrients available for plants. Nitrogen mineralization is an indication of biologically active N fraction in soil (Gregorich et al., 1994) and is used as an index of N availability for plant growth (Andrews et al., 2002a; Canali and Benedetti, 2006) because it provides an indication of soil capacity to release inorganic N for plant uptake (Gregorich et al., 1994; Canali and Benedetti, 2006). Soil microbial activity and biomass, and enzymatic activity have been found to be early responders to changes induced by tillage and soil disturbance (Gregorich et al., 1997; Raiesi and Beheshti, 2014; Paz-Ferreiro and Fu, 2016).

The initial steps for developing an effective SQI are to identify soil properties that provide the most information regarding critical soil functions associated with the goal for which the assessment is being made so they can be included in a minimum data set (MDS), and integrated into an overall SQI using appropriate mathematical and statistical techniques, and scoring functions (linear and nonlinear) (Doran and Parkin, 1996; Andrews et al., 2002a; Bastida et al., 2006; Masto et al., 2008). Using this approach, a high SQI value is desirable because it indicates better soil capacity to function and for example sustain plant productivity (Andrews et al., 2002a; Karlen et al., 2006; Armenise et al., 2013). Generally, soils under conservation tillage practices have a higher SQI than plowed ones under a variety of climatic conditions and across different ecosystems (Griffiths et al., 2010; Sharma et al., 2005; Erkossa et al., 2007; Zobeck et al., 2008; Aziz et al., 2013).

The main objective of this study was to establish a MDS and an overall SQI using several soil attributes related to plant growth and nutrition after using chisel and rotary plows as non-inversion tillage (*i.e.*, RT system) and moldboard and disk plows (*i.e.*, CT system) as inversion tillage over six years in Central Iran. Our primary goal was to identify potential soil quality indicators for MDS that discriminate the two tillage systems. We hypothesized that (1) the overall SQI would help to differentiate tillage systems and (2) soil microbial properties would be the most important indicators for assessing SQI because of their high sensitivity to tillage and physical disturbance. In Central Iran, due to the predominance of calcareous soils with low SOM storage and poor structure, and more importantly sever water deficiency, conservation tillage systems are still very rare practices, as local smallholder farmers want to avoid the problems of soil compaction and aeration that might occur in the absence of CT. To our knowledge, this is the first report in our region of soil quality assessment under different tillage practices, using soil microbial parameters with potential as indicators of soil quality.

2. Materials and methods

2.1. Study site, experimental design and soil sampling

The study site was located at the Agricultural Research Station of Shahrekord University (32°19′32″N; 50°51′52″E). Mean annual rainfall and temperature for 1940–2011 at the site, which is located 2070 m asl, has averaged 325 mm and 11.5 °C, respectively. The experiment was arranged in a randomized complete block with four tillage systems: (1) moldboard plowing (MP) at a depth of 17–18 cm; (2) disk plowing (DP) at a depth of 17 cm; (3) chisel plowing (CP), at a depth of 14 cm, and (4) rotary plowing (RP), using a rotary harrow (tiller) at a depth of 10 cm. Each tillage system was replicated three times (*i.e.*, three blocks). The soil (Typic Calcixerepts) had a pH (in water) of 7.95 and contained 5.84 g kg^{-1} organic C, 0.49 g kg^{-1} total N and 350 g kg^{-1} $CaCO_3$. Its texture was loam with sand, clay and silt contents of 290, 260, and 450 g kg^{-1}, respectively. Additional site, soil characteristic, tillage treatment, crop, and other cultural practices are fully described in Kabiri et al. (2015). Tillage treatments were from 2005 to 2011, but soil samples were collected in September–October 2008, 2009 and 2011 before tillage operations. The last crop that was cultivated before sampling was barley sown in fall, 2009 and harvested in summer, 2010. The mean annual C inputs from plant aboveground biomass was ca. 1800 kg C ha^{-1} $year^{-1}$, assuming a 50% carbon content of the plant material on a dry-weight basis for all the tillage treatments (Kabiri et al., 2015). Three individual soil samples from the 0–20 cm depth were taken with a shovel after removing the dead surface litter and mixed thoroughly to provide a composite sample for each replicate. Visible roots, organic residues and stone fragments were removed manually at the time of sampling. Soil samples were crushed and passed through a 2-mm sieve before determining organic C and total N concentrations using air-dried ground subsamples. Field moist soil subsamples (<2 mm) were used for microbial biomass and activity analyses and to quantify enzyme activities.

2.2. Soil chemical and biochemical analysis

Detailed soil analysis information is presented in Kabiri (2014). In brief, soil pH (in 1:2.5 soil–water) was determined using a glass electrode, soil organic C was determined by the Walkley and Black

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