Soil & Tillage Research 107 (2010) 17–25

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland

M.J. Imaz [a,*], I. Virto [a], P. Bescansa [a], A. Enrique [a], O. Fernandez-Ugalde [a], D.L. Karlen [b]

[a] Departamento de Ciencias del Medio Natural, Área de Edafología y Química Agrícola, E.T.S.I. Agrónomos, Universidad Pública de Navarra, Campus Arrosadia s/n, 31006 Pamplona, Spain

[b] USDA-ARS, National Soil Tilth Laboratory, 2110 University Boulevard, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Received 6 April 2009
Received in revised form 9 February 2010
Accepted 11 February 2010

Keywords:
Soil quality
Mediterranean soils
Conservation tillage
Minimum data set

ABSTRACT

No-tillage (NT) practices for rainfed cereal production in semi-arid Mediterranean soils can conserve water and increase crop productivity, but producers are reluctant to adopt NT because of potential increases in penetration resistance and bulk density. We hypothesized that understanding soil quality could encourage NT adoption, but methods for selecting and assessing soil quality indicators needed to be developed for this region. Our objectives were to (1) identify the most sensitive indicators for evaluating long-term tillage and residue management within this region using factor analysis, and (2) compare soil quality assessment using those indicators with traditional evaluations using changes in water retention, earthworm activity and organic matter stratification ratio. Several soil physical, chemical, and biological indicators were measured within conventional tillage, minimum tillage, and NT (with and without stubble burning) treatments that represent a wide agro-climatic area in NE Spain. Sampling depth and management treatments significantly affected several indicators when evaluated individually and collectively. Principal component analysis identified three factors that accounted for 75 and 85% of the variation in soil measurements for 0–5- and 5–15-cm depth increments. Only two factors per depth showed significant differences among the four treatments. For both depth increments, one factor grouped soil physical attributes, and the other organic matter and biological properties. The indicators with the greatest loadings were identified as the most sensitive in each factor. These were penetration resistance, particulate organic matter (POM) and total organic matter within the 0–5 cm layer, and aggregate stability and POM within the 5–15-cm increment. Factor scores were positively correlated to soil water retention, earthworm activity and organic matter stratification, which were all greater in NT, regardless of stubble management. We conclude that (1) multivariate analyses are useful for selecting appropriate soil quality indicators, and (2) that adopting NT on Mediterranean semi-arid cropland can have several positive effects on soil quality within this region.

1. Introduction

Semi-arid soils in the Mediterranean basin generally have low organic matter levels because of historical exploitation, low carbon inputs, and a climate that favors mineralization. In Eastern Spain and other similar areas, soils also frequently have high amounts of carbonates and in some cases excess soluble salts that can significantly affect their physical properties (Muneer and Oades, 1989; Szabolcs, 1989). Biological activity, as expressed by net respiration and decomposition rates is also hindered by dry soil and warm climatic conditions (Zhou et al., 2006).

For rainfed agriculture in this area, water availability is the primary factor controlling crop productivity, so any soil and crop management practices that can enhance soil water storage and availability are likely to increase yield and overall productivity. No-tillage (NT) and crop residue retention have been shown to retain more water in these semi-arid Mediterranean soils, not only because of reduced evaporation (Lampurlanés and Cantero-Martínez, 2006), but also because no-tillage often results in the development of a new and more extensive pore system that enhances soil water holding capacity (Bescansa et al., 2006a). Tillage is often justified for these soils because, as reported in other areas (Arrouays et al., 2002), producers are concerned that without it, compaction often results in higher bulk densities and increased penetration resistance, especially in the upper few centimeters (Schjønnning and Rasmussen, 2000; Bescansa et al., 2006b). Perhaps by developing criteria for assessing soil quality, producers will be able to understand all aspects of soil management and thus be more willing to adopt NT practices and gain the water conservation, soil organic matter, and crop yield benefits of those practices (Bescansa et al., 2006b).

* Corresponding author. Tel.: +34 948 168443; fax: +34 948 168930.
E-mail address: mj.imaz@unavarra.es (M.J. Imaz).

0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.02.003

Soil quality has been 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). Its assessment is best viewed as an integrative indicator of sustainable land management, as it often reflects environmental quality, food security, and economic issues (Larson and Pierce, 1994; Lal, 1999; Herrick, 2000). With soil as a multifunctional resource (Singer and Erwin, 2000), soil quality assessment must be approached considering both the ecosystem characteristics and primary purpose for which the evaluation is being made (Karlen and Stott, 1994; Andrews et al., 2004). With regard to agricultural production and adoption of NT for enhanced water conservation, a high quality rating equates to having high productivity with improvement in soil or as little environmental degradation as possible (Govaerts et al., 2006).

Soil quality assessment must account for both inherent and dynamic soil properties and processes and must be holistic, accounting for all soil processes and interactions within soils (Karlen et al., 2003). For a specific site, assessment will be influenced by many factors including tillage, crop rotation, animal- or green-manure applications and other management factors, as well as climate and soil type. Ideally soil quality should be easy to measure, able to reflect changes in soil functions, sensitive to variations in management, and accessible to as many users as possible (Shukla et al., 2006). Furthermore, the site-specific nature of soil quality may actually require different soil property measurements depending upon the specific agroecosystem for which the assessment is being made (Govaerts et al., 2006; Rezaei et al., 2006; Shukla et al., 2006; Yemefack et al., 2006; Marinari et al., 2006).

The first step toward soil quality assessment is the selection of soil quality indicators (SQI), that is the soil properties and processes that will provide a minimum data set for evaluation (Andrews et al., 2004). Care must be taken to ensure that these SQIs accurately represent both human-induced and natural or inherent changes in the soil for which the evaluation is being made (Wienhold et al., 2004; Yemefack et al., 2006). With regard to assessing NT in cereal rainfed systems in Mediterranean semi-arid areas, enhanced structural stability and earthworm activity (Virto et al., 2007), organic matter and calcium carbonate stratification (Moreno et al., 2006) and biological status (Madejón et al., 2007) are among the indicators that would be expected to be useful for making the evaluation. However, few studies have been devoted to actually determining the minimum set of indicators for soil quality assessment in the semi-arid Mediterranean region (Zornoza et al., 2007b), and therefore, information on various SQI for this region is lacking.

The objectives for this study were (1) to identify the most sensitive SQI for evaluating long-term tillage and residue management within a semi-arid Mediterranean agroecosystem using factor analysis and (2) to compare soil quality assessment using those SQI with a soil quality evaluation using well-known indicators for that agroecosystem such as water retention, earthworm activity and the organic matter stratification ratio. We focused on rainfed cereal production systems, because they are widespread in the Mediterranean region (Monfreda et al., 2008), and yet poorly studied in relation to soil quality assessment.

2. Materials and methods

2.1. Experimental site

The experimental site was located in Olite (Navarre, NE Spain) (42°27′19″N; 18°10′00″W; 402 m a.s.l.). It has been used for demonstration purposes for more than 10 years because it is representative for the type of soils and cropping systems for rainfed cereal production in the Upper Ebro Valley (Bescansa et al., 2006b). The soil in this site is a fine-clayey Calcic Haploxerept (Table 1, Soil Survey Staff, 2003). Haploxerepts are abundant throughout the Mediterranean basin, covering more than 70,000 km^2 in Spain alone (IGN, 2006) and frequently being devoted to agriculture. In the Upper Ebro Valley in Navarre, where the study site is located, agricultural rainfed land covers more than 116,000 ha with 85% of the area devoted to cereal cropping (Gobierno de Navarra, 2009). Similar percentages are expected in other rainfed Mediterranean cropland areas in Spain and other Mediterranean countries.

Table 1
General soil characteristics in the studied soil. Mean ± standard deviation.

Soil depth (m)	0–0.30	0.30–0.75	0.75–1.05
Particle size distribution (g kg^{-1})			
Sand (50–2000 μm)	171 ± 45.6	315	277
Silt (2–50 μm)	411 ± 23.3	322	328
Clay (<2 μm)	413 ± 18.1	363	395
Bulk density (mg m^{-3})	1.52 ± 0.10	1.76	1.79
$CaCO_3$ (g kg^{-1})	326 ± 16.1	360	335
pH (water)	8.29 ± 0.02	8.50	8.20
Electrical conductivity (dS m^{-1})	0.23 ± 0.06	1.52	4.54
Cation exchange capacity (cmol kg^{-1})	19.7	20.7	21.6

The site had been cultivated using conventional tillage and used for cereal production for decades. The climate in this portion of Spain is described as being Dry subhumid (C1B′2db′4), according to the classification of Thornthwaite (1948). Mean annual evapotranspiration is 740 mm and mean monthly temperature is 13.5 °C. The average annual precipitation is 525 mm with 18% being received during the summer (July–September). This makes this site representative of the climate in a wide area around the Mediterranean basin.

2.2. Experimental design

The experimental design was a randomized block with four replications. Plots were 9 m × 24 m in size. A total of six soil and crop residue management practices were included in each block, four of which were evaluated to determine soil quality effects. They were the four more common practices for rainfed cereal production in the region: conventional tillage (CT), minimum tillage (MT), no-tillage (NT) and no-tillage with stubble burning (NTSB). Stubble burning under NT was included as a treatment because it has traditionally been used in semi-arid areas for pest and weed control and to facilitate soil management (Virto et al., 2007), and because until recently it was the common practice in the studied area. Conventional tillage consisted of mouldboard ploughing (0.25 m deep) in late summer, followed by secondary tillage with a harrow for seedbed preparation before seeding (late October). Crop residues were incorporated into the arable layer during tillage. Seeding was accomplished using a coulter-seeder. Minimum tillage consisted of chisel ploughing (0.15 m deep) and secondary tillage and seeding as for CT. A direct seeder that opened a seed-furrow 30–50 mm deep, was used for NT and NTSB. For NTSB, stubble was burnt with a low-intensity fire just before seeding. Barley (*Hordeum vulgare* L. var. Tipper) was planted each year at a sowing rate of 158 kg/ha. Nitrogen and P fertilization were similar for all treatments, averaging 100–27–0 kg N–P–K ha^{-1} year^{-1}. Superphosphate was used as basal dressing in September every other year. Urea was used every year for N fertilization.

2.3. Soil sampling

For this study, soil samples were collected 10 years after the original field experiment was initiated. Disturbed and undisturbed