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Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems

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ABSTRACT

Long-term agricultural production with different tillage systems and crop rotations affect soil health, and thereby influence agricultural sustainability. However, quantifying and integrating the numerous soil health attributes is complex. One method of measuring overall soil health is the Cornell Soil Health Assessment (CSHA) used in New York; however, its applicability for other regions should be evaluated. Soil samples were collected from the 0–15 cm depth in 2009 and 2010 at four temperate, rainfed long-term experimental sites in Ontario (Ridgetown, Delhi, Elora, and Ottawa) and we evaluated the impact of tillage systems and crop rotations on 15 soil attributes. Based on a principal component analysis (PCA), the first two components accounted for 62% of the cumulative variability. The PCA eigenvectors were used to weight individual CSHA scores and develop the new Ontario Soil Health Assessment (OSHA) overall score. The OSHA scoring system was 2–10 times more sensitive than the CSHA in showing numerical differences for soil health among different tillage systems and crop rotations, which may help growers to more clearly see differences in soil health under different management practices. No-till (NT) compared to conventional tillage (CT) had significantly greater OSHA scores at Ridgetown, Delhi, and Elora, but there was no difference at Ottawa. At Ridgetown and Elora, crop rotations which included winter wheat or alfalfa tended to have higher OSHA scores, while lowest scores were with monoculture corn (monoC) or soybean–corn (S–C or S–S–C–C). This study provides the first soil health assessment for Ontario and a framework for improving overall soil health testing elsewhere.

1. Introduction

Maintaining and building soil health is an essential component of long-term sustainable agriculture. However, no single measurement can quantify soil health because it must be inferred by using a framework for integrating many soil quality attributes (Carter et al., 1997). Soil quality can be defined as the capacity of a soil to function, which reflects sustained biological productivity, environmental quality, and plant and animal health (Karlen et al., 1997). The term soil health defines soil as a dynamic system, and its functions are mediated by management (Doran and Zeiss, 2000). Important indicators of soil health are therefore responsive to agricultural management, often reflected with changes of soil structure, porosity, infiltration, soil rooting characteristics, plant available water, soil cover, soil acidity, electrical conductivity, plant nutrients (i.e., N, P, K), organic matter, microbial biomass, and microbial diversity (Allen et al., 2011). A healthy soil will produce high crop yields under favorable weather conditions, but also have a high capacity to withstand extreme weather events and reduce nutrient loss. Therefore soil health is crucial for increasing the adaptability and resiliency to climate change. Research must focus on methods of maintaining or improving soil health, and long-term experiments (>10–30 years) are needed to understand the impact of management on soil biological, chemical, and physical characteristics (Arshad and Coen, 1992).

Holistic measurements of soil health are complex because one must integrate biological, chemical, and physical properties, processes and interactions (Karlen et al., 2003). The Cornell Soil Health Assessment (CSHA) was developed to provide one value indicating soil health; it integrates measurements of numerous soil attributes, including aggregate stability, organic matter, active C, nutrient levels, texture, etc. (Idowu et al., 2009, 2008). Using the CSHA, individual soil attributes are scored (0–100) based on measurements, from which an un-weighted average is derived for the overall soil health score. Thus, the CSHA score provides an

Abbreviations: A, alfalfa; B, barley; C, corn; CEC, cation exchange capacity; CSHA, Cornell Soil Health Assessment; CT, conventional tillage; mono, monoculture; NT, no-tillage; O, oat; PCA, principal component analysis; PMN, potentially mineralizable N; R, rye; rc, undersown red clover; S, soybean; T, tobacco; W, winter wheat.

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easily interpretable measurement characterizing overall soil health (i.e., the higher the value, the better the soil health). On a for-fee basis since 2007, farmers may use the CSHA to inform their management decisions (Gugino et al., 2007; Idowu et al., 2008). However, the simple un-weighted average approach of the CSHA may result in a biased soil health score due to extreme values from individual soil attributes. Improvements in calculating or computing the overall soil health score may be required for a more meaningful representation of overall soil health (Van Eerd et al., 2014). Furthermore, research is needed to assess the applicability of the CSHA for Ontario soils and elsewhere.

Agricultural activities (tillage systems or crop rotation) can affect soil health. Karlen et al. (2013) consider the moldboard plow to have had the greatest negative effect on soil quality attributes. Although some studies encourage growers to adopt less aggressive tillage practices (Karlen et al., 2013), others have found limited differences among tillage systems on soil quality indicators such as C sequestration (Baker et al., 2007; Gregorich et al., 2005). When studying tillage system effects on soil organic C across Canada, Angers et al. (1997),Gregorich et al. (2005), and McConkey et al. (2003) found the impact of management on soil quality attributes to differ depending on climate, region, or soil texture. Therefore, more research is needed to better understand the regional impacts and interactions among soil characteristics, climate, and agricultural management on soil health. There are several field experiments that have been actively maintained for up to 30 years in Ontario (Congreves et al., 2014a), which presents an opportunity to investigate the impact of long-term agricultural production on soil health. An integrated and detailed analysis is required to measure the net impacts of long-term tillage (no-tillage (NT) vs. conventional tillage (CT)) and crop rotations (monoculture or rotations with and without undersown red clover) on soil quality attributes in Ontario.

We hypothesize that no-till and diverse crop rotations improve soil quality attributes and overall soil health, compared to conventional tillage and monoculture cropping. By identifying which tillage system and/or crop rotation practices best maintain or improve soil health, growers will have the opportunity to strategically plan their management accordingly. Therefore, the objectives of this research were to determine the impact of long-term tillage systems and crop rotation on soil health attributes at various long-term sites throughout Ontario, and to contribute to an improved soil health scoring framework which could be used in Ontario and elsewhere.

2. Materials and methods

2.1. Experimental design and management

Soil health attributes were assessed at Ridgetown, Delhi, Elora, and Ottawa, Ontario where experimental designs had fixed effects of tillage, crop rotation, and tillage × crop rotation. At each site, there were four replicates, two tillage practices (NT and CT), three to eight crop rotations. In all experiments, crops were rainfed and crop rotations were repeated so that all crop phases were present in each year. Ontario has a humid continental climate, located in the north temperate zone with monthly total precipitation and mean temperature available elsewhere (Gaudin et al., 2015a, acceptedGaudin et al., 2015a, accepted). At all sites as per typical production practices, winter wheat (*Triticum aestivum* L.) was planted in the fall shortly after soybean (*Glycine max* L.) harvest and wheat was harvested the following year in July or August with no crop planted until the next year. The typical depth of soil disturbance for NT, moldboard plow and cultivation was 5 cm, 15–20 cm and 10–15 cm, respectively.

At Ridgetown (42°26′ N 81°53′ W) on a clay loam soil with 27% sand, 37% silt, and 36% clay (Orthic Humic Gleysol) in 1995, a long-term tillage system and crop rotation trial was established in a split-plot design with four replicates, as described by Van Eerd et al. (2014). The main plot factor was tillage: NT (no soil disturbance except during planting) and CT (moldboard plow in the autumn followed by spring cultivation for seedbed preparation, as per typical production practices). Crop rotation was the split-plot factor; which included monoculture corn (*Zea mays* L.) (monoC), monoculture soybean (monoS), soybean–winter wheat (S–W), corn–soybean–winter wheat (C–S–W), and soybean–corn (S–C) rotations. Fertilizer applications were previously reported (Van Eerd et al., 2014); briefly, 100 kg ha^{-1} of starter (6-24-24) applied at corn planting, with a sidedress injection of 120 kg N ha^{-1} of urea ammonium nitrate (28-0-0) annually. For winter wheat 100 kg N ha^{-1} as calcium ammonium nitrate (27-0-0) was broadcast on the soil surface and no N fertilizer was applied for soybean production.

At Delhi (42°52′ N 80°31′ W) on a sandy loam soil with 75% sand, 17% silt, and 8% clay, (Brunisol; Gray Brown Luvisol) in 1988, a crop rotation and tillage system experiment was established in a randomized complete block design with four replicates. Agronomic management was described by Wanniarachchi et al. (1999). Crop rotations included monoC, tobacco (*Nicotiana tabacum* L.)–tobacco–rye (*Secale cereale* L.) (T–T–R) and S–W. Each crop rotation was produced under conventional tillage (spring moldboard plow with secondary tillage) or NT management (no soil disturbance except at planting). Starter fertilizer applications to corn included 6-24-6 at 341 kg ha^{-1} or 5-10-31 at 100 kg ha^{-1} with a sidedress application of 150 kg N ha^{-1} of urea ammonium nitrate.

At Elora (43°52′ N 80°21′ W) on a silty loam soil with 27% sand, 57% silt, and 17% clay, (Gleyed Melanic Brunisol) in 1980, a crop rotation and tillage system experiment was established in a split-plot design with four replicates. Crop rotation was the main plot factor and tillage was the split-plot factor. Raimbault and Vyn (1991) and Wanniarachchi et al. (1999) described the site and agronomic management. The eight crop rotations included monoC, monoculture alfalfa (*Medicago sativa* L.) (monoA), corn–corn–oat (*Avena sativa* L.)–barley (*Hordeum vulgare* L.) (C–C–O–B), corn–corn–oat–undersown red clover (*Trifolium pretense* L.)–barley–undersown red clover (C–C–O/rc-B/rc), corn–corn–soybean–soybean (C–C–S–S), corn–corn–soybean–winter wheat (C–C–S–W), corn–corn–soybean–winter wheat–undersown red clover (C–C–S–W/rc), and corn–corn–alfalfa–alfalfa (C–C–A–A). Tillage systems consisted of CT (autumn moldboard plow with secondary spring disk cultivation), and NT (no soil disturbance except at planting). Starter fertilizer applications included 0-20-20 at 157 kg ha^{-1} to corn, with a sidedress injection of 420 L ha^{-1} as urea ammonium nitrate. Thus, 160 to 170 kg N ha^{-1}, 23-32 kg P ha^{-1} and 50–90 kg K ha^{-1} were applied annually for corn production at Elora (Munkholm et al., 2013; Raimbault and Vyn, 1991). No fertilizer was applied to soybean, but 300 and 200 kg ha^{-1} of 34-0-0 was broadcast for winter wheat and barley production, respectively.

At Ottawa (45°23′ N 75°43′ W) on a sandy loam with 58% sand, 30% silt, and 12% clay, (Melanic Brunisol) in 1992, crop rotation and tillage treatments were established in a randomized complete block design with four replicates. Descriptions of agronomic practices at Ottawa were reported by Angers et al. (1997) and Bolinder et al. (1999). Rotations included monoC, monoS, C–S–W, and monoculture W (monoW). Tillage included conventional (autumn moldboard plow with spring cultivation) and NT (no soil disturbance except at planting). Fertilization was applied according to provincial recommendations, similar to the other three locations.