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Quantitative soil quality indexing of temperate arable management systems

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ABSTRACT

Soil quality assessment can provide a practical approach for early detection of adverse influences of management practices. Our objective was to develop soil quality indices (SQI) for assessing the effects of current arable management practices on soil quality for temperate maritime soils. The study was conducted on twenty arable sites with conventional or minimum tillage and mono-cropping or crop rotation. Twenty-two soil properties were measured as potential indicators of soil quality, and those indicators that were responsive to management were considered as a total data set. Principal component analysis was used to determine a minimum data set (MDS), and four indices of soil quality were calculated using linear/non-linear scoring functions and additive/weighted additive methods. Visual evaluation of soil structure (VESS) was used to validate these indices. Total nitrogen, carbon nitrogen ratio, magnesium, aggregate size distribution, bulk density, penetration resistance and soil respiration were identified as the MDS (independent variables with $r < 0.7$). All four SQI differed significantly by VESS class ($P < 0.05$), but the linear additive index showed the best discrimination by management practices ($P < 0.05$). The study indicated the positive influences of minimum tillage in combination with crop rotation on soil quality in Ireland, and indicated a detrimental effect of mono-cropping. The method developed in this study can provide a practical, quantitative tool for assessing soil quality under agricultural management systems.

1. Introduction

Agricultural management practices play an important role in the prevention of soil degradation and the sustainability of crop productivity in countries with temperate maritime climate such as Ireland and the United Kingdom (Black et al., 2002; Dillon et al., 2008, 2010; Munkholm et al., 2013). Arable systems in Ireland typically use conventional plough cultivation or minimum tillage for cereal crop production (Lafferty et al., 1999; TSDP, 2012). Most tillage farms are located in the eastern half of Ireland where this study was conducted and there is greater management intensity compared to other regions (TSDP, 2012). Soil quality (SQ), which is associated with water, food and environmental quality (Lal, 1999, 2001; Monreal et al., 1998), has been suggested as a means of evaluating the sustainability of land management systems (Herrick, 2000). While comprehensive information about SQ in Ireland does not exist, the general consensus based on limited information is that SQ is good under Irish agricultural systems (OECD, 2008). Over the last decade, the pressure on SQ has increased as a result of management intensification (Brogan et al., 2002; Lehane and O'Leary, 2012). This indicates the importance of monitoring the effects of current management on soil condition and quantification of SQ for early warning of adverse impacts from change in management.

Mechanized arable agriculture typically uses conventional ploughed cultivation or conservation tillage for cereal crop production (Moreno et al., 1997). Quantifying the effects of arable systems on soil properties is crucial for monitoring, evaluating and understanding the impact of management practices on soil condition and the sustainability of soil productivity and agricultural systems (Karlen et al., 2011, 2013b). The soil quality concept, “the capacity of a soil to function within ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health” (Doran and Parkin, 1994), offers an integrated approach that brings multiple indicator properties together (Nortcliff, 2002; Ditzler and Tugel, 2002), and in the context of arable production, can be focused on both agricultural and environmental sustainability (Govaerts et al., 2006). There is no universal list of indicator properties suitable for all regions and ecosystem functions (Arshad and Coen, 1992;

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Seybold et al., 1998), but selected indicators must be sensitive to management practices and related to the primary purposes of the SQ evaluation such as the crop production capability of soil, while not being influenced by short-term weather conditions (Doran et al., 1996; Hussain et al., 1999). Selected indicators should not be specific to a soil type in order to be used for monitoring SQ (Brogan et al., 2002). Soil attributes that have been suggested as important soil quality indicators are bulk density, penetration resistance, infiltration rate, organic carbon, soil respiration, microbial biomass, nutrient availability, pH, particle size distribution and aggregate stability (Larson and Pierce, 1994; Arshad and Coen, 1992; Doran and Parkin, 1994; Karlen et al., 1997; Fernandes et al., 2011; Lima et al., 2013). Soil organic carbon (SOC), cation exchange capacity, base saturation, pH, available phosphate and bulk density were suggested as potential indicator of SQ in Ireland (Brogan et al., 2002), and soil respiration was found as practical biological indicator in a temperate maritime climate (Yuste et al., 2003). In general, more than one indicator is required for assessing the effects of tillage management systems (Nannipieri et al., 1990; Masto et al., 2008; Andrews et al., 2004), but reducing data redundancy using principal component analysis (PCA) allows for the definition of a minimum data set for a specific circumstance (Andrews et al., 2002; Rezaei et al., 2006; Govaerts et al., 2006).

Soil quality indices (SQI) that integrate selected soil properties into a single index have been developed using a three step process: (i) indicator selection, (ii) indicator interpretation and scoring, and (iii) integration of scores into an index (Andrews et al., 2002, 2004; Karlen and Stott, 1994; Qi et al., 2009). Selection is based on the purpose of the index and the function of interest (Karlen and Stott 1994; Doran and Parkin, 1994), scoring is used to scale all indicators into the range 0–1 (Andrews et al., 2002; Masto et al., 2008) and integration is usually by a defined equation (e.g., Bastida et al., 2006; Sinha et al., 2009). A simpler, yet still reliable approach that has been developed in parallel with SQI is visual evaluation of soil structure (VESS, Guimarães et al., 2011). This is based on the idea that soil structure is a fundamental integrating indicator of overall soil quality (Mueller et al., 2013). VESS considers a range of important soil characteristics such as aggregate strength, shape, porosity and roots, which are critical for overall soil quality (Askari et al., 2015; Ball et al., 2007, 2013; Guimarães et al., 2011). The practical use of VESS and its reliability under arable and grassland systems in Ireland has been demonstrated by Askari et al. (2013) and Cui et al. (2014). VESS is a semi-quantitative approach that is a complementary method to laboratory analyses, (Askari et al., 2013; Ball et al., 2007), but it is not suitable for all soils. An SQI, sensitive to tillage management, developed using a minimum number of soil properties would be valuable for quantitative assessment of the sustainability of arable management practices.

The objective of this study was to develop a soil quality index for the production function of soil suitable for evaluating the effects of arable management practices (conventional and minimum tillage, rotation and mono cropping) on soil quality. The method was demonstrated for a particular climatic region and its arable management systems, but can be used to develop SQI applicable to any particular situation thus offering a practical SQI tool for management support, monitoring and policy assessment.

2. Materials and methods

2.1. Site characterization

Twenty arable fields representing different agricultural management systems typically found in Ireland (between latitude 52°12′4″N and 53°53′3″N; longitude 6°22′42″W and 7°34′56″W) were selected for a cross-sectional survey to collect data for the development of an SQI sensitive to the effects of management practices on soil quality. Soil sampling and field measurements were conducted from August to November 2011. The average annual precipitation in study area is between 750 mm and 1000 mm, and mean daily temperature varies from 12.3 °C to 15.7 °C in summer and 4.0 °C to 7.6 °C in winter (http://www.met.ie). Minimum and conventional tillage were the dominant tillage systems (Lafferty et al., 1999; Dillon et al., 2008, 2010) and more than 80% of crop production at the time was cereals, especially wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (TSDP, 2012). Conventional tillage is based on plough systems, which invert soil and are usually associated with crop residue burial and secondary seedbed preparation, while minimum tillage does not invert the soil and the crop residues are maintained at the surface. The study sites were selected to be

Table 1
VESS score, management and soil information for each site.

Sites	Tillage type	Crop system	Crops	Dominant soil type	Ave, VESS score	
					mean	Std.
1	MT	R	Wheat, bean	Typical brown earths	1.70	0.43
2	MT	R	Wheat, potato	Typical brown earths	2.64	0.38
3	MT	S	Barley	Typical luvisols	1.56	0.41
4	CT	S	Barley	Typical luvisols	2.00	0
5	MT	R	Wheat, bean	Typical luvisols	1.90	0.62
6[a]	MT	R	Wheat, bean	Typical luvisols	–	–
7	MT	S	Wheat	Typical luvisols	1.75	0.06
8	MT	R	Wheat, bean, OSR	Typical brown earths	1.76	0.03
9[a]	MT	R	Wheat, bean, OSR	Typical brown earths	–	–
10[a]	CT	S	Wheat	Typical luvisols	–	–
11	CT	R	Wheat, bean, barley	Typical brown earths	1.80	0.45
12	CT	R	Wheat, bean, barley	Typical brown earths	1.86	0.5
13	CT	R	Maize, wheat	Typical luvisols	3.21	0.57
14	CT	R	Maize, wheat	Typical luvisols	2.14	0.3
15	CT	S	Wheat	Typical luvisols	2.93	0.53
16	MT	R	Barley, oat, wheat, bean	Typical brown earths	2.40	0.55
17	CT	R	Barley, oat, wheat, bean	Typical brown earths	1.40	0.55
18	CT	R	Wheat, oat, OSR	Typical luvisols	2.60	0.55
19	CT	S	Barley	Typical luvisols	2.60	0.55
20	CT	S	Barley	Typical luvisols	2.4	0.55

MT, minimum tillage; CT, conventional tillage; R, tillage with crop rotation; O, tillage with one crop; OSR, oilseed rape; Ave, Average; VESS, visual evaluation of soil structure; dominant soil types were identified according to SIS (2014).
[a] Excluded sites.