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Indices for quantitative evaluation of soil quality under grassland management

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ABSTRACT

Objective: The objectives of this study are to determine appropriate indicators, the most appropriate scoring function (linear or non-linear) and integrating procedure (additive and weighted additive) for a soil quality index for typical temperate, maritime grassland management (e.g. livestock grazing and silage production).
Methods: The study was conducted on twenty grassland sites classified by three levels of management intensity. Twenty-one soil properties were measured as potential indicators of soil quality, and the visual evaluation of soil structure was applied to select indicators responsive to management and for the validation of the indices. Indices were calculated using linear and non-linear scoring, followed by additive and weighted additive integration. Principal component analysis used with the total dataset of indicators sensitive to management to determine a minimum dataset.
Results: Soil organic carbon (SOC), total nitrogen, aggregate size distribution, bulk density, bulk density of ≤2 mm fraction, extractable potassium and carbon–nitrogen ratio (CN) were the indicators that comprised the total dataset, while SOC, CN and bulk density of ≤2 mm fraction were the minimum dataset. The management intensity influenced each indicator in different ways, and the index calculated using minimum dataset and nonlinear weighted additive integration had the best discrimination ability.
Conclusions: The average soil quality index values were lower under higher intensity management, and indicated that management intensification was tending toward an adverse impact on soil quality under grassland systems in Ireland.
Practice: There was no evidence that current grassland management was having a long-term detrimental effect on soil quality for grassland production, but the trend suggested that increasing intensity might cause management difficulties due to soil limitations in the future.
Implications: The indexing approach in this study provides a practical, time and cost effective method for quantitative evaluation of soil quality under temperate maritime grassland management.

1. Introduction

Grassland is the dominant land use in Ireland, supporting very productive livestock enterprises and it has a substantial role in how environment and soil resources are used (Lafferty et al., 1999). Current grassland management systems are believed to influence soil quality (SQ) with a feedback to agricultural productivity. Therefore maintaining SQ, preventing soil degradation and evaluating the effects of increasing management intensity on soil properties are of particular interest especially in the context of "sustainable intensification" (Bone et al., 2012; Garnett et al., 2012; Pretty, 1997). A goal of maximum long-term productivity without decreasing SQ and causing soil degradation (Govaerts et al., 2006; Qi et al., 2009) is a prerequisite for a sustainable grassland agriculture system. Quantifying SQ under agricultural systems to evaluate the influence of management intensity on soil productivity is imperative for early detection of adverse effects of management practices (Barrios and Trejo, 2003; Mairura et al., 2007).

The SQ concept can be controversial due to the complex interaction of soil, plants, anthropic and climatic factors within an ecosystem (Carter, 2002). A commonly used definition for SQ is "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). Different methods have been developed for SQ evaluation, from qualitative or semi-quantitative visual approaches (e.g. Ball et al., 2007; Shepherd, 2009) to quantitative methods based on laboratory analysis and calculating SQ indices using mathematic and statistical methods (e.g. Andrews et al., 2004; Karlen et al., 1997; Larson and Pierce, 1994). The indexing methods are most commonly used (Mohanty et al., 2007; Qi et al., 2009) usually integrating several indicators associated with soil functions appropriate to the intended use into a quantitative factor that

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can be used for multi-objective decision making (Karlen and Stott, 1994). SQ indices (SQI) have been successfully applied at many scales and locations (e.g. Andrews et al., 2002a; Aparicio and Costa, 2007; Arshad and Martin, 2002; Glover et al., 2000; Masto et al., 2008). SQI usually define a combination of bio-chemical and physical indicators through application of a scoring equation to organize measured soil attributes into a single index (Doran and Parkin, 1994; Qi et al., 2009).

There is no comprehensive SQ index that can be used as a universal method across regions and scales (Qi et al., 2009; Sun et al., 2003, Zhang et al., 2004), therefore many SQI have been developed for specific purposes and indices are usually valid under particular environmental conditions (e.g. Andrews et al., 2002b; Imaz et al., 2010). An integrated SQI is commonly developed using a three-step process: indicator selection, indicator scoring, and integration of scores into an index (Andrews et al., 2002a, 2004; Stott et al., 2011). This approach can provide practical results, which are comparable within agricultural systems (Armenise et al., 2013). Doran and Parkin (1994) suggested a simple multiplicative equation as a framework to determine a SQI considering socio-economic, geographic and climatic issues. Karlen and Stott (1994) identified soil functions to evaluate soil quality under different management system where a systems engineering approach was utilized to define a range of soil attribute scores with an additive method to calculate a single index for soil quality (Karlen and Stott, 1994; Larson and Pierce, 1994). This approach was used by Hussain et al. (1999) to evaluate the effect of management practices under arable management, by Melo Filho et al. (2007) under natural forest, and by Lima et al. (2013) for three different rice management systems. All concluded that the methodology was suitable for detecting the effect of management practices and was responsive to the change of SQ. In general, non-linear scoring methods are preferred to linear methods to represent soil conditions (Andrews et al., 2002a; Li et al., 2013b; Pierce et al., 1983). A non-linear scoring equation was suggested by Bastida et al. (2006) and Sinha et al. (2009) as a practical approach as employed by Zhang et al. (2011) to quantify SQ and evaluate the effects of different vegetation types by land use. Available N, metabolic quotient, MBC, urease, polyphenol oxidase, and bulk density were selected as the minimum dataset (MDS) using principal component analysis (Zhang et al., 2011). This method was later introduced as a modified SQI by Li et al. (2013b) for assessing the influences of the intensity of human disturbance on four types of grasslands and had a good capability for evaluating the SQ of alpine grasslands. Accurate assessment of SQ requires selecting and interpreting suitable soil indicators related to soil functions that cannot be measured directly (Ditzler and Tugel, 2002; Nortcliff, 2002). The co-linearity of soil properties and considerable time and cost required for comprehensive soil data collection and analysis reveal the necessity of developing a minimum dataset (MDS) based on maximizing relevant information and reducing data redundancy (Doran and Jones, 1996; Li et al., 2007). Principal component analysis (PCA) is widely used for defining a MDS and reducing data redundancy through correlation analysis among soil properties (Andrews et al., 2002a; Govaerts et al., 2006; Li et al., 2007).

A good indicator should be correlated to critical soil functions and should be precise, science-based, easy to measure and sensitive to management systems (Andrews et al., 2004; Karlen et al., 1997). In addition, parameters such as location, climate, soil condition and management goals must be considered when choosing appropriate soil indicators (Riley, 2001; Shukla et al., 2006). Several bio-chemical and physical attributes have been suggested as useful and practical indicators for SQ assessment, including total and organic carbon, total nitrogen, bulk density, infiltration rate, pH, cation exchange capacity, total porosity, aggregate size distribution and stability, penetration resistance, soil respiration, extractable phosphate, magnesium and potassium (Arshad and Coen, 1992; Carter, 2002; Doran and Parkin, 1996; Fernandes et al., 2011; Karlen et al., 1997; Lima et al., 2013). Organic matter has been suggested as an important SQ indicator for a variety of soil functions. It has a key role in fertility, nutrient availability and aggregate stability (Pojasok and Kay, 1990; Yao et al., 2013b). Soil respiration is sensitive to soil disturbance so it can act as practical indicator for early detection of soil degradation (Sparling, 1997). An individual indicator cannot reflect all soil functions of interest (Andrews et al., 2004), and more than one soil property is usually needed for SQ assessment (Masto et al., 2008, Nannipieri et al., 1990).

Similar to indices of soil quality, visual soil assessment methods such as Visual Evaluation of Soil Structure (VESS, Guimarães et al., 2011) have been shown to be practical and reliable approaches for evaluating soil structural quality (Askari et al., 2013; Ball et al., 2013; Mueller et al., 2013). VESS mainly focuses on soil structural quality, but it considers a range of soil attributes such as aggregate strength, size, shape, soil porosity and roots that are important for overall soil quality (Ball et al., 2007, Guimarães et al., 2011). Soil structural quality influences several important soil functions such as soil productivity, biological activity, root growth, soil physical stability and nutrient cycling (Kavdır and Smucker, 2005). Visual methods can explain more than soil structure and could be used for general soil quality rating (Ball et al. 2013; Mueller et al., 2013). The reliability of VESS as a complementary approach to laboratory analyses for assessing soil quality under Irish maritime temperate soils has been demonstrated by Askari et al. (2013) and Cui et al. (2014). Subjectivity is only an important issue when using VESS if not properly implemented, and while it is not suitable for all soil quality assessment purposes, it can be closely related to many physical and biochemical indicators of SQ (Askari et al., 2014; Mueller et al., 2013).

The objectives of this study were to determine appropriate indicators for assessing soil quality by focusing on the productivity function of the soil, and to identify the most appropriate scoring function (linear or non-linear) and integrating procedure (additive or weighted additive) for calculating an SQI, judged by ability to detect the effects of management intensity on soil conditions, as characterized using Visual Evaluation of Soil Structure (Askari et al., 2013; Cui et al., 2014). The intention was to identify a minimum dataset for quantitative evaluation of SQ under typical temperate, maritime grassland management (e.g. livestock grazing and silage production).

2. Materials and methods

2.1. Site characterization

The study was conducted using twenty grassland sites in Ireland that were located between latitude 52° 8′ N and 54° 20′ N and longitude: 6° 32′ W and 8° 19′ W (ca. 25,000 km^2). The mean daily temperature in winter ranged from 4 °C to 8 °C, in summer from 12 °C to 16 °C, and average annual precipitation was between 750 and 1000 mm (http://www.met.ie). The soils in the study area mainly consisted of Grey Brown Podzolics, Brown Podzolics, Brown Earths, Gleys, Rendzinas, Lithosols and Peat, and the dominant soil forming processes were leaching, gleying and calcification (Gardiner and Radford, 1980). Prior to field sampling, management information was recorded through semi-structured interviews with the farmer at each site. A questionnaire was developed to collect the necessary information regarding current management practices in each field. The information included type of farm, paddock age, grazing and silage management, stocking rate, reseeding information and fertilizer strategy. More details regarding the location of studied sites, management information and nutrient inputs was presented by Cui et al. (2014).

Each site was characterized based on the type of farm (dairy, beef, beef plus dairy, mix sheep and other cattle), frequency of reseeding (less than 10 years, 10 to 20 years, more than 20 years and no reseeding), stocking rate (classified as low (less that 2.51 cows per hectare), medium (2.51 to 3) or high (more than 3 cows per hectare) based on McCarthy et al. (2012) and whether used for grazing, silage or both. This type of management information is usually used to characterize grassland systems (e.g. Baudracco et al., 2010; Macdonald et al., 2008; McCarthy et al., 2012; O'Donnell et al., 2008). A combination of management information (summarized in Table 1) was used to classify