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Indices for quantitative evaluation of soil quality under grassland management

Mohammad Sadegh Askari *, Nicholas M. Holden

UCD School of Biosystems Engineering, University College Dublin, Dublin 4, Ireland

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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

* Corresponding author at: Room 325, UCD School of Biosystems Engineering, University College Dublin, Dublin 4, Ireland. Tel.:+353 870979531(mobile); fax: +353 1 7167415.
E-mail address: mohammad.askari@ucdconnect.ie (M.S. Askari).

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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

Table 1
Management practices and intensity classification for each sample site.

Site	Farm type	Reseeding frequency (years)	Management	Stocking rate	K mean clustering		
					Cluster	Distance	Intensity class
1	D	10–20	S + G	L	1	0.894	High
2	D	10–20	S + G	H	1	1.265	High
3	M	NO	G	M	3	0.943	Low
4	D + B	10–20	G	M	2	0.981	Mid
5	D	<10	S + G	L	1	1.000	High
6	D + B	10–20	G	M	2	0.981	Mid
7	D + B	>20	G	L	2	1.515	Mid
8	B	10–20	S + G	M	2	0.720	Mid
9	B	10–20	S + G	M	2	0.720	Mid
10	M	NO	G	L	3	0.745	Low
11	D	<10	S + G	M	1	0.632	High
12	D	10–20	S + G	M	1	0.447	High
13	B	NO	G	L	3	0.471	Low
14	B	<10	S + G	L	2	1.186	Mid
15	B	<10	G	L	2	1.232	Mid
16	B	10–20	S + G	L	2	0.793	Mid
17	B	NO	G	L	3	0.471	Low
18	B	NO	G	M	3	0.745	Low
19	B	NO	G	L	3	0.471	Low
20	B	10–20	S + G	M	2	0.720	Mid

D, dairy farm; B, beef farm; M, mixed sheep and cattle farm; D + B, mixed dairy and beef farm; G, only grazing; S + G, both silage and grazing; Stocking rate: H, high (>3 cows/ha); M, medium (2.51 to 3 cows/ha); L, low (<2.51 cows/ha); High: high intensive pasture; Mid: medium intensive pasture; Low: low intensive pasture. More detail of management, which was not used for intensity classification in this study can be found in Cui et al. (2014).

the studied sites into three levels of management intensity, and due to the small number of sample sites a K-means clustering analysis (Hartigan and Wong, 1979) was used to identify major clusters of management intensity.

2.2. Field sampling

Field sampling and measurements were undertaken from September to December 2011. At each site, a 30 m^2 plot was laid out with random orientation in a representative part of the field with uniform soil and land cover. Five sub-plots (2 m^2), approximately equal distance apart were selected for sampling and field measurements based on walking a 'W' between the diagonal corners of the sampling square. Gateways, unusually dry or wet areas, headlands and highly trafficked areas were avoided. At each sub-plot three replicate core samples were taken for analyses of total porosity and bulk density, after removing the grass layer, using a ring with 5 cm height and 5 cm diameter. Around 2 kg loose soil was also collected from 0 to 10 cm depth, bagged and stored in cool, dark conditions for laboratory analysis. In total 100 sampling sub-plots (five at each site) were sampled in triplicate for topsoil and the results were averaged for each sub-plot. Soil sorptivity was measured according to the method presented by Philip (1957) using a ring (25 cm height and 10 cm diameter), and initial amount of water for the soil sorptivity calculation was determined based on top soil permeability (Sepaskhah et al., 2005). A portable soil compaction meter (FIELDSCOUT SC900) was used to determine near-surface penetration resistance to 10 cm depth (Lowery and Morrison, 2002).

2.3. Laboratory analysis

Chemical, physical and biological properties were determined to develop soil quality indices and assess the effects of management intensity. Twenty-one soil attributes were measured per sampling point, each as an average of three replicates. Bulk density (BD) was determined based on the core method (Grossman and Reinsch, 2002), and gravel more than 2 mm diameter was separated from the samples to calculate the BD of the 2 mm fraction ($BD_{2\ mm}$). Soil water content and total porosity were determined by oven drying (105 °C overnight, Topp and Ferre, 2002) and the gravimetric method (Flint and Flint, 2002) using the same cores employed for bulk density. Microbial soil respiration was assessed using the amount of CO_2 evolution at 20 °C (Horwath and Paul, 1994) using fresh soil. The amount of CO_2 released from 20 g soils over 10 days of incubation was calculated from the volume of hydraulic acid (0.5 N) required to attain pH 7 for the 10 ml of sodium hydroxide used for collecting the CO_2. Dry aggregate size distribution was determined and presented as the mean weight diameter (MWD) by placing 100 g of loose air dried samples in a column of sieves (10, 5.6, 4.75, 2, 1, 0.5 and 0.25 mm) and shaking with a shaker (Retsch VS 1000) for 10 min (Nimmo and Perkins, 2002). Particle size distribution was determined using the pipette method (Gee and Or, 2002), and classified based on the USDA system. Prior to chemical analysis the soils were air dried and passed through a 2 mm sieve. Extractable calcium (Ca), magnesium (Mg) and potassium (K) were determined using an inductively coupled plasma-atomic emission spectrograph (Varian Inc. — Vista-PRO CCD Simultaneous ICP-AES) and were extracted by Morgan solution (Soltanpour et al., 1996). Extractable phosphate (P) was determined by spectrophotometer (Spectronic Helios Alpha — Uni-cam UV6-420) using a colorimetric method (Kuo, 1996). pH was determined using a standard pH meter in a 1:1 soil–water ratio (Thomas, 1996). Soil inorganic carbon (IC), total nitrogen (TN) and total carbon (TC) were measured using an inorganic carbon analyzer (Skalar Primacs SLC-IC analyzer) and a dry combustion carbon and nitrogen analyzer (LECO Tru-Spec CHN analyzer) as described by Matejovic (1997) and Wright and Bailey (2001). CEC was calculated using the sum of exchangeable cations method (Sumner and Miller, 1996).

2.4. Selection of indicators

Visual evaluation of soil structure (VESS) (Askari et al., 2013; Guimarães et al., 2011) was used to assess soil structural quality (Sq score) at each site and to select the indicators that best represented soil quality under the grassland management being evaluated. Sq values were classified into three groups; "good" (<2) meaning no changes in management practices are needed, "fair" (2 to <3) where long-term improvements are required and "poor" (≥3), where short-term improvements are called for (Ball et al., 2007). Only those indicators that were significantly different by Sq class were regarded as suitable for development of an SQI. Soil samples were randomly allocated to either a calibration set (70%) for developing the SQI or a validation set (30%) for testing the SQI. Analysis of variance (ANOVA) of the calibration dataset was used to select those attributes that were significantly different ($P < 0.05$) by soil quality class and thus members of the total dataset (TDS) for developing the SQI.

2.5. Minimum datasets

Principal component analysis (PCA) was employed on the standardized data matrix of the TDS to reduce data redundancy and identify the most appropriate indicators for assessing soil quality. The eigenvalue was used as a criterion to determine the number of principal components, and the components with eigenvalues ≥1 were deployed for the identification of the MDS. The components with eigenvalues <1 had less variation than an individual variable (Brejda et al., 2000). To enhance the interpretability of the component a Varimax rotation was performed on selected PCs (Flury and Riedwyl, 1988; Li et al., 2013a). The weighted loading values in each component were used to select the indicators, with ten percent of the highest weighted loading as a threshold for selection (Andrews et al., 2002a; Govaerts et al., 2006; Mandal et al., 2008; Yao et al., 2013a). The correlation among remaining variables in each component was calculated to identify the variables that were redundant (variables with high correlation coefficient and low weighted loading) for elimination, and finally the remaining independent indicators were chosen as the MDS (Rezaei et al., 2006).

2.6. Developing and validating soil quality indices

The SQI were developed in three steps: selection of appropriate soil properties, transformation into unit-less scores and aggregation into an index (Andrews et al., 2004). Both MDS and the TDS were used to develop SQI. The appropriate scoring algorithm was chosen by interpreting each indicator based on its influence on soil productivity. The values of attributes were transferred into scores using non-linear and linear scoring methods. “More is better”, “less is better” and “midpoint optimum” approaches are available (Hussain et al., 1999; Karlen and Stott, 1994), but only “more is better” and “less is better” were considered for this study. For non-linear scoring a sigmoidal function (Eq. (1)) was used (Bastida et al., 2006):

$$S_{NL} = a/\left(1 + (x/x_0)^b\right) \tag{1}$$

where, S_{NL} is the non-linear score of the variable between 0 and 1, a is the maximum score, equal to 1 in this study, x is the soil variable value, x_0 is the mean value of the variable and b is the slope assumed to be -2.5 for “more is better” and $+2.5$ for “less is better” (Sinha et al., 2009; Zhang et al., 2011).

For linear scoring, “more is better” (Eq. (2)) and “less is better” (Eq. (3)) functions were used:

$$S_L = (x-l)/(h-l) \tag{2}$$

$$S_L = 1-((x-l)/(h-l)) \tag{3}$$

where, S_L is the linear score between 0 and 1, x is the variable value, l is the minimum value and h is the maximum value (Masto et al., 2008).

The scores of indicators were integrated into indices using additive (Eq. (4)) and weighted additive (Eq. (5)) methods (Andrews et al., 2002a).

$$SQI_A = \sum\nolimits_{i=1}^{n} S_i/n \tag{4}$$

$$SQI_W = \sum\nolimits_{i=1}^{n} W_i S_i \tag{5}$$

where, S_i is the indicator score (non-linear or linear), n the number of variables integrated in the index and W_i the weighing value of the indicators (Masto et al., 2007, 2008). The indicators from the TDS were weighted by respective communality, calculated from the PCA as the ratio of each indicator's communality and the sum of communalities (Li et al., 2013a; Qi et al., 2009). For the MDS, weight of indicators was determined by the variation of each respective PC (%), normalized to unity (Andrews et al., 2002a; Sinha et al., 2009).

Finally eight soil quality indices were calculated (Fig. 1) and the validation dataset was used to test them. The SQI that could differentiate soil quality classes with the validation set were considered suitable for use as practical tools for SQ assessment under temperate maritime grassland management.

2.7. Statistical analysis

Prior to statistical analysis, the normality of all datasets was tested using the Kolmogorov–Smirnov test and visual examination of histograms. Consequently, Mg, K, TN, P, and penetration resistance were log-transformed, TC and OC were inversion-transformed and Ca was

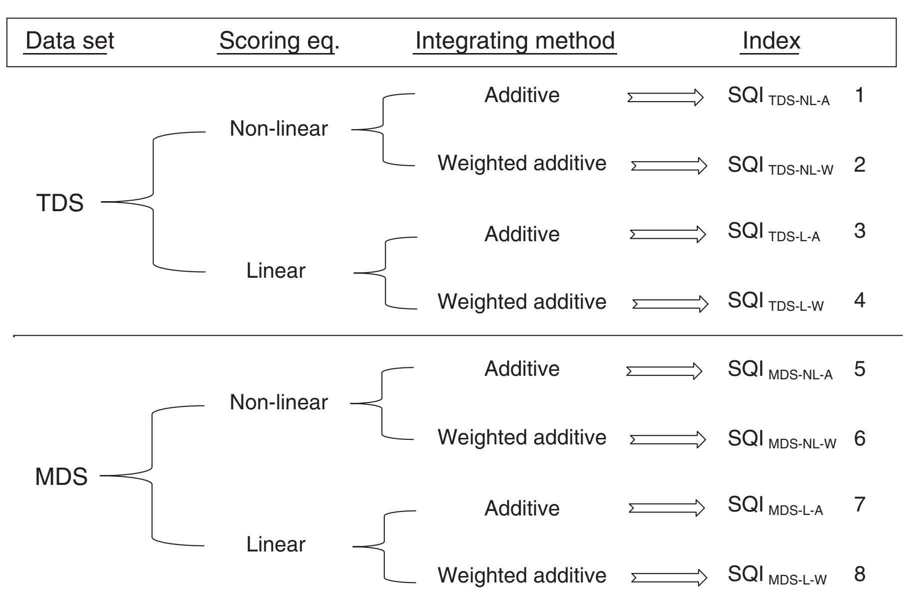

Fig. 1. The soil quality indices calculated for this study using TDS, MDS, scoring and integration combinations.

Table 2
The difference between soil properties measured as potential indicators of soil quality and randomly allocated to either a calibration or validation dataset.

Soil quality indicators	Calibration		Validation		Calibration vs validation		ANOVA on calibration	
	Mean	SD	Mean	SD	p = (Levene's test)	p = (T-test)	F	p
Aggregate size distribution (MWD)	2.46	0.69	2.38	0.54	0.188	0.593	9.50	0.00
Bulk density (g/cm^3)	0.81	0.12	0.82	0.12	0.861	0.546	5.03	0.01
Bulk density in particles <2 mm (g/cm^3)	0.79	0.12	0.81	0.12	0.933	0.419	6.14	0.00
Porosity (%)	64.77	6.22	62.86	7.08	0.632	0.180	2.35	0.10
pH	5.62	0.66	5.61	0.59	0.364	0.980	0.49	0.62
Total nitrogen (%)	0.54	0.13	0.54	0.13	0.682	0.987	15.05	0.00
Total carbon (%)	5.85	1.44	5.96	1.49	0.886	0.758	20.90	0.00
Organic carbon (%)	5.82	1.43	5.93	1.49	0.903	0.743	20.66	0.00
CN ratio	10.95	0.92	11.13	0.91	0.828	0.370	5.63	0.01
Calcium (ppm)	2657	2067	2547	1450	0.538	0.948	1.03	0.36
Magnesium (ppm)	203	96	211	83	0.891	0.560	0.57	0.57
Potassium (ppm)	171	156	200	169	0.962	0.389	6.78	0.00
Phosphate (ppm)	10.70	10.33	11.51	10.53	0.588	0.803	2.22	0.12
Sorptivity (cm s$^{-0.5}$)	0.06	0.05	0.06	0.05	0.817	0.579	0.75	0.48
Penetration resistance (kPa)	1271	524	1251	482	0.640	0.988	0.95	0.39
Water content (%)	50.14	14.58	50.72	13.28	0.592	0.851	0.46	0.64
Sand (%)	40.33	12.66	41.10	13.56	0.598	0.785	14.83	0.00
Silt (%)	34.39	7.67	34.20	8.23	0.654	0.914	11.84	0.00
Clay (%)	25.29	6.66	24.70	6.63	0.890	0.687	9.31	0.00
CEC	15.41	10.63	15.00	7.61	0.499	0.850	1.60	0.21
Soil respiration (mg C kg^{-1} day^{-1})	23.28	6.30	23.99	5.23	0.231	0.590	0.02	0.98

SD, standard deviation.

square root transformed to improve their normality. The homogeneity of variance and the mean difference between calibration and validation sets were examined using Levene's and T tests. Scoring, indexing and statistical analyses were performed using Microsoft Excel and SPSS v. 18.0 (SPSS Inc.) to classify management intensity and assess the effects of management system on soil quality. Univariate analysis of variance (ANOVA) and least significant difference (LSD) were conducted to choose the soil indicators, validate indices and compare SQI by management intensity with 95% confidence. Reducing data redundancy was achieved using principal component analysis (PCA) on the standardized values of indicators and the correlation matrix to determine the MDS.

3. Results

Twenty-one properties were measured as potential indicators related to management intensity effects on soil quality (Table 2). The homogeneity of variance of soil properties in the calibration and validation sets was confirmed by Levene's test, and the mean comparison (T test), and indicated there was no significant difference between validation and calibration mean values. The random selection of the validation set reliably represented the sample distribution (Table 2). VESS indicated 45% of sites had good soil structural quality, 45% fair and 10% poor soil structural quality (Table 3). Soil parameters that reflected difference by grassland management intensity under temperate, maritime climate were identified by their differentiation by VESS class, and were selected as indicators of soil quality based on the objective of this study. ANOVA of the calibration set showed eleven properties were significantly different by soil structure quality class ($P < 0.05$) (Table 2). The percentage sand, silt and clay were fixed properties that cannot normally be changed by management and TC was approximately equal to SOC (the differences mostly were less than 0.02%), therefore these properties were excluded from the TDS. The TDS was seven soil properties

Table 3
The average value and standard deviation of TDS and visual scores for each site.

Sites	ASD (MWD)		BD (g/cm)		BD$_{2\ mm}$ (g/cm)		SOC (%)		TN (%)		CN		K (ppm)		Sqv	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1.84	0.22	0.92	0.05	0.87	0.04	5.91	0.31	0.47	0.02	12.70	0.39	122.55	82.82	1.44	0.40
2	2.27	0.15	0.97	0.06	0.94	0.04	5.64	0.37	0.45	0.03	12.58	0.27	174.67	106.96	2.60	0.37
3	0.95	0.11	0.91	0.04	0.88	0.03	5.35	0.29	0.49	0.04	11.01	0.29	45.64	28.68	1.93	0.16
4	1.57	0.08	0.94	0.05	0.93	0.04	3.64	0.37	0.31	0.03	11.69	0.37	215.81	72.39	3.00	0.24
5	1.70	0.20	0.94	0.02	0.93	0.02	4.73	0.40	0.40	0.03	11.90	0.34	64.13	6.27	4.00	0.00
6	2.17	0.21	0.87	0.05	0.85	0.04	4.92	0.38	0.49	0.04	10.08	0.11	111.50	20.20	2.84	0.15
7	2.73	0.35	0.77	0.04	0.77	0.04	6.08	0.37	0.57	0.03	10.84	0.09	222.15	85.76	2.80	0.11
8	2.17	0.10	0.76	0.02	0.76	0.02	6.38	0.38	0.59	0.04	10.86	0.19	596.81	232.08	1.29	0.40
9	2.33	0.31	0.80	0.06	0.79	0.06	5.62	0.36	0.51	0.03	11.03	0.23	114.89	26.58	2.09	0.48
10	2.84	0.33	0.86	0.04	0.83	0.06	6.18	0.84	0.59	0.07	10.45	0.35	74.96	28.97	1.77	0.13
11	3.55	0.28	0.89	0.04	0.89	0.03	6.11	0.74	0.60	0.07	10.21	0.17	133.08	77.54	2.65	0.20
12	2.93	0.22	0.93	0.03	0.92	0.03	4.60	0.24	0.46	0.02	10.19	0.20	114.76	80.93	2.70	0.01
13	2.95	0.28	0.69	0.05	0.69	0.05	6.46	0.77	0.69	0.08	9.35	0.29	196.32	80.23	2.73	0.01
14	2.92	0.29	0.80	0.03	0.80	0.03	4.60	0.17	0.43	0.02	10.77	0.15	34.78	6.41	2.61	0.34
15	2.74	0.20	0.63	0.08	0.62	0.06	9.78	0.24	0.80	0.02	12.33	0.25	360.73	177.27	1.44	0.41
16	2.50	0.29	0.86	0.02	0.84	0.03	5.09	0.09	0.48	0.01	10.76	0.20	262.64	94.03	1.54	0.51
17	2.91	0.29	0.73	0.08	0.73	0.08	5.60	0.44	0.57	0.05	9.79	0.13	154.39	47.24	1.95	0.10
18	2.09	0.28	0.69	0.03	0.68	0.03	8.47	0.84	0.77	0.07	11.10	0.15	413.32	68.80	1.07	0.15
19	2.38	0.17	0.69	0.05	0.69	0.05	7.12	0.57	0.66	0.06	10.84	0.24	135.35	91.34	1.60	0.44
20	3.20	0.08	0.56	0.04	0.54	0.03	4.73	0.68	0.41	0.06	11.54	0.15	48.93	25.73	2.76	0.01

SD, standard deviation; ASD, aggregate size distribution; BD, bulk density; BD$_{2\ mm}$, bulk density at 2 mm particle size; SOC, soil organic carbon; TN, total nitrogen; CN, carbon–nitrogen ratio; K, extractable potassium; Sq, VESS score.

for developing SQI (Table 3): aggregate size ranged from 0.82 to 4.02 MWD (mean weight diameter), bulk density from 0.51 to 1.03 g cm^{-3}, bulk density of ≤2 mm fraction from 0.51 to 0.99 g cm^{-3}, extractable potassium from 26 to 956 ppm, total nitrogen from 0.28 to 0.84%, soil organic carbon from 3.25 to 10.16% and CN ratio from 8.9 to 13.1.

3.1. Site description and classification of intensity

All sites were characterized based on farm type, grazing and silage management, frequency of reseeding and stocking rate (Fig. 2). Based on the K-mean clustering, 25% of fields were classified as high intensity, 45% as medium and 30% as low intensity (Table 1).

3.2. Minimum dataset

Three PCs that explained 83% of the variance of the original data had eigenvalues more than 1, and the residual components made a very small contribution to total variation (Table 4). The Eigenvectors (loading matrix of selected PCs) after VARIMAX rotation indicated SOC and TN had loading values within 10% of the highest factor in the first PC (Table 4, 46% of variance). They were significantly correlated (Table 5, r = 0.93), therefore SOC, which was associated with the highest loading value, was selected as the indicator of PC1. For the PC2 (22% of variation), BD and $BD_{2\ mm}$ were within the 10% of highest loading factor, and due to high correlation (Table 5, r = 0.99) $BD_{2\ mm}$ was chosen as the indicator of PC2. Only CN ratio was within the 10% of highest loading value of PC3 and was therefore selected to represent this component. SOC, bulk density (≤2 mm) and CN ratio were selected as the MDS for evaluating soil quality under temperate maritime grassland management.

Table 4
Result of the principal component analysis of the TDS.

PCs parameters	PC1	PC2	PC3		
Eigenvalue	3.23	1.52	1.05		
Variance (%)	46.19	21.71	14.95		
Cumulative (%)	46.19	67.90	82.85		
Indicator		Eigenvector		Communality	TDS Weight
SOC	**0.885**	−0.287	−0.202	0.894	0.154
TN	**0.884**	−0.31	0.124	0.905	0.156
K	0.749	−0.006	−0.013	0.561	0.097
BD_{2mm}	−0.215	**0.959**	0.098	0.976	0.168
BD	−0.216	**0.943**	0.162	0.961	0.166
CN	−0.04	−0.04	**0.913**	0.838	0.144
ASD	0.005	−0.355	−0.735	0.666	0.115

ASD, aggregate size distribution; BD, bulk density; BD_{2mm}, bulk density at 2 mm particle size; SOC, soil organic carbon; TN, total nitrogen; CN, carbon nitrogen ratio; K, extractable potassium. Boldface and underlined loading values correspond to parameters selected from the PCs for correlation analysis.

3.3. Soil quality indices

Eight SQI were calculated (Fig. 1) with linear and non-linear scoring functions (Eqs. (1), (2) and (3)) used for normalizing the indicators. For SOC, TN, K, and aggregate size distribution a "more is better curve" and for CN, BD and $BD_{2\ mm}$ a "less is better curve" were used for scoring (Table 6). The communalities and weighs of the TDS showed that $BD_{2\ mm}$ had the highest and extractable K showed the lowest contribution to the indices (Table 4). For the MDS the final normalized index (SQI-6 and SQI-8) was:

$$\begin{aligned} SQI &= (0.462/0.829) * S1 + (0.217/0.829) * S2(0.15/0.829) * S3 \\ &= (0.557 * S1) + (0.262 * S1) + (0.181 * S3) \end{aligned}$$

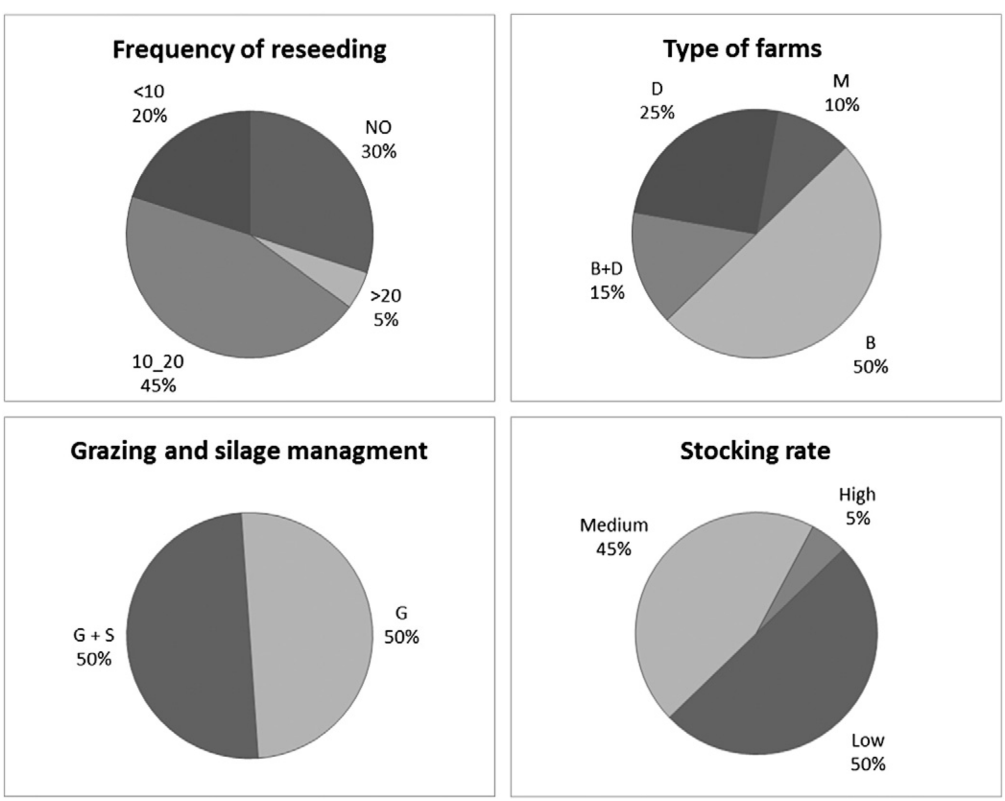

Fig. 2. Percentage of sampling sites under each management practice, D, dairy farm; B, beef farm; M, mixed sheep and cattle farm; D + B, mixed dairy and beef farm; G, only grazing; S + G, both silage and grazing.

Table 5
Correlation matrix of the TDS.

Indicators	ASD	BD	$BD_{2\ mm}$	TN	OC	CN	K
ASD	1						
BD	−0.370**	1					
$BD_{2\ mm}$	−0.348**	**0.985****	1				
TN	0.231	−0.467**	−0.466**	1			
SOC	0.089	−0.414**	−0.438**	**0.932****	1		
CN	−0.424**	0.176	0.104	−0.228	0.133	1	
K	0.018	−0.240*	−0.219	0.466**	0.462**	−0.032	1

ASD, aggregate size distribution; BD, bulk density; $BD_{2\ mm}$, bulk density at 2 mm particle size; SOC, soil organic carbon; TN, total nitrogen; CN, carbon–nitrogen ratio; K, extractable potassium. Boldface and underlined loading values correspond to parameters selected from the PCs for correlation analysis.
** Correlation is significant at $p < 0.01$ (2-tailed).
* Correlation is significant at $p < 0.05$ (2-tailed).

Table 6
Type of scoring curves and the parameter values for the non-linear scoring function (Eq. (1)) for the TDS.

Indicators	Scoring curve	Mean (x0)	Slope (b)	R^2
ASD	More is better	2.46	−2.5	0.9974
BD	Less is better	0.81	2.5	0.9999
$BD_{2\ mm}$	Less is better	0.79	2.5	0.9999
TN	More is better	0.54	−2.5	0.9996
SOC	More is better	5.82	−2.5	0.9997
CN	Less is better	10.95	2.5	0.9999
K	More is better	171.20	−2.5	0.9806

ASD, aggregate size distribution; BD, bulk density; $BD_{2\ mm}$, bulk density at 2 mm particle size; SOC, soil organic carbon; TN, total nitrogen; CN, carbon–nitrogen ratio; K, extractable potassium.

where S1, S2 and S3 are the scores (either linear or non-linear) of SOC, $BD_{2\ mm}$ and CN ratio, respectively.

3.4. Validating the SQI

Testing the SQI using the validation dataset and comparing to soil structural quality class indicated that all eight SQI could be used for assessing soil quality. The indices developed using non-linear scoring equations had higher F-values compared to the linear indices and they were mostly significantly different at $P < 0.01$, with exception of the SQI-5, which was significant at $P < 0.05$ (Table 7). While the weighted additive method did not affect the TDS indices (SQI-1 to -4) very much, it increased the differentiating ability of the MDS indices (SQI-5 to -6). The best discriminating capability was obtained for SQI-6 ($P = 0.004$), which was developed using MDS, and weighted additive method and the poorest was SQI-7 ($P = 0.054$) which was only significant at $P < 0.1$.

3.5. Effects of management intensity on soil quality

The capability of each SQI for differentiating the influence of management intensity was evaluated using ANOVA (Fig. 3). Overall soil quality was reduced by intensification. The linear SQI (SQI-3, -4, -7 and -8) were significantly different by intensity class ($P < 0.05$, Fig. 3) while nonlinear SQI develop using TDS (SQI-1, $P = 0.2$ and SQI-2, $P = 0.07$) could not distinguish between low and medium intensity sites. The indices produced using MDS were significantly different by management intensity ($P < 0.05$, Fig. 3). No statistically significant differences were found between intensity classes by aggregate size distribution, and extractable K (Table 8). SOC and TN were not significantly different between high and medium intensities (Table 8, $P = 0.86$ and $P = 0.34$, respectively) while no significant differences were observed between low and medium intensities for BD and $BD_{2\ mm}$ ($P = 0.43$). CN ratio varied significantly among all intensity treatments (Table 8) and was the most powerful property for discriminating the intensity classes among the soil quality indicators selected. By considering the 95% confidence intervals of means for SQI-6 between Sq classes and management intensity (Table 9), a value of 0.46 was identified as the cut-off between poor and fair Sq classes and between high and medium management intensities. A value of 0.52 was identified as the cut-off between the fair and good Sq classes and between medium and low management intensities.

4. Discussion

4.1. Soil quality indicators

Twenty one soil properties that have been suggested in the literature (e.g. Ditzler and Tugel, 2002; Doran and Parkin, 1996 Karlen and Stott, 1994; Karlen et al., 1997; Larson and Pierce, 1994; Lima et al., 2013; Masto et al., 2007; Qi et al., 2009) as potential indicators of soil quality under different ecosystems, and these were chosen to develop the soil quality indices. In addition, due to the difference between BD and $BD_{2\ mm}$ (Page-Dumroese et al., 1999) and the importance of $BD_{2\ mm}$ to soil functions such as water transmission (Rawls et al., 1998) and root penetration (Pierce et al., 1983), bulk density of the <2 mm fraction was also included. The suggested indicators vary by location and purpose so it is impossible to select a universal list (Qi et al., 2009, Zhang et al., 2004). In this study, the properties were chosen to reflect the impact of management practices on temperate, maritime grassland soils by focusing on productivity. Soil respiration is used to assess soil biological condition under agricultural management (Bastida et al., 2006). It is sensitive to soil disturbance and water tension, and might be a practical for early detection of soil degradation (Sparling, 1997). Total and organic carbon (Krull et al., 2004), total nitrogen (Liu et al., 2014), pH (Doran and Parkin, 1994), cation exchange capacity (Larson

Table 7
Mean comparison and homogeneity of variances for each SQI among soil structural quality (VESS) class.

Index	Calibration				Validation			
	Homogeneity of variances		ANOVA		Homogeneity of variances		ANOVA	
	L	p-Value	F	p-Value	L	p-Value	F	p-Value
SQI 1	1.36	0.26	8.45***	0.001	1.80	0.19	6.24***	0.006
SQI 2	1.48	0.24	9.96***	0.000	1.11	0.35	6.14***	0.006
SQI 3	2.12	0.13	9.47***	0.000	0.33	0.72	4.57**	0.019
SQI 4	2.22	0.12	9.82***	0.000	0.23	0.80	4.32**	0.023
SQI 5	1.32	0.27	14.55***	0.000	0.18	0.83	5.39**	0.011
SQI 6	2.08	0.13	17.38***	0.000	0.90	0.42	6.85***	0.004
SQI 7	1.47	0.24	9.79***	0.000	0.09	0.91	3.25*	0.054
SQI 8	3.84	0.03	13.10***	0.000	1.40	0.26	5.45**	0.010

L, Levene statistic; F, F statistic.
*** Significant difference at $p < 0.01$.
** Significant difference at $p < 0.05$.
* Significant difference at $p < 0.1$.

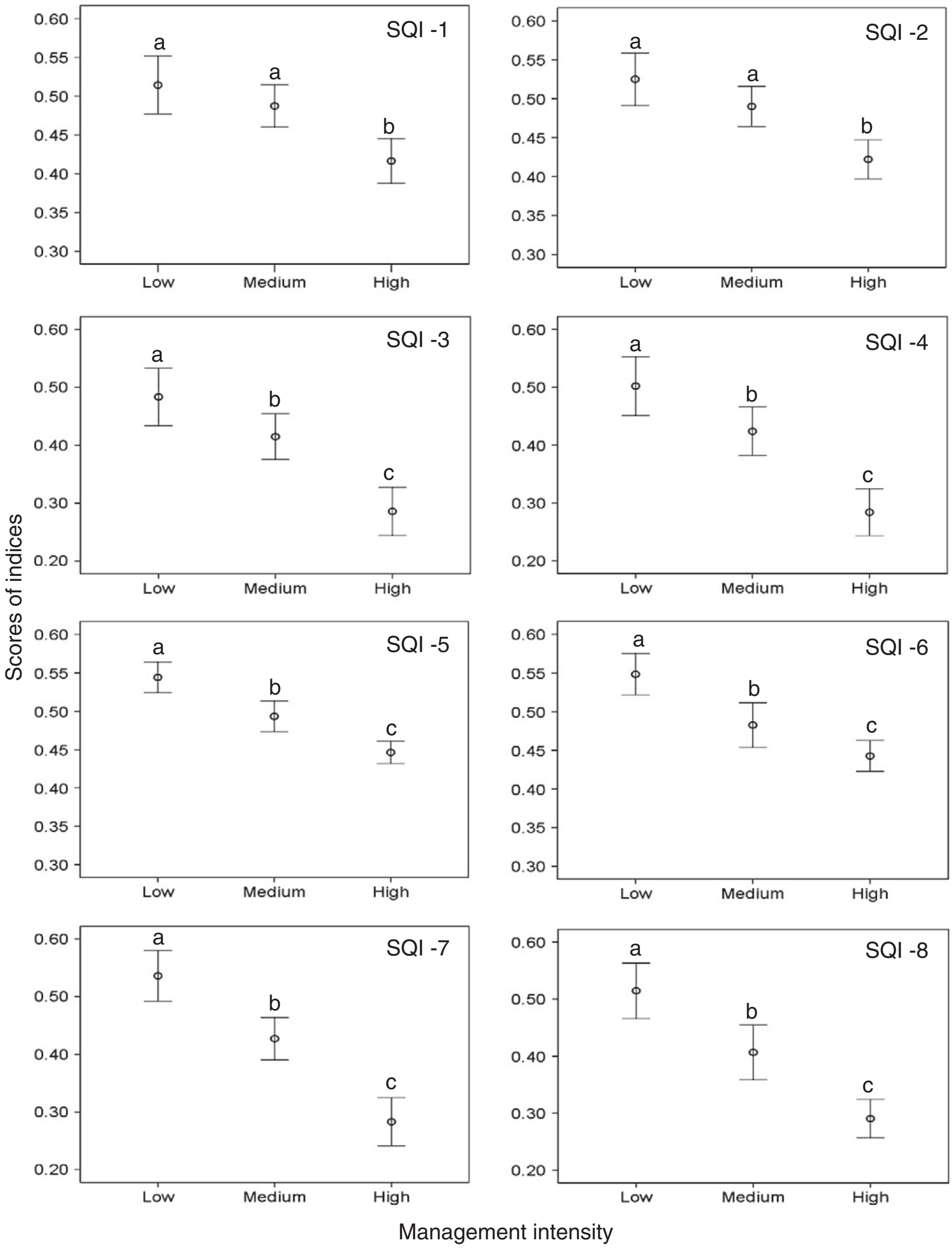

Fig. 3. Comparison of soil quality indices by intensity class (derived by k means clustering) with 95% confidence interval; points with the different letter for each intensity class were significantly different at $p < 0.05$.

Table 8
Mean comparison of TDS by management intensity calculated by K-means clustering.

Comparison between intensity classes	ASD		BD		$BD_{2\ mm}$		OC		TN		CN		K	
	MD	*p*	MD	*p*	MD	*p*	MD	*p*	MD	*p*	MD	*p*	MD	*p*
Low vs medium	0.13	0.406	0.02	0.430	0.02	0.432	0.880**	0.004	0.120**	0.000	0.674**	0.001	48.695	0.383
Low vs high	0.10	0.560	0.172**	0.000	0.160**	0.000	1.131**	0.001	0.156**	0.000	1.093**	0.000	48.159	0.396
Medium vs high	0.02	0.878	0.155**	0.000	0.142**	0.000	0.251	0.858	0.035	0.340	0.419*	0.044	96.854	0.083

MD, mean difference; ASD, aggregate size distribution; BD, bulk density; $BD_{2\ mm}$, bulk density at 2 mm particle size; SOC, Soil organic carbon; TN, total nitrogen; CN, carbon–nitrogen ratio; K, extractable potassium.

** Significant difference at $p < 0.01$.

* Significant difference at $p < 0.05$.

Table 9
Statistical parameters of SQI-6, 95% of mean confidence intervals were use to identify the cut-off values between VESS classes and intensity levels.

Statistical parameters	VESS classes			Management intensity		
	Good	Fair	Poor	Low	Medium	High
Minimum	0.43	0.34	0.29	0.42	0.29	0.36
Maximum	0.70	0.63	0.53	0.68	0.70	0.57
95% CIM (upper limit)	0.58	**0.49**	**0.44**	0.58	**0.51**	**0.46**
Mean	0.55	0.47	0.40	0.55	0.48	0.44
95% CIM (lower limit)	**0.52**	**0.46**	0.35	**0.52**	**0.45**	0.42
Std. error	0.01	0.01	0.02	0.01	0.01	0.01
Std. deviation	0.08	0.07	0.07	0.07	0.10	0.05

CIM, confidence interval of mean; boldface and underlined loading values correspond to scores were considered to identify cut-off values.

and Pierce, 1994), and extractable anion and cations (Li et al., 2013a; Masto et al., 2008) have all been used as effective chemical indicators of soil quality. They were considered as important properties related to nutrient supply, plant growth, soil aggregate stability, fertility and productivity. Of the physical properties, bulk density, porosity, aggregate size distribution, penetration resistance, sorptivity and soil texture, are commonly suggested by researchers for assessing soil aeration, strength and physical resistance to root growth (Drewry et al., 2008; Reynolds et al., 2008), retention of nutrients and water, soil erosion and runoff (Bastida et al., 2008; Doran and Parkin, 1994, 1996).

Sq scores were generally less than 3, which was an indication of moderate (45% of sites) to good (45% of sites) soil structural conditions, and around 10% of sites were poor with Sq $\geq$ 3. The measured soil properties summarized (Table 2) had ranges consistent with previous studies in Ireland (e.g. Curtin and Mullen, 2007; Diamond and Shanley, 2003; Kurz et al., 2006), which indicated that the study sites were representative of dominant soils under grassland in Ireland. Soil nutrient status was relatively high in the study area, especially nitrogen, phosphate and potassium because of regular fertilizer application. The calcium and magnesium content could be related to soil parent material, which mainly consisted of limestone drift, limestone bedrock, shale, sandstone and glacio-marine drift (Collins and Cummins, 1996). Soil pH, which can influence nutrient cycling (Kemmitt et al., 2005) and biological activity (Wang et al., 2006) was mostly >5. Soil acidity can be affected by liming, which is a typical way to correct soil acidity in Irish agricultural systems (Coulter and Lalor, 2008). SOC was highly correlated with soil nitrogen, which is a critical contributor to dynamics of SOC (Kaštovská et al., 2012), and with VESS scores that indicated the importance of SOC in the creation and sustainability of soil aggregates (Malamoud et al., 2009). The range of penetration resistance and bulk density was mostly less than the restriction threshold for root growth at 2500 kPa and 1.5 g cm^{-1}, respectively (Håkansson and Lipiec, 2000; Hassan et al., 2007). Overall physical properties indicated moderate to good soil condition that was consistent with the VESS scores reported.

Depending on the expected soil function, land use and management system for which SQ is being evaluated, many indicators can be measured (Karlen et al., 1997), but measuring all is very time consuming and costly. In addition conventional methods for selecting proper indicators based only on the PCA (Govaerts et al., 2006; Rezaei et al., 2006) or differentiating between management treatments (Imaz et al., 2010) may not reflect actual soil quality regardless of the management system for which the soil quality is being evaluated. Selection of indicators that are sensitive enough to detect the effects of management systems on soil quality is essential (Doran et al., 1996). For this study the indicators were evaluated compared to VESS structural quality scores (Sq) because VESS has been shown to reflect agricultural management under temperate maritime conditions and can be used for overall soil quality assessment (Askari et al., 2013; Ball et al., 2007, 2013; Cui et al., 2014; Guimarães et al., 2013; Mueller et al., 2013). Soil texture was excluded from the analysis because it is a fixed soil property and cannot be readily influenced by management. The amount of inorganic carbon was very low and for many samples was zero therefore only SOC was used. The parameters of the TDS indicated the variation of recent soil conditions and would be suitable for detecting the effects of management intensity over the short term. They can be considered as essential indicators for assessing the sustainability of grassland management in Ireland. Of the soil properties in the TDS, Ryals et al. (2014) and Li et al. (2014) reported that SOC and TN were two key indicators of soil quality under grassland management and they have been included in other proposed datasets (Masto et al., 2008). SOC and TN increase in soil can be linked to aggregation, decrease in bulk density, root system development and microbial activity in the rhizosphere (Caravaca et al., 2003; Sinha et al., 2009, Wei et al., 2009). Potassium was also suggested as an important indicator by Li et al. (2013a) because it is associated with the long-term fertilization and nutrient supply (Masto et al., 2008). Data redundancy was reduced effectively by identifying the MDS using PCA. Among the effective indicators in the TDS, ASD and K, which were eliminated in the MDS, were not sensitive enough to differentiate management intensity (Table 8). Thus, the better differentiating ability of indices developed using MDS among intensity levels compared to the indices calculated using TDS could be associated with the exclusion of ASD and K. These results showed that an appropriate reduction in the number of indicators to form an MDS still provides enough information for evaluating management intensity impact on soil quality.

4.2. Soil quality indices

Using the TDS for developing SQI can result in a more comprehensive outcome, but by reducing the number of indicators to a MDS, time and cost of measuring effective indicators is reduced with a relatively small price in terms of the quality of the SQI (Qi et al., 2009). The nonlinear approach was suggested by Sinha et al. (2009), Zhang et al. (2011) and Li et al. (2013b) as proper method for indexing soil quality while the linear method is regarded as simple and practical (Masto et al., 2008). Indexing using linear scoring equations was associated with greater variance of indicators so non-linear indices might be assumed to represent the system functions better than linear indices (Andrews et al., 2002a). The validation data indicated better differentiation by non-linear indices (Table 7) as found by Andrews et al. (2002a) and Masto et al. (2008) who compared linear and non-linear indices. The weighted additive approach increased the contribution of $BD_{2\ mm}$, BD, SOC and TN in the TDS indices and SOC in the MDS indices compared to the additive approach. Weighting resulted in improvement to discrimination ability using MDS indices highlighting the importance of SOC for evaluating soil quality under grassland. The framework used for indexing soil quality under temperate, maritime grassland, particularly the nonlinear equation and weighted integration, was responsive to the difference in soil quality indicated by VESS (Table 7), and was suitable for detecting the effect of management intensity (Fig. 3). This result is similar to previous research in other conditions (e.g. Andrews et al., 2002a, 2004; Arshad and Martin, 2002; Bastida et al., 2006; Hussain et al., 1999; Karlen and Stott, 1994; Li et al., 2013b; Lima et al., 2013; Masto et al., 2008; Sinha et al., 2009). The methodology is based on a mathematical approach that is easy to understand for soil scientists and land managers and can provide a flexible indexing method that can be modified for specific regions and particular management goals. While the choice of soil functions and relevant indicators can make the application of SQI subjective to personal and regional determination (Carter, 2002), the approach presented was more practical than statistical factor indices of SQ such as the General Indicator of Soil Quality (GISQ, Velasquez et al., 2007). Statistical factors have no inherent meaning so interpreting them based on variable scores could lead to mistakes (Rossi et al., 2009). In general, the value of indices, particularly SQI-6 (Table 9) mostly suggested good to moderate soil quality in the studied area, which was consistent with VESS the scores.

4.3. Evaluation of soil quality under different management intensity

The importance of type of farm, grazing and silage management, frequency of reseeding and stocking rate has been well demonstrated (e.g. Ernst and Siri-Prieto, 2009; Franzluebbers and Stuedemann, 2009; Sparling and Schipper, 2004). Increase in stocking rate was reported as a major factor in the reduction of soil productivity for Irish farms (Baudracco et al., 2010; McCarthy et al., 2012). Despite efforts to determination the most appropriate stocking rate (e.g. McCarthy et al., 2013; O'Donnell et al., 2008), recommended stocking rate for grazing systems are still a controversial issue. The high portion of sites categorized as beef farms (50%, Fig. 2) with low stocking rate and a frequency of reseeding of 10 to 20 years that were equally divided between grazing and grazing plus silage resulted in most of the sites (45%) being classified as medium management intensity.

The alternative K means clustering method used to classify sites into low, medium and high intensity pastures (Table 1) revealed a trend of better soil quality under less intensive management. All the high intensity sites by this method were dairy farms that trend toward increased milk production through time (Dillon et al., 2008; Lips and Rieder, 2005; O'Donnell et al., 2008), which seems to be suggesting a detrimental pressure on the soil resource. Management intensification was associated with reduced SOC, TN and increased bulk density and CN, which resulted in poorer soil quality and reduction of soil productivity. The effect of intensity influenced each indicator in different ways, with chemical indicators such as SOC and TN responding to change at medium intensity and physical properties including BD responding under high intensity. The CN ratio difference between intensity classes might reflect an impact on the rate of input and decomposition of organic matter and manure (Karaca et al., 2011; Mary et al. 1996).

The average index values were lower under higher intensity management as found by Glover et al. (2000), Lima et al. (2013) and Li et al. (2013b). A greater stocking rate, more human activity and overall greater intensity of land management can make it difficult to maintain and improve soil quality (Sparling and Schipper, 2004). SQI-6 was the best index for evaluating the impact of management intensity on soil quality due to its ability to differentiate soil quality classes and management intensity levels. The cut-off values of SQI-6 (0.46 and 0.52) between Sq classes and management intensity levels, identified using the 95% confidence interval of the mean (Table 9), is a conventional approach for choosing cut-off points (Kakade et al., 2014; Singh, 2006). The critical levels of SQI-6 indicated a close relationship between management intensity and soil conditions. Intensification can improve soil fertility in the short term due to fertilization, but it can result in soil compaction, erosion and degradation of physical attributes as well as SOC loss and reduction in nutrient availability (Maia et al., 2009, Marzaioli et al., 2010; Moscatelli et al., 2007; Savadogo et al., 2007). This trend was observed using the selected indicators and SQI-6, and the approach indicated that a better understanding of soil quality under temperate maritime (specifically Irish) grasslands will provide a practical method for early detection of adverse impact of management on the soil resource.

5. Conclusion

The bulk density of the <2 mm fraction, soil organic carbon and carbon–nitrogen ratio can be used for assessing soil quality under temperate maritime grassland management. A nonlinear weighted additive method produced the most reliable soil quality index using this minimum dataset. A MDS using bulk density of the field sample would also be reliable, so SQI can be determined under temperate, maritime climate (specifically Irish grassland) using routinely measured soil properties using just two methods, a CN analyzer and bulk density. This is far less time and resource consuming than an SQI using the TDS of SOC, TN, CN, BD, $BD_{2\ mm}$, ASD and K, and orders of magnitude more efficient than using the vast range of indicators suggested in the literature. The data from this study suggested that management intensification was having an adverse impact on soil quality under Irish grassland management. This situation needs to be addressed by a targeted survey of soil quality in light of policy targets for production from the grassland based agri-food sector.

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