Chapter 12
Rapid Evaluation of Soil Quality Based on Soil Carbon Reflectance

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Abstract Many studies have considered spectroscopy for measurement of soil carbon (SC), and there is potential for spectroscopy to be used as a cost and time effective approach to assess soil quality (SQ). In this research, the relationship between SC and SQ in Irish grassland soils was studied; particularly the efficiency of spectroscopy and chemometric techniques for assessing SC and its contribution to SQ. The study was conducted using 20 sites with 5 replicates per site (n = 100 soil samples). Twenty soil properties were measured using standard methods as soil quality indicators. Management intensity was classified using K-means clustering, and the results reflected a trend in soil properties indicative of poorer SQ under more intensive management. Soil porosity, CN ratio and SC were selected as a minimum data set using principal component analysis and SC was the most discriminating indicator of the impact of management intensity on SQ. Soil visible and near-infrared spectra showed a good efficiency ($R^2 = 0.91$, RMSE = 0.4, RPD = 2.94) for prediction of SC. Spectroscopy and chemometric analysis allowed rapid evaluation of SC, and because of the strong relationship with management intensity, can provide a rapid, low cost, quantitative method for evaluating SQ under grassland management.

Keywords Spectroscopy • Soil carbon • Soil quality • Grassland

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Introduction

Soil carbon (SC) plays an important role in sustainable soil and land management (McBratney et al. 2000; Florinsky et al. 2002) and was reported as one of the most important indicators for evaluating soil quality (SQ) because it is associated with most ecosystems and productivity functions (Jarecki and Lal 2005; Reynolds et al. 2007). SC is positively correlated with SQ and is sensitive to ecosystem management (Moreno et al. 2006; Spargo et al. 2008). Therefore, increasing and maintaining SC is crucial for sustainable use of soil resources and crop production (Ghosh et al. 2012). Pastures have the potential to transform large amounts of carbon to soil organic carbon (SOC) (Wright et al. 2004). More than 90 % of organic carbon in pasture is located underground as root biomass or SOC (Schuman et al. 1999; Silveira et al. 2013). It can enhance the activity of soil microorganisms, soil C mineralization, rhizosphere production and SQ (Schuman et al. 1990; Frank and Groffman 1998; Wright et al. 2004). Grasslands, found in most regions of the world are considered a globally significant carbon resource, and are the main land use in Ireland, supporting very productive livestock enterprises and carbon-rich soils (Lafferty et al. 1999). Assessing the effect of current management systems on grassland soil is of particular interest because of the need to monitor and manage recognized threats to soils (Semikolennykh 2008) and for national carbon inventory reporting (Kiely et al. 2010).

Management practices affect the quantity of SC through biomass production, product extraction (e.g. milk, meat, silage) and inputs such as organic fertilizers (Lal et al. 1999; West and Marland 2002; Arshad et al. 2004) and erosion (Eynard et al. 2005). The aim of increasing management intensity is to maximize animal production by "sustainable intensification" (Pretty 1997; Garnett et al. 2012), thus the carbon balance in the soil can be changed (Conant et al. 2001; Lal 2002; Silveira et al. 2013). A sustainable management intensity will increase, or maintain at a high level, the quantity of SC and contribute to the sustainability of agricultural systems and SQ improvement (Guo and Gifford 2002). SC is regarded as a key indicator of soil health in the UK (Anon 2006; Bhogan et al. 2009).

Visible (VIS) and Near inferred (NIR) spectroscopy and chemometric analysis have been used for SC analysis, offering potential cost and time effective analysis (Chang et al. 2001; O'Rourke and Holden 2011) compared to methods such as chromate oxidation (Walkley and Black 1934), loss-on-ignition (Ball 1964) and combustion (Allison et al. 1965). Prediction of SC by NIR in the laboratory produces accurate models ($R^2 > 0.9$) and reasonable standard error (Chang et al. 2001; Brunet et al. 2007; Grinand et al. 2012). The efficiency of spectroscopic techniques offers potential for SQ assessment (Brown et al. 2005; Cécillon et al. 2009), Accurate SC estimation linked with SQ using visible (VIS) and NIR spectra could be a rapid and cost effective method for SQ monitoring. This research examined the potential of SC as an indicator of SQ in Irish grassland using spectroscopic techniques. The objectives were to evaluate the impact of management intensity on SC and SQ, and to assess the efficiency of spectroscopy for prediction of SC as an indicator of SQ.

Materials and Methods

The study was conducted at 20 grassland sites in Ireland (latitude 52°8′N and 54°20′N; longitude: 6°32′W and 8°19′W; mean daily temperature winter: 4.0–7.6 °C, and summer: 12.3–15.7 °C; average annual precipitation in eastern Ireland: 750 and 1,000 mm; www.met.ie). Soil and crop management practices were recorded through individual semi-structured interviews with each farmer. Field measurements were taken from September to December 2011. At each site within a representative 30 m^2 plot, with random orientation relative to the field boundaries and avoiding atypical areas such as gateways, unusually dry or wet areas, headlands and highly trafficked areas, 5 points equal distance apart were sampled from 0 to 10 cm depth across the central diagonal of the plot for laboratory analysis. Twenty soil properties were measured using standard methods as SQ indicators (Table 12.2). Soil total carbon (TC), and soil inorganic carbon (IC) were measured using a dry combustion carbon and nitrogen analyser (LECO Tru-Spec CHN analyser and Skalar-Primacs SLC-IC analyzer) that was described by Matejovic (1997) and Wright and Bailey (2001). All samples had low inorganic carbon content and therefore total carbon was approximately equal to SOC. For this paper, the term SC is used to avoid confusing with the more exact term total carbon. Samples were also analysed by spectroscopy by first crushing and passed through a 200 μm sieve, re-drying at 30 °C for 14 h in an oven to eliminate the effects of moisture content and acquisition of reflectance spectra using a Foss VIS-NIR Systems 6500 (Foss NIRSystems, Denmark) in the wavelength range 400–2,498 nm, with 2-nm intervals. Noise regions (400–450 and 950–1,000 nm in VIS and 1,000–1,050 and 2,450–2,498 nm in NIR) were cropped. In order to improve the linearity of spectra, reflectance data were converted to absorbance using the log (1/Reflectance). Samples were selected randomly for calibration (70 %) and validation (30 %) sets, and partial least-squares regression was used to develop a total carbon model using Unscambler software (version X10; CAMO software, Oslo, Norway). The calibration model was evaluated based on a combination of the coefficient of determination (R^2), root mean squared error (RMSE), and ratio of predicted deviation (RPD). The normality of all data sets was tested using the Kolmogorov-Smirnov test and visual examination of histograms.

Management was initially categorized by farm type (dairy, beef, beef plus dairy, mix sheep and other cattle), frequency of reseeding (less than 10 years, 10–20 years, more than 20 years and no reseeding), stocking rate which was categorized in low (less that 2.51 cow per hectare), medium (2.51–3) and high (more than three cow per hectare) based on McCarthy et al. (2012), grazing and silage management system, as typically used to characterize grassland systems, e.g. Macdonald et al. (2008), O'Donnell et al. (2008), Baudracco et al. (2010) and McCarthy et al. (2012). However, because of the relatively small number of sample sites (20), a more robust approach was deployed using K-means cluster analysis (Hartigan and Wong 1979) to identify three major clusters of management intensity using the management data for each site. Multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA) were then performed on soil variables to explore the effect of management intensity on SQ indicators, and only those attributes that were significantly different ($P < 0.05$) by management intensity were considered further. Principal component analysis (PCA) was applied to determine a minimum data set (MDS) for evaluating the effect of management intensity on SQ based on the method described in detail by Rezaei et al. (2006) and Li et al. (2013). The first three principal components (PC) with eigenvalues >1 that explained around 73 % of variation of all variables were selected, and the indicators with loading values within 10 % of the highest weighted loading factor were considered for the correlation test to determine the MDS. Stepwise discriminant analysis was used to select the SQ indicator that was most discriminating between the three levels of management intensity according to the method describes by Brejda et al. (2000) and Nosrati (2013). All statistical analyses were performed using SPSS v. 18.0 (SPSS Inc).

Results and Discussion

Conventional classification of management intensity using descriptive properties of the farm systems was not suitable for analyzing the data because membership of each class was very small. Based on the K-mean clustering, 25 % of fields were classified high intensity, 45 % percent medium intensity and 30 % low intensity (Table 12.1). The 20 SQ indicators (Table 12.2) had ranges consistent with previous studies (Diamond and Shanley 2003; Kurz et al. 2006; Curtin and Mullen 2007), which indicated that the study sites were representative of the range of grassland soil in Ireland. Of the 20 properties, only 13 were significantly different ($p < 0.05$) by management intensity, and thus used as the total dataset (TDS) for assessing SQ (Table 12.2). The K means clustering reflected a trend in soil properties indicative of poorer SQ under more intensive management.

The MDS derived from PCA was SC from PC1, soil porosity (SP) from PC2 and CN ratio from PC3. From the stepwise discriminant analysis the first discriminant function explained 85.3 % of the total variance and the second 14.7 %. SC had the greatest discriminating power between the management intensity classes:

$$\text{Function1} = \mathbf{13.964\,(SC)} + 0.934\ (\text{CN}) - 0.073\ (\text{SP}) \tag{12.1}$$

$$\text{Function2} = \mathbf{20.241\,(SC)} + 0.255\ (\text{CN})0.144\ (\text{SP}) \tag{12.2}$$

The application of PCA and discriminant analysis reduced data redundancy by identifying the most relevant soil properties for detecting the impact of management intensity on SQ (Rezaei et al. 2006; Li et al. 2013). For the Irish grassland soils studied, intensification of management resulted in lower SC, which was associated with poorer SQ. These trends are consistent with previous research on management intensity (e.g. Potter et al. 2001; Leifeld and Fuhrer 2009), and perhaps reflect an increase of carbon mineralization and residue quality leading to SC losses (Silveira et al. 2013). Improving

Table 12.1 Management practices and intensity classification in each site

Sites	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* mix sheep and cattle farm, *D+B* mix dairy and beef farm, *G* only grazing, *S+G* both silage and grazing, Stocking rate: *H* high (>3 cows/ha), *M* medium (2.51–3 cows/ha), *L* Low (<2.51 cow/ha), *High* high intensive pasture, *Mid* medium intensive pasture, *Low* low intensive pasture

grassland management can have an impact on the carbon sequestration, which is associated with SC accumulation (Conant et al. 2001; Lal 2008), but there is little research to indicate the best intensification management for sustainable soil quality. Increasing SC improves SQ because it is reflected in porosity, bulk density (Miralles et al. 2009), promotion of infiltration, reduction of soil erosion and compaction (Islam and Weil 2000; Miralles et al. 2009), structure stability (Stevens 2008), water storage, nutrient cycling and other soil attributes which are related with soil productivity and environmental protection (Gilley et al. 1997; Miralles et al. 2009).

Accurate prediction of SC using VIS-NIR spectroscopy is required to facilitate research to find the best management options for sustainable livestock production from grasslands, and high resolution monitoring for SQ. Prior to calibration, the homogeneity of variance of SC in the calibration and validation sets ($p > 0.85$) was confirmed by Levene's test, and the mean comparison (T test) indicated there was no significant difference between validation and calibration mean values ($P > 0.46$). The random selection of the validation set reliably represented the samples distribution. The best SC prediction was achieved from the NIR region (Table 12.3) in both calibration ($R^2 = 0.95$, RMSE = 0.34) and validation ($R^2 = 0.94$, RMSE = 0.34,

Table 12.2 Soil properties measured as potential indicators of Soil Quality

SQ indicator	Mean	Std	TDS	TDS range High	Mid	Low	Measurement method
Aggregate size distribution (MWD)	2.44	0.64	✗				Nimmo and Perkins (2002)
Bulk density (g/cm^3)	0.81	0.12	✓	0.85–1.03	0.51–0.99	0.6–0.96	Grossman and Reinsch (2002)
Bulk density <2 mm (g cm^{-3})	0.80	0.12	✓	0.81–0.99	0.51–0.97	0.6–0.92	Grossman and Reinsch (2002)
Porosity (%)	64.20	6.51	✓	49.9–67.4	50.3–82.3	46.6–78.3	Flint and Flint (2002)
pH	5.61	0.64	✓	5.0–6.7	4.9–7.1	4.3–7.0	pH meter 1:1 (Thomas 1996)
Total Nitrogen (%)	0.54	0.13	✓	0.4–0.7	0.3–0.8	0.4–0.8	Matejovic (1997), Wright and Bailey (2001)
Total Carbon (%)	5.88	1.45	✓	4.3–7.2	3.3–10.2	4.9–9.5	Matejovic (1997), Wright and Bailey (2001)
SOC (%)	5.85	1.44	✓	4.3–7.2	3.25–10.16	4.89–9.40	Matejovic (1997), Wright and Bailey (2001)
CN ratio	11.00	0.91	✓	9.9–13.1	10–12.6	8.9–11.4	
Calcium (PPM)	2,624	1,896.6	✗				Soltanpour et al. (1996)
Magnesium (PPM)	205.26	92.12	✗				Soltanpour et al. (1996)
Potassium (PPM)	179.87	159.45	✗				Soltanpour et al. (1996)
Phosphate (PPM)	10.94	10.35	✗				Kuo (1996)
Sorbtivity (cm s$^{-0.5}$)	0.06	0.05	✓	0.10–0.40	0.03–0.11	0.03–0.08	Philip (1957)
Penetration resistance (Kpa)	1,265	509.54	✓	632–2,695	397–1,951	491–2,944	Penetrometer (FIELDSCOUT SC900)
Water content (%)	50.31	14.14	✗				Topp and Ferre (2002)
Sand (%)	40.56	12.87	✗				Gee and Or (2002)
Silt (%)	34.33	7.80	✓	17–40	20–50	20–43	Gee and Or (2002)
Clay (%)	25.11	6.62	✓	13–35	13–34	16–40	Gee and Or (2002)
Soil respiration (mg C kg^{-1} day^{-1})	23.50	5.98	✓	15.8–31.5	10.8–39.0	6.7–29.3	Horwath and Paul (1994)

From these a total dataset (TDS) (properties that differed by management intensity) and a minimum dataset (MDS) (the most discriminating properties) were identified

High high intensive pasture, *Mid* medium intensive pasture, *Low* low intensive pasture, *TDS* total data sets, *Std* standard deviation

Table 12.3 Spectral analyses results by wavelength range and pre-processing

	Wavelength range	Latent variables	RPD	Model	R^2	RMSE
Prediction models	NIR+VIS	10	2.94	Calibration	0.93	0.39
				Validation	0.91	0.40
	VIS	7	2.06	Calibration	0.82	0.62
				Validation	0.83	0.57
	NIR	11	3.42	Calibration	0.95	0.34
				Validation	0.94	0.34
Optimum preprocessing						
Max Normalization	NIR+VIS	13	3.20	Calibration	0.93	0.38
				Validation	0.92	0.38
Mean center Std Scale	NIR+VIS	10	2.97	Calibration	0.93	0.39
				Validation	0.92	0.38

NIR near infrared, *VIS* visible

RPD = 3.42) models, but the VIS–NIR region also showed a robust model in calibration (R^2 = 0.93, RMSE = 0.39) and validation (R^2 = 0.91, RMSE = 0.4, RPD = 2.94) sets. Preprocessing transformations did not improve the accuracy of the models (Table 12.3). The results were similar to O'Rourke and Holden (2011, 2012), and confirm the capability of VIS-NIR spectroscopy for quantitative assessment of SC especially in NIR regions without applying particular preprocessing methods. Therefore, this approach is likely to provide time and cost effective for assessing the impact of management systems on the quality of Irish grassland soils.

Conclusion

The relationship between management intensity, and SQ indicated that for current management practices, increased intensity, typified by sward management and stocking rate, resulted in a decrease in SQ. The most powerful discriminating property was SC, thus it could be used for rapid assessment and monitoring of SQ change with changes to grassland management. While SC alone will not be suitable for a full SQ assessment, it does reflect a range of biological, chemical and physical properties of the soil so is a good integrating variable.

Spectroscopy proved to be a reliable technique for rapid, low cost analysis of SC. This means that high sampling resolution (spatial and temporal) can be deployed for monitoring grassland SQ with a robust spectroscopic analysis. The study indicated a promising future for the application of spectral data sets for quantitative and direct evaluation of SQ based on integrating indices and discrimination of multiple facets of SQ.

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