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Application of Dexter's soil physical quality index: an Irish case study

O. Fenton[1†], S. Vero[2], R.P.O. Schulte[3], L. O'Sullivan[1], G. Bondi[1], R.E. Creamer[4]

[1]Teagasc, Environmental Research Centre, Johnstown Castle, Co. Wexford, Ireland
[2]Agricultural Catchments Programme, Teagasc, Environmental Research Centre, Johnstown Castle, Co. Wexford, Ireland
[3]Farming Systems Ecology, Wageningen University, The Netherlands
[4]Soil Biology and Biological Soil Quality, Wageningen University, The Netherlands

Abstract

Historically, due to a lack of measured soil physical data, the quality of Irish soils was relatively unknown. Herein, we investigate the physical quality of the national representative profiles of Co. Waterford. To do this, the soil physical quality (SPQ) S-Index, as described by Dexter (2004a,b,c) using the S-theory (which seeks the inflection point of a soil water retention curve [SWRC]), is used. This can be determined using simple (S-Indirect) or complex (S-Direct) soil physical data streams. Both are achievable using existing data for the County Waterford profiles, but until now, the suitability of this S-Index for Irish soils has never been tested. Indirect-S provides a generic characterisation of SPQ for a particular soil horizon, using simplified and modelled information (e.g. texture and SWRC derived from pedo-transfer functions), whereas Direct-S provides more complex site-specific information (e.g. texture and SWRC measured in the laboratory), which relates to properties measured for that exact soil horizon. Results showed a significant correlation between S-Indirect (S_i) and S-Direct (S_d). Therefore, the S-Index can be used in Irish soils and presents opportunities for the use of S_i at the national scale. Outlier horizons contained >6% organic carbon (OC) and bulk density (B_d) values <1 g/cm^3 and were not suitable for S_i estimation. In addition, the S-Index did not perform well on excessively drained soils. Overall correlations of S_i with B_d and of S_i with OC% for the dataset were detected. Future work should extend this approach to the national scale dataset in the Irish Soil Information System.

Keywords

agriculture • soil • soil physical quality • soil quality • soil structure

Introduction

Internationally, soil-specific farming (Rattan and Stewart, 2016) is a concept that will become increasingly important as precision farming is a reality on farms. However, soils are heterogeneous and thereby control many aspects of sustainability (e.g. environmental losses along different pathways and attenuation of such losses). Such heterogeneity influences paddock management decisions directly (Humphreys *et al.*, 2008; Huebsch *et al.*, 2013). Soil quality (Wilson and Maliszewska-Kordybach, 2000) is concerned with physical (the focus of the current study), chemical and biological aspects of soil across soilscapes and, therefore, defines the capacity of agricultural soil to deliver multiple functions, such as primary productivity, nutrient cycling, water filtration (Fenton *et al.*, 2011; Jahangir *et al.*, 2013), habitat for biodiversity and carbon sequestration (Karlen *et al.*, 1997; Wiebe 2003; Schulte *et al.*, 2015). This capacity can be overextended, resulting in degradation of the system by compaction (Soane and van Ouwerkerk, 1998; Vero *et al.*, 2013), erosion (Regan *et al.*, 2010, 2012; Sherriff *et al.*, 2015), loss of soil organic carbon (SOC) (Grandy and Robertson, 2007) or impedance of other soil functions (Creamer *et al.*, 2010).

In Europe, to achieve harmonisation and coordination of soil data, the recommended national soil mapping resolution is 1:250,000, which has been implemented in Ireland. This resolution is only capable of identifying problems at the regional scale. However, "reference profiles" taken during this mapping process provide detailed soil property information at a local scale. Such profiles are termed "modal profiles". These can be classified according to diagnostic characteristics, which have developed as a result of soil genesis (Simo *et al.*, 2014). This classification system results in the determination of soil types (soil subgroups) and landscape units in which they are typically found occurring together. These diagnostic characteristics define the drainage class of a modal profile (O'Sullivan *et al.*, 2015), the organic matter (OM) status and so on (Simo *et al.*, 2015).

In addition to the traditional soil classification of modal profiles, a wide range of soil chemical, physical and biological properties are measured throughout the profile. The soil physical data associated with modal profiles can be used to determine a value of soil

†Corresponding author: O. Fenton
E-mail: owen.fenton@teagasc.ie

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physical quality (SPQ) within the SPQ Index as described by Dexter (2004a) using S-theory and is identified as a key metric of overall soil quality (Dexter, 2004a) (Table 1).

Table 1. Dexter's SPQ Index

S–value	SPQ Index
<0.020	Very poor
0.020 – 0.035	Poor*
0.035 – 0.050	Good
>0.050	Very good

*Soils with values <0.035 are considered degraded.
SPQ = soil physical quality.

The S-Index is derived from the relationship between the gravimetric soil water content and the natural log of matric tension. This is calculated as the slope of the soil water retention curve (SWRC) (Equation 1).

$$\text{S-term} = -n(\theta_{gs} - \theta_{gr})\left[2n-1\right)/]^{(1/n)-2} \qquad (1)$$

Where q_{gs}, q_{gr} are gravimetric saturated and gravimetric residual water contents [see Armindo and Wendroth (2016) for a critical review, including assumptions made based on interpretation of the van Genuchten (1980) equation].

Based upon the S-theory, the S-term offers a singular value, which is considered reflective of overall SPQ, and the S-term can be considered suggestive of not only physical quality but also both chemical and biological quality. The S-theory proposes that soil physical properties and behaviour are essentially controlled by soil structure, which is expressed as pore size distribution (measured by SWRC). This is traditionally measured in the laboratory using pressure plates (or equivalent devices) (American Society for Testing and Materials [ASTM], 2008). The S-term is defined as the absolute value of the slope (known as S-value) of the SWRC at its inflection point (Dexter, 2004a). Therefore, according to the S-theory, several aspects of soil physical behaviour reflect the same S-term regardless of soil type (Dexter and Czyż, 2007). Thus, the S-Index offers a simple scale that has the same physical meaning regardless of soil type and can therefore be used to compare SPQ across soil horizons, soil types and spatial scales. When a soil structure becomes degraded, the shape of the SWRC changes (Thu *et al.*, 2007) and hence, the S-term and associated interpretation of SPQ will change accordingly. Dexter (2004a, 2004b, 2004c) presents the S-theory with an associated S-Index, which evaluates the S-term of a soil relative to threshold values indicative of SPQ status (ranging from very poor to very good –Table 1). According to Dexter (2004a), the advantage of this S-Index is that the degraded threshold value holds true across soil types. If this were true, the S-Index would have distinct advantages over other methods of quality assessment, which would differ depending on the soil type in question. The S-Index is not without its opponents, e.g. de Jong van Lier (2014) suggested that the S-theory presents no advantage over bulk density (B_d) and total porosity as a measure of soil quality, as the work involved to elucidate these parameters is much less than the production of an entire SWRC. This is true where the S-Index is being utilised in upper horizons to track the effects of tillage management over time for instance (e.g. Keller *et al.*, 2007). The objective of this research is to test the applicability of the S-Index system by utilising all soil horizons within a profile.

In practice, an SWRC can be inferred via pedo-transfer functions (PTFs) using simple data (i.e. textural class or particle size distribution) (Moncada *et al.*, 2014) in cases where complex data (i.e. measured SWRCs) are not available. In brief, measurement of the SWRCs can be costly and time consuming, requiring the application of pressure to a saturated soil sample, as well as the monitoring of outflow over a prolonged period, subsequent to which a fitting equation such as that of van Genuchten (1980) is applied. Conversely, PTFs use easily and rapidly measured "simple" data to estimate the van Genuchten parameters from extensive reference databases such as ROSETTA (Schaap *et al.*, 2001). The reliability of PTFs to accurately characterise the properties of field soils has been questioned (Schaap and Leij, 1998; Khodaverdiloo *et al.*, 2011), and increasing the data inputs has been shown to increase their reliability. A demonstration of simple versus complex physical data sources was provided by Vero *et al.* (2014), who found that although higher-quality soil physical data (direct approach) allow better estimation of soil hydraulic parameters, reduced resolution (indirect approach) may be sufficient for some applications, e.g. estimation of unsaturated zone solute travel time (Vero *et al.*, 2014; Fenton *et al.*, 2015). This type of "simple" data is very useful and is more readily available at larger scales but lacks details regarding the macro-porosity of the soil in question. Such soil structural or physical data are important when questions regarding larger scales need answering, e.g. what would the average SPQ of agricultural soils be in Ireland? Simple data may not suffice at an extremely localised scale, e.g. where the SPQ may vary within a subplot region as a result of compaction within a vehicle wheel rut (Vero *et al.*, 2013).

Hence, S-terms can be categorised into "S-indirect (S_i)" or "S-direct (S_d)", where simple and complex data streams are utilised, respectively (Figure1). The former provides a generic characterisation (average) of a particular soil horizon, which would be applicable to similar soil horizons elsewhere or within the same subgroup (Simo *et al.*, 2015), whereas the latter provides site-specific information, which relates to that exact soil horizon at that location on the farm (Dexter and Czyż, 2007). Therefore, this information can be used to ascertain the SPQ of a paddock at that location. This information can be used by the farmer to make assertions about past management and plan present and future management strategies.

Nationally, the most detailed soil physical and chemical dataset in Ireland is the Co. Waterford Monograph, produced as part of the National Soil Survey (NSS) (Diamond and Sills, 2011). Unlike other Irish soil datasets, the Co. Waterford Monograph contains all the data necessary to follow the simple-to-complex approach, as presented in Figure 1. Therefore, this dataset allows for the calculation of both S_i (generic data in Figure 1) and S_d (measured data in Figure 1) horizon-specific terms and facilitates direct comparison of S_i and S_d with each other. In addition, other parameters such as organic carbon (OC) are also included to examine what soils are not suitable for assessment with the S-Index.

The overall aim of the study was to assess SPQ. The objectives of the present study were to 1) investigate the relationship between SPQ status assessed via the S_i and S_d methods, 2) outline conditions that preclude the use of S-Index for the soils examined and 3) point the way forward for use of this S-Index nationally. The first objective was carried out by developing a regression comparing S_i and S_d terms for all horizons from 17 soil profiles within the Co. Waterford dataset. The second objective was carried out by examining all S-terms that did not comply with this regression and examining all data available for these horizons, e.g. OC%, B_d (in grams per cubic centimetre [g/cm^3]).

Materials and methods

Comparison of S_i and S_d

To assess S_i versus S_d, horizon-specific soil physical data obtained from 17 soil profiles (114 horizons) within the Co. Waterford NSS (Diamond and Sills, 2011) were assessed. A link to the entire dataset is available at http://gis.teagasc.ie/

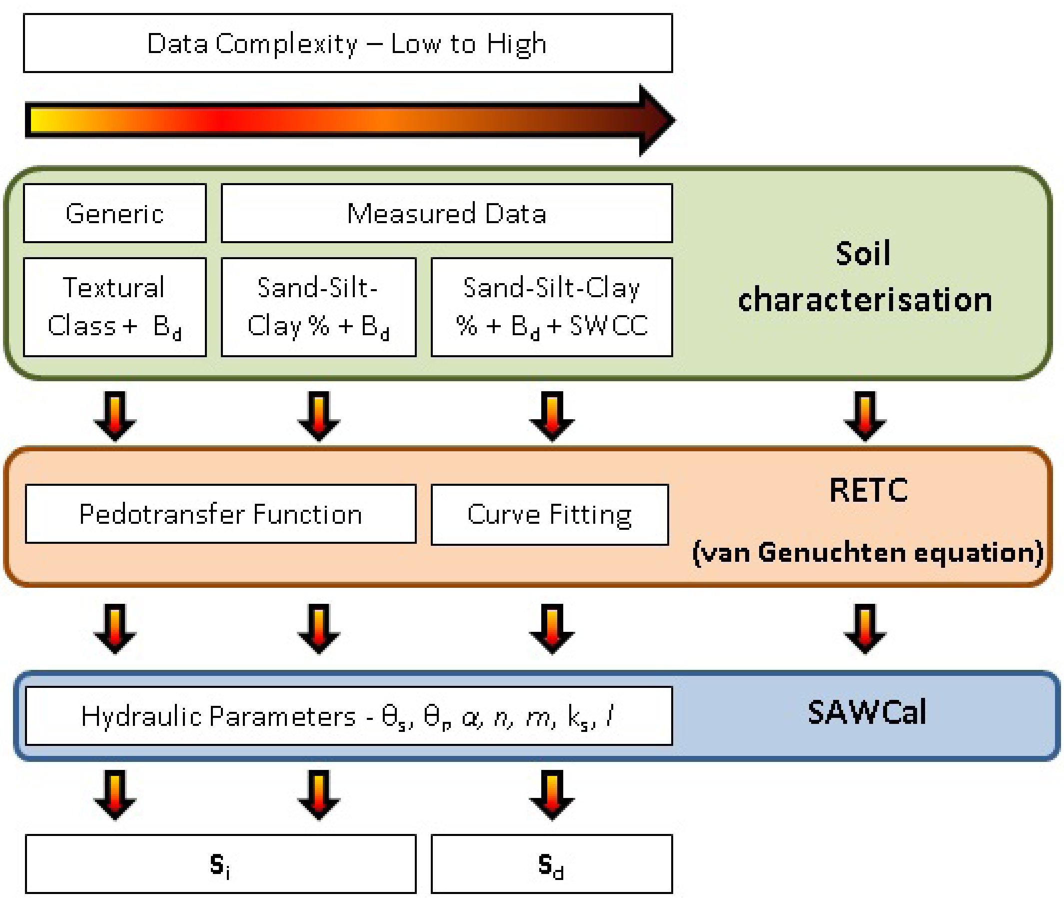

Figure 1. Conceptual diagram of low- to high-complexity data sources, and corresponding S_i and S_d approaches. S_i is deemed as “simple” and has been determined in the present study from the middle stream here (sand–silt–clay percentage + B_d). S_d is deemed “complex” and determined from the third stream (sand–silt–clay percentage + B_d + SWCC, curve-fitting approach). B_d = bulk density; SAWCal = soil available water calculator; Sd = S-direct; Si = S-indirect; SWCC = soil water characteristic curve.

soils/downloads.php. General classification characteristics and the drainage classes of the 17 soils are presented in Table 2. The entire dataset was separated into the following Great Soils Groups: Brown Earths, Luvisols, Alluvial Soils, Brown Podzolics, Podzols and Surface water Gleys. The soil physical data used in the present study are as follows: B_d (grams per cubic centimetre [g/cm^3], clod method), sand–silt–clay percentage (pipette method, British Standard (BS) 1796; British Standard Institution, 1989) and SWRC (0 to –1.5 hPa) (sand box and pressure plate; Richards, 1948), which were used to derive the S-term.

The retention curve retention curve (RETC) software (Schaap *et al.*, 2001), which incorporates both SWRC fitting equations (S_d) [e.g. water retention curves have been fitted to the van Genuchten equation (van Genuchten, 1980) with the Maulem (1986) constraint (m=1 – 1/n)] and the ROSETTA (Schaap *et al.*, 2001) PTF (S_i), was used for the conversion of soil physical data into hydraulic parameters. The following parameters were obtained as outputs for all horizons (according to both indirect and direct approaches): saturated water content (q_s), residual water content (q_r), fitting parameters (a, *n, m*); tortuosity (*l*); and saturated conductivity (k_s). For horizon-specific S_i determination, ROSETTA was used to infer soil hydraulic parameters based on sand–silt–clay percentage as well as B_d data only. For S_d determination, both horizon-specific sand–silt–clay percentage, B_d and measured water retention data were used, from which soil water characteristic curves (SWCCs) were constructed. Horizon-specific S_i and S_d terms were determined according to Dexter (2004a) (Equation 1) using the parameters q_s, q_r, a, and n as input data to the soil available water calculator (SAWCal) model (Asgarzadeh *et al.*, 2014).

Table 2. The soils of the Waterford Survey, as they appear in the national representative profiles of Co. Waterford (Red Book series), used in the present study

Group	Height AMSL, m*	Parent material	Great Soil Group	World Reference Base	H	Series	Drainage class
Regosol	5	Alluvium	Alluvial	Haplic fluvisol (humic dystric siltic)	8	Coolfinn (presently known as Feale)	Poor
Plaggen	20	Irish sea till	Brown earth	Haplic phaeozem (anthric albic epieutric)	8	Ardmore	Well
	24	Glaciofluvial sand	Brown earth	Haplic regosol (humic eutric arenic)	7	Curragh	Excessive
Grey brown podzolic	30	Sandstone > limestone till	Luvisol	Haplic luvisol	9	Dungarvan	Well
	65	Sandstone > shale > limestone till	Luvisol	Cutanic endostagnic luvisol (chromic)	6	Kilmeaden	Well
Brown earth	70	Sandstone till	Brown earth	Haplic cambisol (humic eutric)	5	Broomhill	Well
	80	Sandstone till	Brown earth	Haplic phaeozem (anthric albic epieutric)	8	Clashmore	Well
	90	Volcanic till/bedrock	Brown earth	Haplic cambisol (humic epidystric oxyaquic)	7	Kill	Well
	120	Shale till	Brown earth	Haplic cambisol (humic eutric)	4	Clonroche	Well
Brown podzolic	20	Sandstone limestone gravel	Brown podzolic	Entic podzol	2	Callaghane	Excessive
	160	Shale till and bedrock	Brown podzolic	Leptic cambisol (humic dystric)	2	Slievecoiltia	Well
Podzol	152	Sandstone rock	Podzol	Placic albic podzol (endoskeltic)	6	Drumslig	Well
	165	Sandstone till	Podzol	Placic albic histic podzol	8	Ahaun	Moderate to imperfect
Gley	27	Sandstone > limestone till	Surface-water gley	Haplic stagnosol (hypereutric)	6	Killadangan	Poor/imperfect
	30	Sandstone > shale>limestone till	Surface-water gley	Haplic stagnosol (hypereutric)	7	Waterford	Poor
	45	Shale > volcanic-sandstone till	Surface-water gley	Haplic stagnosol (hypereutric)	7	Clohernagh	Poor
	145	Sandstone till	Surface-water gley	Haplic stagnosol (humic hypereutric)	6	Lickey	Poor

*It is important to include landscape position as this is important for soil drainage classification.
H = number of horizons with data suitable for the present study; AMSL = above mean sea level.

Boundary conditions for use of S_i in investigated soils

Correlation of S_i versus S_d using all horizons from Table 2 identified outlier horizons, and these were examined in more detail. The S-term reflects both textural and structural porosity and the contribution of each to total porosity. Imposed management will affect the structural porosity more than textural porosity, changing the slope of the inflection point on an SWCC when the curve has been plotted as gravimetric water content against the natural logarithm of the pore water suction, thereby changing the S-term. In terms of examining horizons across an entire soil profile, the ratio between textural and structural porosity becomes important and, therefore, consistency or differences in S_i down the profile may indicate a horizon that needs greater inspection, i.e. clay content or B_d change.

An assessment of how the S-Index behaved across soil drainage classes was also conducted. For Irish soils, Simo *et al.* (2014) and Schulte *et al.* (2015) have established indicative soil drainage classes using diagnostic features identified as part of the Irish soil classification. Poorly draining soils were defined as those showing mottling within 40 cm of the surface. Poorly draining soils may also contain an argic horizon (i.e. where a 20% increase in clay content is found in a lower horizon compared to the above horizon), which should denote a change in S_i, compared with an overlying layer. Poorly draining soils may also have a spodic horizon (leaching of iron (Fe)/(aluminium (Al) from upper horizons to lower horizons, whereby Fe/Al is precipitated, in extreme cases resulting in an Fe pan (should denote a S_i change). Both argic or spodic horizons may cause stagnation.

Soils with >40 cm of an organic layer are classified as peat. Peat soils are mainly composed of organic materials in which particle size distribution of the mineral fraction has little textural significance (therefore, not suitable for S_i allocation). Moderately drained soils display mottling at depth (40–80 cm depth) but lack OM accumulation. However, an argic or spodic horizon may be present (should denote a S_i change). Imperfectly drained soils also show mottling at the same depth (40–80 cm) but with the presence of some OM accumulation as well as an argic or spodic horizon (should denote a S_i change). Well-drained soils are those that show no evidence of waterlogging and have no argic or spodic horizon (should denote similar S_i terms through profile) present. Excessively drained soils are distinguished by texture alone, whereby the presence of loamy sand or sandy textural classes is dominant (should denote similar S_i terms through profile). These categories represent a spectrum of drainage capacity, with the poorer-drained soils remaining at or above field capacity for several days following a rainfall event, and the better-drained soils rapidly returning to below field capacity within days or even hours. All diagnostic features of the soil profile outlined herein were compiled and collated with horizon-specific S_i data. S_i terms for each horizon were checked, looking for consistency or differences in S_i relative to the horizon above it.

Results and discussion

S_i versus S_d

Regarding the S_i and S_d terms for all horizons examined in this study, the linear relationship is shown in Figure 2 (n=114, S_d=0.635× (S_i) +0.0009 (R^2=0.60, P<0.05). Although S_i is determined by published PTFs for the parameters of the van Genuchten (1980) equation, it is a good approximation of trends in quality of the soils examined. In all cases, the S_d term placed the soil horizon and overall soil profile (taking average of all horizons) at a lower SPQ than the S_i equivalent. The range of S-terms achieved covered the entire SPQ index, as presented in Table 1, namely, from very poor to very good. The upper horizons typically have higher S-terms, while lower terms are observed deeper in the soil profile. While low terms at depth may, in some instances, reflect compaction as a result of management practices, it cannot be assumed to indicate anthropogenic degradation. Lower horizons will naturally exhibit greater B_d than upper horizons, with implications for the calculated S-terms.

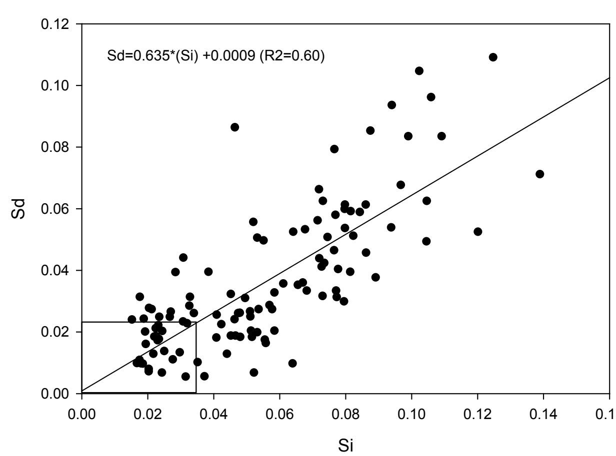

Figure 2. S-Indirect (S_i) versus S-Direct (S_d) S-term for all soil horizons. For example, an S_i value of 0.035 (degradation threshold) equates to an S_d of 0.023 (below threshold). This includes all data from Table 2.

Outlier horizons

Examination of outlier horizons showed discrepancies for OC% and B_d. Dexter (2004a) examined mean clay content (percentage) versus S_i, showing the degradation threshold to occur with clay contents >40%. In Ireland, very few soil horizons exhibit clay contents >40% (Tuohy *et al.*, 2016), with no examples >50%. Soil horizons that exceed 6% SOC (OC% >6, w/w) are considered humose to peaty in nature (Jones *et al.*, 2011). Therefore, other physical properties must be also considered for the vast majority of soils to drive S_i into the degraded zone (<0.035, Table 1). Using PTFs, Dexter (2004a) shows the S_i equivalents where soil textural class and B_d values are known. Here, values of B_d >1 g/cm^3 were only considered. Other authors have also only included soil horizons with B_d values >1 g/cm^3 (e.g. Ghiberto *et al.*, 2015). Therefore, soil horizons with B_d <1 g/cm^3 and an OC% >6 should be removed from the present study and future studies of Irish soils when assessing the SPQ. In addition, excessively drained soils and peat soils were found to be outliers. The former is due to a lack of differentiation across horizons typified in an excessively draining soil. The peat drainage class is associated with B_d values less than that required to infer S-values (minimum B_d <0.5 g/cm^3; Dexter, 2004a), and as discussed previously, are influenced more strongly by OM content than by textural and structural porosity.

Two profiles from the Waterford dataset provide good examples of the conditions that are not suitable for S-value designation. The Coolfinn (Feale) series (Table 2) exhibits S_i values of >0.25. This is an alluvial soil that displays soil horizons (stratifications) of different textures and B_d values, due to its formation by the flooding of river banks. Peaty layers are common and the B_d ranges from 1 to 0.3 g/cm^3. The OC% is always >6 and not suitable for S-terms. Such soils should not be considered for S-theory determination. Alluvial soils represent 7.79% of the County of Waterford and 4.34% of Irish soils. Another outlier example from the Waterford dataset is the podzol of the Drumslig series, in which the upper horizons (A1-A2) have high OC% of 9.9 and 6.6, with associated high S_i terms (0.1 and 0.08, respectively). A correlation between OC% and S_i is presented in Figure 3, where only the data adhering to both criteria (B_d <1 g/cm^3 and an OC% >6) were observed. This shows that once the appropriate data ranges are used (i.e. B_d and OC% ranges, along with the removal of excessively drained profiles), other correlations within the datasets may be elucidated.

When the suitable range of OC% and B_d is adhered to, the S-Index correlates well with other soil parameters, e.g. S_i versus B_d (regardless of texture) (Figure 4). Results from this correlation would indicate that a soil horizon would need to be >1.8 g/cm^3 to become physically degraded soil (negatively affects a soil's ability to perform soil functions), with respect to the 0.035 degradation S-term (at or below) proposed by Dexter (2004a) (Table 1). This could be further developed using a greater dataset and divided into regressions based on individual textural classes. This also has practical implications in the field as B_d (which is easily taken in the field using sample rings of known volume) could be used as a proxy for SPQ.

Further research and conclusions

Utilisation of simple and complex horizon data from 17 representative profiles of the Co. Waterford Soil Survey Monograph produced a significant correlation between S_i and S_d. This means that use of Si on a national basis shows potential to track the SPQ of Irish soils at the presently mapped scale. Outlier horizons showed that soil horizons with OC >6% and B_d values <1 g/cm^3, or excessively drained sandy profiles, are not suitable for S_i estimation. Removal of such horizons and profiles allowed for good correlations among S_i, OC% and B_d (regardless of texture). Future work should extend this approach to a national

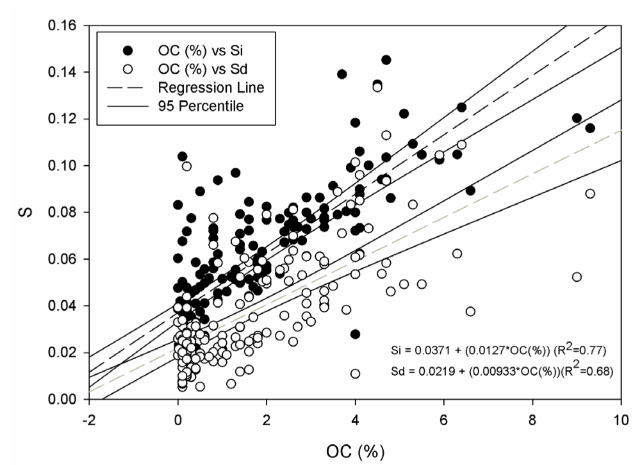

Figure 3. OC% versus S_i and S_d for all horizons, adhering to the OC% threshold of <6 and B_d threshold of >1 g/cm^3. Moreover, the S_i data always returns a higher S-value than the S_d equivalent. B_d = bulk density; OC = organic carbon; Sd = S-direct; Si = S-indirect.

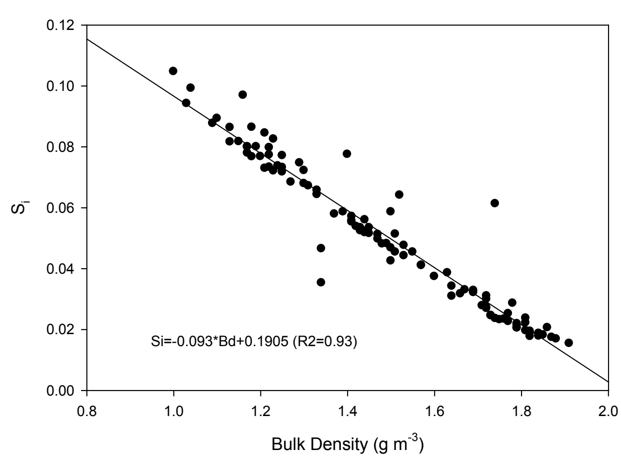

Figure 4. B_d versus S_i taking into account all horizons with B_d >1 g/m^3 and OC%<6 across all textures present within the study. This shows that B_d on its own is a good indicator of S_i.

scale dataset and examine the relationship of these estimates to site-specific visual examination approaches (Emmet-Booth *et al.*, 2016b).

It is important to note that the S_i consistently scored a higher SPQ value than the S_d equivalent and could result in an overestimation of the soil quality of Irish soils; therefore, results must take this into consideration. Overall, however, the examination of S_i values compared with S_d indicates that the use of simple data can potentially be applied to the Irish Soil Information System data to allow the status of Irish soils in relation to their S-term to be described. Further research is currently under way that will apply the S-term to that national level dataset utilising the boundary conditions identified in this work. While the boundary conditions identified here may limit the potential to develop this research from a mapping perspective, future work will explore to what extent the findings of this research are applicable at a soil subgroup classification level. Moreover, at this scale, the use of the S-Index in tandem with other soil parameters will be explored to determine their ranges/influence for the SPQ of Irish soils, e.g. the ranges of soil OC for soils of each category of SPQ in Table 1. This could allow a more nuanced approach towards developing thresholds of soil quality on a country-specific basis, as opposed to applying a universal critical value. At a local level, defining reference S-terms at a soil subgroup level represents a mechanism to potentially allow farmers to better understand their management influence by comparing their S-term against such a reference S-term. Other methods to assess SPQ will also be explored in future research (Armindo and Wendroth, 2016).

In the European Union (EU), despite the withdrawal of the Soil Framework Directive in 2014, the European Commission (EC) remains committed to the objective of the protection of soils, as outlined in the EU Soil Thematic Strategy [COM(2006)231] (EC, 2006). Currently, soil quality is only considered in measures that contribute indirectly to the protection of soils, including policies related to agriculture such as the Water Framework Directive (2000/60/EC) or the Good Agriculture and Environmental Conditions under Pillar 1 of the EU Common Agricultural Policy. The withdrawal of the EU Soil Framework Directive, coupled with the renewed commitment to soil protection for soil quality, means that space now exists for the development of future policy alternatives. Following the application of this index at a national level for Ireland, development of the index across EU jurisdictions could potentially facilitate a harmonised assessment of the overall status of SPQ of European soils.

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