Indicators of soil quality – physical properties (SP1611)

Final Report to Defra

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EXECUTIVE SUMMARY

The condition of soil determines its ability to carry out diverse and essential functions that support human health and wellbeing. These functions (or ecosystem goods and services) include producing food, storing water, carbon and nutrients, protecting our buried cultural heritage and providing a habitat for flora and fauna. Therefore, it is important to know the condition or quality of soil and how this changes over space and time in response to natural factors (such as changing weather patterns) or to land management practices. Meaningful soil quality indicators (SQIs), based on physical, biological or chemical soil properties are needed for the successful implementation of a soil monitoring programme in England and Wales. Soil monitoring can provide decision makers with important data to target, implement and evaluate policies aimed at safeguarding UK soil resources. Indeed, the absence of agreed and well-defined SQIs is likely to be a barrier to the development of soil protection policy and its subsequent implementation.

This project assessed whether physical soil properties can be used to indicate the quality of soil in terms of its capacity to deliver ecosystem goods and services. The 22 direct (e.g. bulk density) and 4 indirect (e.g. catchment hydrograph) physical SQIs defined by Loveland and Thompson (2002) and subsequently evaluated by Merrington et al. (2006), were re-visited in the light of new scientific evidence, recent policy drivers and developments in sampling techniques and monitoring methodologies (Work Package 1). The culmination of these efforts resulted in 38 direct and 4 indirect soil physical properties being identified as potential SQIs.

Based on the gathered evidence, a 'logical sieve' was used to assess the relative strengths, weaknesses and suitability of each potential physical SQI for national scale soil monitoring. Each soil physical property was scored in terms of:

- soil function – does the candidate SQI reflect all soil function(s)?
- land use - does the candidate SQI apply to all land uses found nationally?
- soil degradation - can the candidate SQI express soil degradation processes?
- does the candidate SQI meet the challenge criteria used by Merrington et al. (2006)?

This approach enabled a consistent synthesis of available information and the semi-objective, semi-quantitative and transparent assessment of indicators against a series of scientific and technical criteria (Ritz et al., 2009; Black et al., 2008). The logical sieve was shown to be a flexible decision-support tool to assist a range of stakeholders with different agenda in formulating a prioritised list of potential physical SQIs. This was explored further by members of the soil science and soils policy community at a project workshop.

By emphasising the current key policy-related soil functions (i.e. provisioning and regulating), the logical sieve was used to generate scores which were then ranked to identify the most qualified SQIs. The process selected 18 candidate physical SQIs. This list was further filtered to move from the 'narrative' to a more 'numerical' approach, in order to test the robustness of the candidate SQIs through statistical analysis and modelling (Work Package 2). The remaining 7 physical SQIs were: depth of soil; soil water retention characteristics; packing density; visual soil assessment / evaluation; rate of erosion; sealing; and aggregate stability.

For these SQIs to be included in a robust national soil monitoring programme, we investigated the uncertainty in their measurement; the spatial and temporal variability in the indicator as given by observed distributions; and the expected rate of change in the indicator. Whilst a baseline is needed (i.e. the current state of soil), it is the rate of change in soil properties and the implications of that change in terms of soil processes and functioning that are key to effective soil monitoring. Where empirical evidence was available, power analysis was used to understand the variability of indicators as given by the observed distributions. This process determines the ability to detect a particular change in the SQI at a particular confidence level, given the 'noise' or variability in the data (i.e. a particular power to detect a change of 'X' at a confidence level of 'Y%' would require 'N' samples).

However, the evidence base for analysing the candidate SQIs is poor: data are limited in spatial and temporal extent for England and Wales, in terms of a) the degree (magnitude) of change in the SQI which significantly affects soil processes and functions (i.e. 'meaningful change'), and b) the change in the SQI that is detectable (i.e. what sample size is needed to detect the meaningful signal from the variability or noise in the signal). This constrains the design and implementation of a scientifically and statistically rigorous and reliable soil monitoring programme. Evidence that is available suggests that what constitutes meaningful change will depend on soil type, current soil state, land use and the soil function under consideration. However, when we tested this by analysing detectable changes in packing density and soil depth (because data were available for these SQIs) over different land covers and soil types, no relationships were found. Schipper and Sparling (2000) identify the challenge: "a standardised methodology may not be appropriate to apply across contrasting soils and land uses. However, it is not practical to optimise sampling and analytical techniques for each soil and land use for extensive sampling on a national scale".

Despite the paucity in data, all seven SQIs have direct relevance to current and likely future soil and environmental policy, because they can be related (qualitatively) to soil processes, soil functions and delivery of ecosystem goods and services. Even so, meaningful and detectable changes in physical SQIs may be out of time with any soil policy change and it is not usually possible to link particular changes in SQIs to particular policy activities. This presents challenges in ascertaining trends that can

feed into policy development or be used to gauge the effectiveness of soil protection policies (Work Package 3).

Of the seven candidate physical SQIs identified, **soil depth** and **surface sealing** are regarded by many as indicators of soil quantity rather than quality. **Visual soil evaluation** is currently not suited to soil monitoring in the strictest sense, as its semi-qualitative basis cannot be analysed statistically. Also, few data exist on how visual evaluation scores relate to soil functions. However, some studies have begun to investigate how VSE might be moved to a more quantified scale and the method has some potential as a low cost field technique to assess soil condition. **Packing density** requires data on bulk density and clay content, both of which are highly variable, so compounding the error term associated with this physical SQI. More evidence is needed to show how 'meaningful' change in **aggregate stability** affects soil processes and thus soil functions (for example, using the limited data available, an equivocal relationship was found with water regulation / runoff generation). The analysis of available data has given promising results regarding the prediction of **soil water retention characteristics** and **packing density** from relatively easy to measure soil properties (bulk density, texture and organic C) using pedotransfer functions. Expanding the evidence base is possible with the development of rapid, cost-effective techniques such as NIR sensors to measure soil properties. Defra project SP1303 (Brazier et al., 2012) used power analyses to estimate the number of monitoring locations required to detect a statistically significant change in **soil erosion rate** on cultivated land. However, what constitutes a meaningful change in erosion rates still requires data on the impacts of erosion on soil functions.

Priority cannot be given amongst the seven SQIs, because the evidence base for each varies in its robustness and extent. Lack of data (including uncertainty in measurement and variability in observed distributions) applies to individual SQIs; attempts at integrating more than one SQI (including physical, biological and chemical SQIs) to improve associations between soil properties and processes / functions are only likely to propagate errors.

Whether existing monitoring programmes can be adapted to incorporate additional measurement of physical SQIs was explored. We considered options where one or more of the candidate physical SQIs might be implemented into soil monitoring programmes (e.g. as a new national monitoring scheme; as part of the Countryside Survey; and as part of the National Soil Inventory). The challenge is to decide whether carrying out soil monitoring that is not statistically robust is still valuable in answering questions regarding current and future soil quality.

The relationship between physical (and other) SQIs, soil processes and soil functions is complex, as is how this influences ecosystem services' delivery. Important gaps remain in even the realisation of a conceptual model for these inter-relationships, let alone their quantification. There is also a question of whether individual quantitative SQIs can be related to ecosystem services, given the number of variables.

1. PROJECT OBJECTIVES

The aim of this project was to provide evidence to support the implementation of a meaningful soil monitoring programme in England and Wales. The development of such a programme has been hindered by the limited number of suitable physical soil quality indicators (SQIs) that have been identified so far. Previous work has examined a number of physical soil properties and judged their suitability as SQIs against very specific "challenge" or selection criteria. The latest report (Merrington et al., 2006) found only one property, soil bulk density, met these criteria. Despite 'qualifying' as a suitable SQI, this property alone does not capture the overall quality of soil; for instance, it is not a good indicator of the water transport function of soil, which affects important services such as flood control, crop growth and mitigation of nutrient losses to watercourses. The paucity of physical SQIs represents a significant limitation of current soil monitoring in characterising soil quality.

This project sought to develop physical indicators of soil quality (physical SQIs) to add to the current proposed suite of indicators for any future national soil monitoring. We aimed to identify soil physical properties that indicate the soils' capacity to deliver ecosystem goods and services. It is also important that changes in soil processes, functions and quality are captured by changes in the SQIs (and vice versa). These indicators are needed for the successful implementation of a meaningful soil

monitoring programme in England and Wales. The aims of the project were achieved by carrying out the following specific evidence objectives:

Objective 1.1: Collation and review of previous scientific evidence, reports, data, SQI selection criteria and approach, sampling techniques and monitoring methodologies aimed at identifying salient physical SQIs, in the light of recent scientific advances and developments in soil policy.
Objective 1.2: Identify candidate soil physical properties which meet the specifications required to 'qualify' as meaningful physical SQIs.

Objective 2.1: Evaluation of new scientific evidence, reports, data, SQI selection criteria, sampling techniques and monitoring methodologies aimed at identifying salient physical SQIs
Objective 2.2: Identification of suitable physical SQIs from the findings of Objectives 1.1 and 2.1 above, based on agreed selection criteria, sound science, statistical robustness and feasible data collection methods

Objective 3.1: Consideration of the policy relevance of the candidate physical SQIs identified in Work Package 2
Objective 3.2: Consideration of the cost:effectiveness of the candidate physical SQIs identified in Work Package 2
Objective 3.3. Hold a workshop for the soil science and soil policy community to find agreement on the salient physical SQIs identified in Objectives 1 – 3
Objective 3.4: Propose suitable physical soil quality indicators (SQIs) to be used for soil monitoring in England and Wales

In summary, given advances in research and developments in policy drivers, we revisited and revised the selection of suitable physical soil properties that characterise soils' capacity to deliver ecosystem goods and services. These properties have to be justified as robust, cost:effective indicators of soil quality to be useful in future soil monitoring programmes.

2. LITERATURE REVIEW AND SELECTION OF CANDIDATE PHYSICAL SQIs (details in Work Package 1 Report)

2.1. Collation and review of candidate soil quality indicators – physical properties

The scientific evidence, SQI selection criteria, sampling techniques and monitoring methodologies related specifically to physical SQIs, were collated and reviewed, with consideration of recent scientific advances and developments in soil policy. The 22 direct and 4 indirect physical SQIs defined by Loveland and Thompson (2002) and subsequently evaluated by Merrington et al. (2006), were re-evaluated. The culmination of these efforts resulted in 30 direct and 4 indirect physical indicators being identified as having potential. Where indicators can be measured using different techniques, sub-categories have been listed so that both indicator and methods can be evaluated later using a logical sieve approach (Table 1). While the selection criteria used by Merrington et al. (2006) are considered justifiable, reasons for exclusion of some indicators were not always clearly defined in their text. An updated review of the strengths and weaknesses of all the physical SQIs listed in Table 1 is given in Annex 1 of the Work Package 1 report. This document builds upon the conclusions in Loveland and Thompson (2002) and Merrington et al. (2006) regarding the suitability of different soil physical properties as SQIs.

Table 1. Soil quality indicators – physical properties.

Physical SQI	Sub-category	Indicator
Direct measurements:		
Bulk density (BD)	Kopecki ring	IND1
Bulk density	On-line sensor fusion	IND2
Bulk density	FDR and VIS-NIR spectroscopy	IND3
Packing density	Visual and BD + clay content	IND4
Total porosity	BD and particle density	IND5
Macroporosity	Tension table	IND6
Soil structure	Visual	IND7
Integrated air capacity to 1 m depth	Vol of pores that drain under gravity	IND8

Aggregate stability	Water droplet test	IND9
Dispersion ratio (DR), Water dispersible clay	No definitive method	IND10
Rate of erosion	t ha^{-1} y^{-1}; field, aerial surveys	IND11
Sealing (due to construction and urban development)	Remote sensing	IND12
Disruption/removal	Remote sensing	IND13
Moisture storage capacity, water holding capacity and soil water retention characteristics	Modified moisture release curve	IND14
Available water content	Moisture release curve	IND15
Readily available water content Water held between 0.05 and 2 bar pressure.	Moisture release curve	IND16
Water content	SAR	IND17
Water content	ER	IND18
Water content	EMI	IND19
Soil texture (particle size distribution)	Wet sieving and sedimentation	IND20
Soil texture	VNIRS	IND21
Infiltration/drainage capacity	Permeameter	IND22
Saturated hydraulic conductivity	Permeameter	IND23
Time to ponding	Rainfall intensity	IND24
Sorptivity	Model of infiltration	IND25
Soil temperature	Probe	IND26
Soil temperature	Remote sensing	IND27
Depth of soil	Visual	IND28
Penetration resistance	Penetrometer	IND29
Penetration resistance	Going stick	IND30
Shear strength	Shear box	IND31
Shear strength	Going stick	IND32
Topsoil plastic limit to a depth of 1 m	Rolling and moulding	IND33
Number of locations with erosion features	Remote sensing	IND34
Erodibility / aggregate stability	Rainfall	IND35
Capping (due to rainfall impact and slaking)	% area affected	IND36
Rutting and poaching, topsoil surface conditions	Visual	IND37
Profile description/Visual soil evaluation –	Visual	IND38
Indirect measurements:		
Catchment hydrograph	Hydrograph	IND39
Surface water turbidity, suspended sediment load, sediment fingerprinting	Fingerprinting	IND40
Biological status of rivers with and without sewage treatment works	WFD status	IND41
Number of eutrophication incidents per year	Phosphorous	IND42

2.2. Selection of candidate soil physical properties which meet the specifications required to 'qualify' as meaningful physical SQIs using the logical sieve approach

Ritz et al. (2009) proposed a generic framework that supported a structured approach to the identification of potential biological indicators for monitoring the status and change in soils. They adopted a formalised method for assessing the relative strengths, weaknesses and suitability of each indicator for national scale soil monitoring (Black et al., 2008). To achieve this they developed a defined framework, with associated MS Excel based software tool, referred to as a 'logical sieve'. This approach enabled a consistent synthesis of available information and the semi-objective assessment of indicators against a series of scientific and technical criteria. Black et al. (2008) stated that this approach had two clear advantages: it provided a clear record and audit trail on the decision-making process; and it could accommodate the inclusion of new indicators and/or challenge criteria in the future. The logical sieve was used as a decision-support tool to assist in formulating a prioritised list of potential SQIs.

The logical sieve approach was adapted and used to evaluate the potential of the physical soil quality indicators listed in Table 1. While our approach was similar to that of Ritz et al. (2009), some

adaptations and modifications were made, as explained in the Work Package 1 report. The physical SQIs listed in Table 1 were judged (scored) with regard to 4 separate "Categories":

- soil function – does the candidate SQI reflect all soil function(s)?
- land use - does the candidate SQI apply to all land uses?
- soil degradation - can the candidate SQI express soil degradation processes?
- the challenge criteria used by Merrington et al. (2006)

By considering each of these Categories in turn, the aim was to 'score' each SQI in terms of its capability in meeting the requirements of a meaningful physical SQI. The resultant scores were then collated and used to formulate a list of candidate physical indicators of soil quality. Two broad approaches were used in identifying the most promising SQIs:

- A simple ranking of cumulative (additive) scores (incorporating 0 scores, if any)
- A filtering function (or sieve) which states that if a SQI fails at any point to meet the requirements of a meaningful SQI (i.e. scores 0), then this SQI will 'drop out' of the selection process.

There are a number of scenarios that could be used to interrogate the logical sieve (see Work Package 1 report). Three possible scenarios were run to illustrate the types of question that may be asked by different stakeholders:

- Scenario 1 (S1) runs the sieve without weightings being applied to any of the factors in each of the 4 Categories.
- Scenario 2 (S2) applies higher priority to the provisioning and regulation soil functions considered in Category 1 (Soil functions), by applying a weighting of '4' to provisioning and '3' to regulation soil functions. All other factors are allocated a weighting of '1'. This is justified by the current policy-relevance of provisioning and regulating services delivered by soil.
- Scenario 3 (S3) uses the weighting factor to normalise values across all Categories, so that differences in the number of factors in each Category do not affect the outcome (e.g. Category 1 (Soil Function) includes 4 factors to consider, whereas Category 2 (Land Use) has 7 factors to consider and so on).

Analysis of the results from the 3 Scenarios identified 18 candidate physical SQIs (Table 2). These include the top 10 (25%) cumulative scores, as well as all physical SQIs that 'survived' the sieving process (i.e. they scored >0 in all factors in all Categories). The 18 candidate indicators were further filtered to 7 by moving from the 'narrative' of WP1 to a more 'numerical' approach in WP2 i.e. are data available to test the robustness of the candidate SQIs through statistical/modelling analysis? Also, the remaining SQIs were rationalised in terms of duplications, overlaps /double counting and linkages. Selection was also made on the basis of whether there was scientific evidence regarding:

1. What is the candidate SQI indicative of (i.e. what function is being degraded)?
2. What it is responsive to? How responsive is it? i.e. *sensitivity, responsiveness*
3. What factors may mitigate or accentuate the response? *e.g. soil type, land use*
4. Is this indicator a first order indicator (i.e. a direct measure of the change in soil quality) or a second, third, etc. order indicator (i.e. an indirect measure of the change; e.g. VNIRS, remote sensing)?
5. Are there existing or suspected data-holdings for each indicator?
6. How is it measured?
7. What sampling support does it need?
8. What is the sampling intensity required?

As a result of this process (see Appendix 1 of Work Package 2 report), the physical SQIs to be analysed further in WP2 are:

- Depth of soil
- Soil water retention characteristics
- Packing density/ bulk density
- Visual soil evaluation
- Rate of erosion
- Sealing
- Aggregate stability

3. DATA ANALYSIS AND MODELLING (details in Work Package 2 report)

The remaining indicators and justification for their inclusion can be found in Table 2 (further justification is given in Appendix 1 of Work Package 2 report). The aim for these SQIs was to investigate:

- the uncertainty in their measurement
- the (spatial and temporal) variability in the indicator as given by observed distributions
- the expected rate of change in the indicator

Where data were available, power analysis methods were used to understand the variability of the indicator as given by the observed distributions. The power of an indicator is its ability to detect a particular change at a particular confidence level given the 'noise' or variability in the data (i.e. a particular power to detect a change 'X' at a confidence level of 'Y%' would require 'N' samples). The physical SQIs should ideally be valid across all soil and land management regimes or within a defined sub-set of regimes. The ability of the methods to discriminate change was tested within such data subsets, since these subsets reduce variability and hence decrease the size of detectable change for a given sample size. This is further described in the statistical analysis in the Work Package 2 report. These characteristics determine whether the candidate SQIs will support the implementation of a meaningful soil monitoring programme in England and Wales. We start by considering in more detail the criteria by which to assess indicators and then present a set of 'fact sheets' in which we detail the behaviour of each individual candidate indicator. In each case, where appropriate data were available, we do so quantitatively; otherwise this was done (semi)qualitatively or (where no data exist) qualitatively.

3.1 Basis for the assessment of SQIs (physical properties)

Physical SQIs need to reflect meaningful changes in soil quality at a given location i.e. in the capacity for the soil to function, but also be meaningful with regard to the soil processes they represent (Figure 1). In order to evaluate the effectiveness of the indicator, we need to establish what this meaningful change is, particularly in the relationships between the SQI and the soil function. It is important to note here that what we are evaluating is change; *change* in the SQI itself and relating that change to a change in the processes going on in the soil and in turn relating that change to how the soil functions.

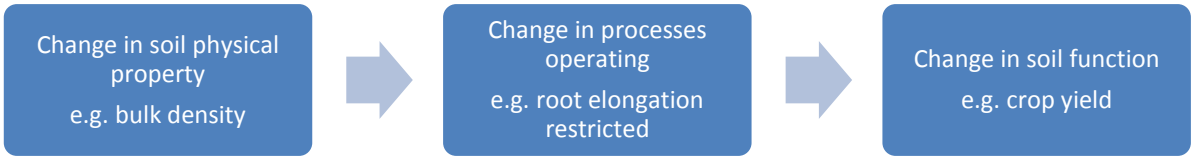

Figure 1. Relationship of soil physical property, process and function

One approach is to take critical values or target ranges for SQIs. The advantage to this approach is in its simplicity: a value of the SQI needs to be ascertained at a given location and the obtained value compared with the range or critical value. The disadvantage to this approach is that it does not capture the dynamic relationships between the SQI and soil functions, and that these may be different for different soil functions, land uses and soil types (Jones, 1983).

Table 2. Soil Quality Indicators (physical properties) carried forward from WP1 to WP2

Candidate physical SQIs from WP1	Comments following WP2 project meeting (see Appendix 1 of Work Package 2 report)	Further consideration in WP2?
1. Bulk density	BD alone is an adequate indicator of soil physical quality, but potentially it can be improved by deriving other indicators that are more closely related to soil quality and performance e.g. packing density.	✓ (as input to packing density and depth of soil)
2. Depth of soil	Effective soil depth defines the volume of soil in which roots can grow. Critical depth is where plant cover achieves values above 40%. Crucial depth is where perennial vegetation can no longer be supported. Affected by rate of soil formation, deposition and degradation processes (erosion, compaction, landslides etc.).Direct impact on the regulation and production function, although this may be only once a critical depth is reached, which in turn depends on site and time specific condition. Some data are available to test this.	✓
3. Infiltration / drainage capacity	Measurements are highly site specific and very temporally variable. So, the robustness and reliability of measurement using currently available techniques are questionable.	×
4. Soil water retention characteristics	Powerful measures of the capacity of the soil to regulate water (hydrology) and produce biomass. Consider pedo-transfer functions as a cheaper proxy for the more expensive lab measurements. This will be explored using a hydrological model. The value of *S* (Dexter's S) is indicative of the extent to which the soil porosity is concentrated into a narrow range of pore sizes. In most soils, larger values of *S* are consistent with the presence of a better-defined microstructure. The S value can be considered as an overall index of physical and structural quality in managed soils. Effectively predicted using pedotransfer functions.	✓
5. Number of erosion features	Captured by another SQI. Rate of erosion (8) is likely to include a survey / count of erosion features.	×
6. Packing density	A measure of dry bulk density (BD), modified by texture. PD = BD + 0.009 C; PD is the packing density (dimensionless), BD the dry bulk density (g cm^{-3}) and C the clay content (wt.%). Direct indicator of soil degradation (soil compaction). Requires data on BD (1) and soil texture / particle size distribution (12). Data holdings were identified as LandIS and some of the ADAS experimental data.	✓
7. Profile description / visual soil evaluation	Visual soil evaluation (VSE) is based on the qualitative or semi-quantitative evaluation of soil properties Used to assess morphological, physical, biological and chemical soil properties, which are visible or possible to distinguish without laboratory analysis. Insufficient data at the national scale to be able to assess how visual evaluation scores relate to soil function or other indicators of soil physical quality through modelling and data analysis in WP2, but the method should be carried forward as a potential low cost field technique to assess general trends in soil condition at the national scale.	✓
8. Rate of erosion	Erosion causes detachment and transport of soil particles / aggregates from the *in-situ* soil mass, leading to a reduction in soil depth / volume (assuming soil bulk density is constant). Mass (tonnes) of soil lost per unit space (hectare) per unit time (year).Direct indicator of soil degradation and loss of function. Monitoring proposed in SP1303. Data available to link erosion rates with soil functioning (production; regulation – see Defra Costs of Degradation Project SP1606; Graves et al., 2011)	✓

9. Sealing	Degree of impervious cover on the soil surface. Can be assessed through remote sensing (satellite and airborne). A sensitive indicator (a step change in soil functioning is likely following sealing) that can be assessed relatively cost effectively.	✓
10.Shear strength (Going Stick method)	Limited data available nationally. Only measures the top 10 cm of the soil.	×
11. Soil structure	Can be captured in 7 above	×
12. Soil texture	See 6 above	✓ (as input to packing density)
13. Surface water turbidity	Sediment finger printing has been used in the Demonstration Test Catchment projects to quantify sediment source apportionment. There are questions regarding the sensitivity and indicator responsiveness, as sediment in a river course is spatially removed from the actual source of soil degradation. National coverage of data is limited.	×
14. Total porosity	Directly related to bulk density (1) and particle density (6). BD is captured in PD (6) and particle density does not generally change in soils	×
15. Bulk density (Kopecki ring)	See 1 above	✓ (as input to packing density and depth of soil)
16. Erodibility/ aggregate stability	An assessment of the stability of soil surface structure. The susceptibility of soil to (i) slaking, (ii) differential swelling, (iii) mechanical breakdown by raindrop impact and (iv) physico-chemical dispersion processes can be inferred by measurements of aggregate stability. Data lacking in England & Wales, no standard assessment procedures and highly variable soil property in space and time. However, data may be available from outside E&W – needs further investigation.	✓
17. Biological status of rivers	Too indirect spatially and temporally from soil sources / degradation processes and difficult to relate to the physical quality of soil.	×
18. Number of eutrophication incidents	Too indirect spatially and temporally from soil sources / degradation processes and difficult to relate to the physical quality of soil.	×

As Merrington et al. (2006) already considered this approach to physical SQIs and the general approach has been further developed in WP1, WP2 focused on the *dynamic* relationships between soil functions and SQIs.

There is, however, only a limited amount of information in the literature on the dynamic relationships between soil functions and particular SQIs. As a result, the assessment of 'a meaningful change' was based on those functions where it was possible to find evidence or make inference in relation to the production and regulation function. These functions are also highly relevant in terms of soil policy (see Work Package 3), given current drivers relating to food security, flood alleviation and carbon losses.

There is a spatial unit over which soil quality status is assessed (plot, field, farm, catchment, national scale). The spatial variability within this unit will introduce variability to the SQI irrespective of whether there are any changes in soil function(s). There are numerous sampling methods and sampling designs possible which minimize the effect of this type of variability. A recent report by Lark et al (2012) reviewed the impact of these different designs on one candidate physical SQI (bulk density). In the current project, land units of increasing spatial size were considered, with the assumption that SQI will be used to assess changes in soil quality at the different spatial scales. A second consideration was the impact of a particular land management practice on the effectiveness of an SQI to indicate change in soil quality. In this case, where data were available, we used a combination of land use, soil type and climate classes to determine the impact these factors may have on the background variability of the SQI under consideration.

3.2. SQI Assessment Structure

For all SQIs investigated, the level of data analysis and modelling is limited by the evidence base available. This varies considerably amongst the 7 SQIs considered. However, for each candidate physical SQI:

- We describe whether the SQI is meaningful with regard to soil functions.
- We review the evidence to determine what relationships exist between the SQI and soil processes and what might constitute meaningful change.
- We assess the spatial variability of the SQI and the implications for sampling. We do so using a combination of spatial statistics and power analyses. This will give an indication of the number of physical samples needed (sample size) to determine whether the SQI has changed to an extent where there are corresponding changes in soil quality. As there are different circumstances under which a SQI may be used, we evaluate sample sizes required for different spatial levels (e.g. plot, field, farm) and for a national assessment considering land use and climate. We also describe a general labour effort related to obtaining physical samples and their respective analytical costs.
- We evaluate alternative (proxy) measurements to the 7 candidate SQIs, either as some linear combination of existing soil measurements (denominated pedotransfer functions) or as readings from sensing systems which correlate with the SQI.

3.3 Statistical Background and Sample Size Calculations

The objective is to detect a change in a SQI and to do so we implemented a set of power analyses. Statistical power is the probability that a specific difference will be detected at a specified level of confidence. The statistical computation is further described and justified in the Work Package 2 report.

3.3.1. Obtaining an estimate of the SQI variability.

Most of the physical SQIs considered here are highly dynamic in space and time, not least because they are sensitive to management inputs, as are the soil functions they are indicating. Given this variability and sensitivity, these changes in soil properties, processes and associated functions are better assessed using a randomized sampling design. It is this design that we will consider here, whilst noting that the sample sizes presented in the statistical power graphs would be smaller, if a paired sampling approach was considered (Lark, 2009). Even so, repeat sampling over time at exactly the same site/ location can be prone to error (for example, the precision of site location).

A further efficiency is introduced if we consider stratification by land use and soil type, because we have *a priori* grounds to expect that changes in SQIs may vary for different land use (e.g. arable v. pasture v. woodland) and soil types (e.g. shallow v. deep soils) (Hill et al., 2003). For example, a change in packing density will have different consequences on different land uses and on different soil

types. We investigated these relationships for those SQIs where we had the available data (i.e. packing density and soil depth).

We used a model based approach to obtain an estimate of the SQI variability. Here, we considered the spatial correlation of the SQI only, and obtained from this a model of the spatial correlation, or variation, denoted by a variogram (Figure 1). This approach allows us to consider the sampling requirements for estimating the change in an SQI over increasing areas, from the field scale upwards.

3.3.2. Applicable analysis to candidate SQIs
The above discussion is predicated on the availability of appropriate data. This is different for the different SQIs we considered, so the level of analysis varies for each SQI.

Packing density
We had access to two large datasets, LandIS (containing data produced by the Soil Survey of England and Wales), which contains the representative profiles for England and Wales and contains approximately 1,250 measurements of bulk density and clay content; these were averaged over soil profiles. We supplemented this with data from ADAS (Defra project BD5001) which added a further 300 short range measurements of bulk density. From these data, we obtained a comprehensive data set for packing density and the variogram (Figure 2). We then obtained estimates of the dispersion variances for areas of increasing size of 5, 10, 25 and 50 km^2. We also considered a random sampled stratified approach based on a set of stratum developed for Defra project SP1606 (Graves et al., 2011), in which soil and land use were combined to generate 'supra'-classifications of the soil / land use combinations in England and Wales.

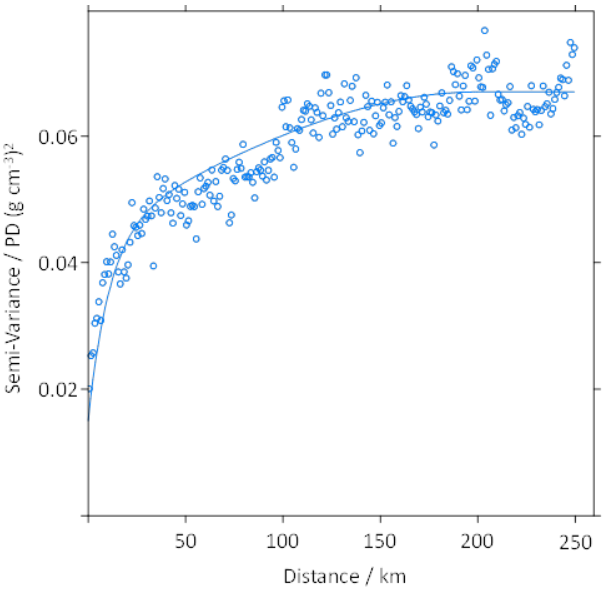

Figure 2. Variogram of Packing Density obtained from data from LandIS (NSRI, Cranfield University) and ADAS (Defra project BD5001).

Soil Water Retention Characteristics. A total of 2,480 soil profiles for which soil water retention data were available were extracted from the LandIS database. From these, and using hydrological models, the SQIs associated with soil water retention characteristics were derived. Pedo-transfer functions were calculated based on this dataset.

Soil Depth. The only adequate dataset available to us in this case is the LandIS dataset (Soil Survey of England and Wales). These data comprise profiles across England and Wales with depth measurements restricted to the top 150 cm in most sampled profiles. This means many data points do not represent accurately the full depth of soil. We therefore only considered those soils identified as 'shallow soils' in the soil survey, to avoid the unrealistic (truncated) soil depth data. Also, shallow soils are likely to be soils where functions may be compromised if depth changes. This gave 177 soil

profiles. Power analysis was based on a variance estimate from the stratified mixed model described above.

Aggregate Stability. There is no national dataset on aggregate stability. The most geographically extensive dataset we sourced was generated as part of Defra project SP0519: Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration, led by Professor Whitmore and Dr Chris Watts of Rothamsted Research. Data on aggregate stability on a range of soil types and land uses was obtained for a set of test sites across England. The power analysis was based on a variance estimate from the stratified mixed model described above.

Rate of Erosion. The statistical analysis and sampling design for monitoring the rate of erosion is comprehensively covered in Brazier et al. (2012) as part of Defra project SP1303 Developing a cost-effective framework for monitoring soil erosion in England and Wales. This includes power analyses based on variability of data on erosion rates at the national scale.

Soil Sealing. A classified satellite image can cover the entire area of interest, depending on the scale of survey and resolution of image required. As the area of interest is not sampled, power analysis is not appropriate here. We discuss here pixel size (sample support) and different satellite images that are available to determine sealing of soil and degree of imperviousness.

Visual Soil Evaluation. This is qualitative / semi quantitative assessment of soil quality and we discuss its suitability to monitor *change* in soil quality (not just the baseline soil quality), especially as many schemes are based on categorical (i.e. scores) rather than continuous data (i.e. absolute values as is given for packing density and depth of soil for example).

3.4 Summary of Fact Sheets (full details in Work Package 2 report)

3.4.1. Packing Density.
In this case we consider two approaches; one based on a set of stratum developed for Defra project SP1606 (Total Costs of Soil Degradation; Graves et al., 2011) in which soil, land use and climate are combined to generate 'supra'-classifications of the soils in England and Wales. If spatial and temporal variability in packing density was dependent on land use, soil type or climate, this implies a different sampling regime is required for different geographical areas if the monitoring is to be statistically robust. This exercise also explored whether meaningful changes in packing density (i.e. ones that reflected a change in soil processes and functioning) might be different for different land use / soil / climate combinations. In other words, would the functioning of arable soils with high clay content be more affected by a change in PD than woodland soils on sand? The results from the power analysis are shown in Figure 3 (national data) and Figure 4 (data at different spatial scales).

We also determined the sample size needed if a change is to be determined over areas of increasing size using a model based approach described earlier (geostatistics). Figure 4 shows that if we wish to determine a given change in PD for a given spatial area (field; 5 and 10 km^2), farm (25 km^2) and at the landscape level (50 km^2) we increasingly need a larger sample size to determine this change within this spatial area. If we further consider factors which affect the spatial variability of PD such as land use, then this information will reduce the number of samples needed at the landscape scale.

3.4.2. Soil Water Retention Characteristics.
The relevant data available consisted of volumetric moisture content measured at pressure heads (expressed in water height equivalents) of 0.5, 1, 4, 20 and 150 m. In addition, total porosity (derived from measured bulk density and particle density) was used as an approximation of the moisture content at saturation, θ_{sat} (= 0m pressure head). For each soil, the water retention function represented by the Van Genuchten equation was fitted to the data using θres, α and n as fitting parameters. The Dexter's S index was calculated using the fitted parameters and converted into S_g using Eq. 6. θ_{sat}, estimated from the porosity, θ_{fc} (measured at both 0.5 and 1m pressure head) and θ_{PWP} (measured at 150m pressure head) were used to calculate the indicators: plant available water capacity (PAWC), air capacity (AC; or drainable porosity) and relative field capacity (RFC). It was not possible to calculate macroporosity (M) because measurements of the moisture content, θ_m (occurring at 0.1m pressure head) were not given.

Assessment of pedotransfer functions

BD, texture (clay, silt and sand content) and organic C content are available for the same soils in the LandIS database. Two types of pedotransfer functions (PTFs) were considered and discussed in Work Package 2 report. Results of this analysis are shown in Tables 3 and 4 and in Figure 5.

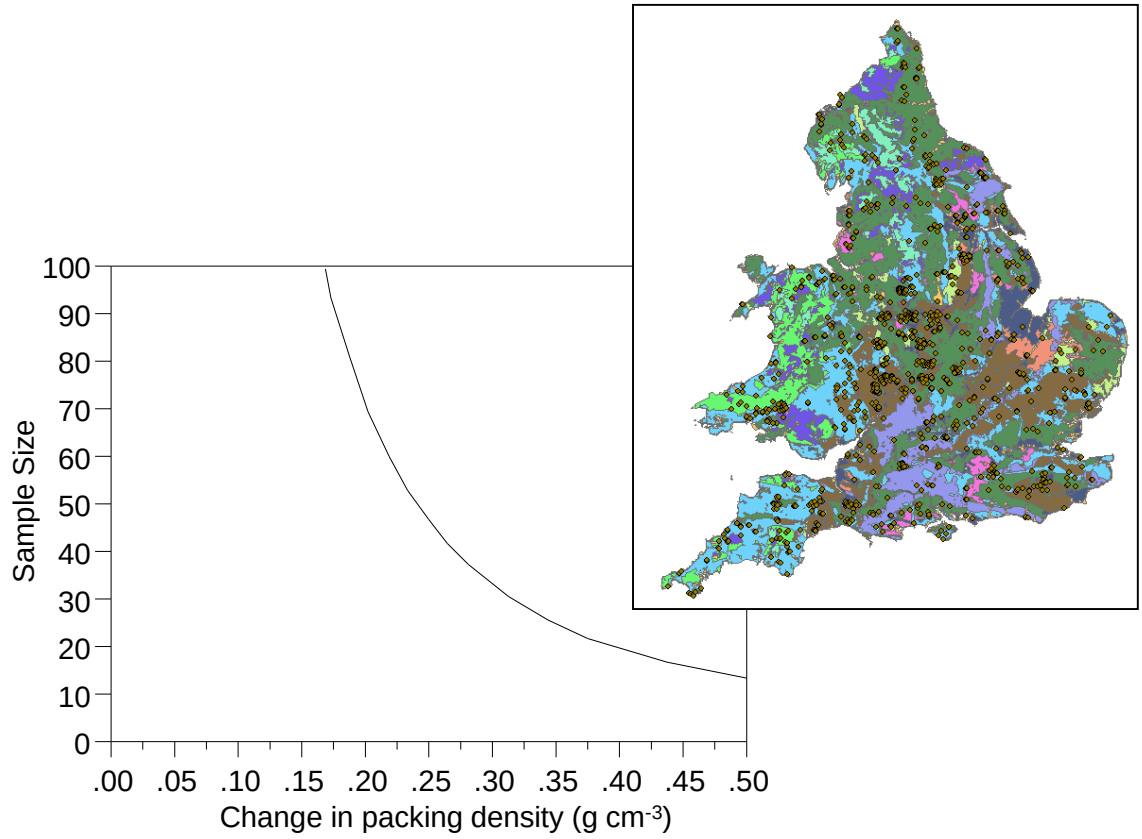

Figure 3. Results from the power analysis based on land use by soil strata. The insert shows the spatial distribution of the data points superimposed on the land use /soil classification (see Defra project SP1606 for details regarding the stratification).

Table 3. Soil Water Retention Characteristics: Fit results from pedotransfer functions based on LandIS data (BD, Clay, Silt and Sand and Organic C content)

	S_v		S_g		Drainable Porosity		Plant Available Water		Relative Field Capacity	
	RSQ	conc R	RSQ	conc R	RSQ	conc R	RSQ	conc R	RSQ	conc R
multiple regression	0.56	0.73	0.82	0.85	0.53	0.65	0.58	0.72	0.61	0.78
Multivariate Adaptive Regression Splines (MARS)	0.72	0.75	0.87	0.9	0.71	0.08	0.68	0.82	0.73	0.85

RSQ = R^2 statistic; conc R = concordance correlation

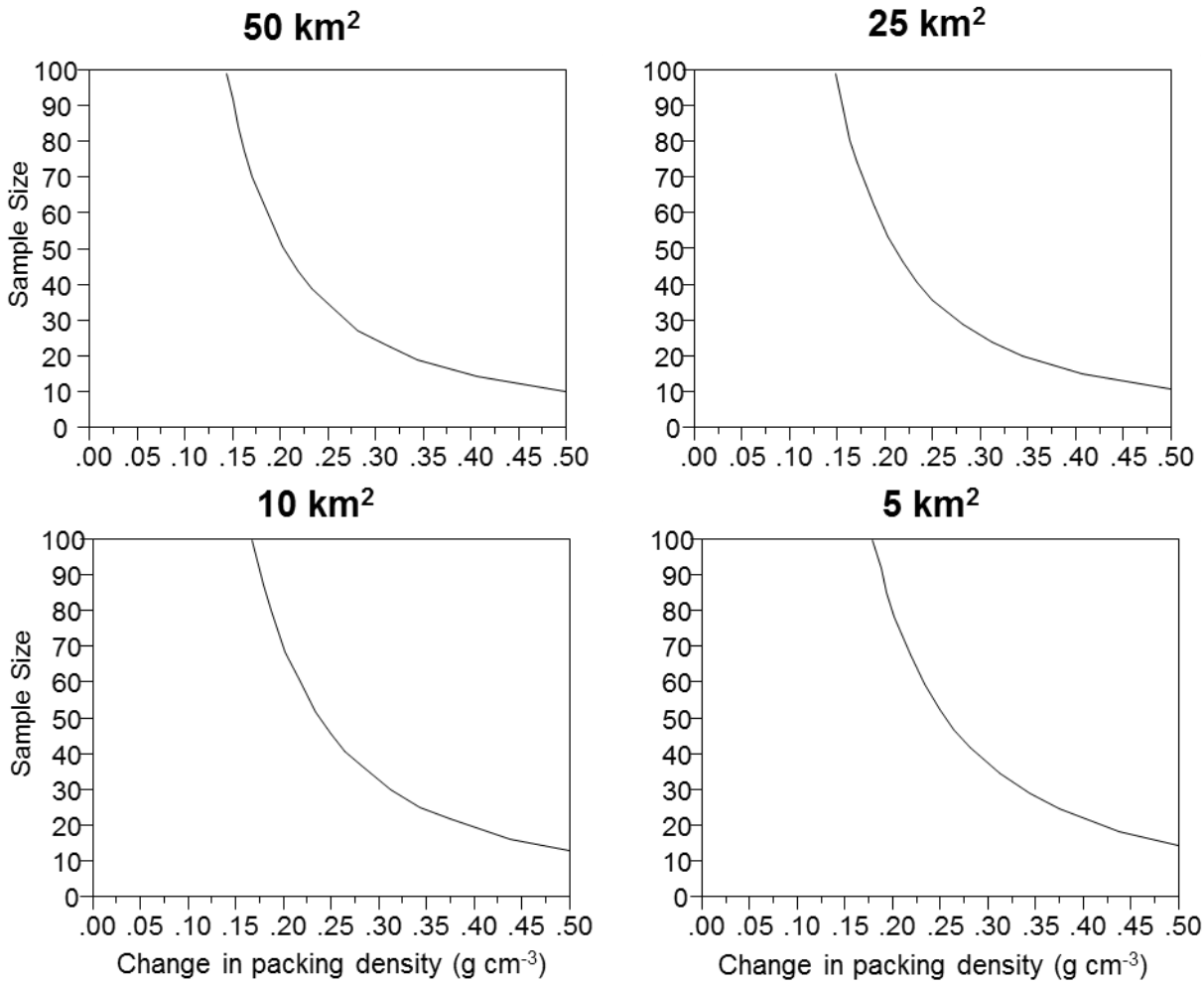

Figure 4. Power analysis using a model based approach in which the variation of different regions (size of spatial unit) is obtained from the spatial correlative structure (variogram in Figure 2)

Table 4. Variable importance in Multivariate Adaptive Regression Splines fitting. Numbers refer to rankings of importance

	S_v	S_g	Drainable Porosity	Plant Available Water	Relative Field Capacity
BULK DENSITY	2	2	2	2	2
CLAY	3	2	2	2	1
SILT	0	1	0	2	2
SAND	1	2	2	2	2
ORGANIC_CARBON	1	2	1	3	1
LU_GROUP	0	0	0	0	0
SUBGROUP	1	1	4	1	3
SERIES	4	4	2	3	2

In summary, we can obtain adequate performance (R^2 of 0.5 to 06) if we use standard regression approaches. This is significantly improved with Multivariate Adaptive Regression Splines (MARS)

using data which are available for England and Wales (R^2 > 0.8; Table 3). It is therefore feasible to derive Soil Water Retention Characteristics SQIs using PTFs based on bulk density, texture and organic C measurements. In Defra project SP1305 (Subproject B), the sampling requirement, under different sampling regimes, is considered for BD and organic C, and the report suggests that for a plot of 20 by 20 m, 25 aggregated samples would be required. This is indicative of the sampling effort needed to determine the input data for the PTFs.

3.4.3 Aggregate Stability

Only very limited datasets exist to assess aggregate stability across different land uses and soils at the national scale (England and Wales) (Thompson and Peccol, 1995; Merrington et al., 2006). However, Defra project SP0519 (Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration) used measurements of aggregate stability to describe and rank the likely behaviour of soil under the influence of rain. A number of simple aggregate stability tests were designed to allow rapid screening of a relatively large number of representative soil type / land use combinations in terms of their susceptibility to aggregate breakdown. The database showed measurements of aggregate stability are capable of discriminating between different soil types and management practices (Chris Watts, pers.comm.). These relationships are under investigation currently. General relationships between aggregate stability and measurements of a wide range of key physical and chemical soil properties were deduced, including easily-measurable soil properties such as organic carbon and clay content. The resultant database was made available to the current project by Dr. Chris Watts and Prof. Andy Whitmore of BBSRC Rothamsted Research. However, as the authors of that work point out, the data generated from the field experiments was limited, in terms of geographical distribution, environmental conditions, simulated plot scale and replication.

One major challenge is extrapolating results from the individual aggregate scale to larger spatial scales at which related soil processes (e.g. infiltration, runoff generation, erosion) and soil functions (e.g. provisioning) take place. For example, from these data, relationships between aggregate stability (as measured by the 3 different methods used) and surface runoff, through flow and erosion appear to be very weak or non-existent (for example, Figure 6 shows the relationship between aggregate stability and runoff; others are shown in Work Package 2 report). Therefore currently there is no evidence that aggregate stability is an effective SQI of the water regulation function.

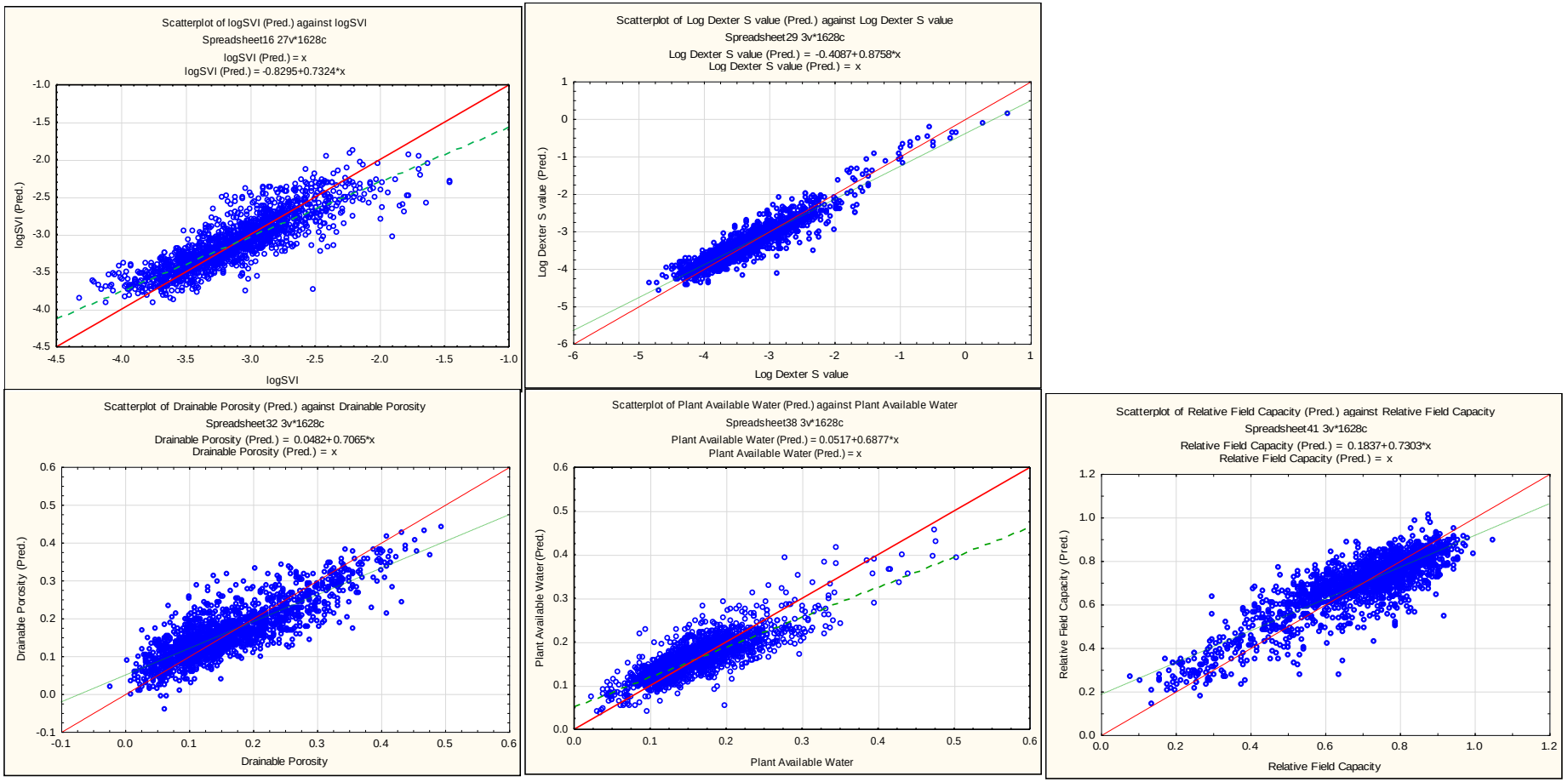

Figure 5. Biplots representing the predicted SQI versus observed SQI based on the MARS pedotransfer functions. Note SVI in these graphs refers to S_v and Dexter S refers to S_g

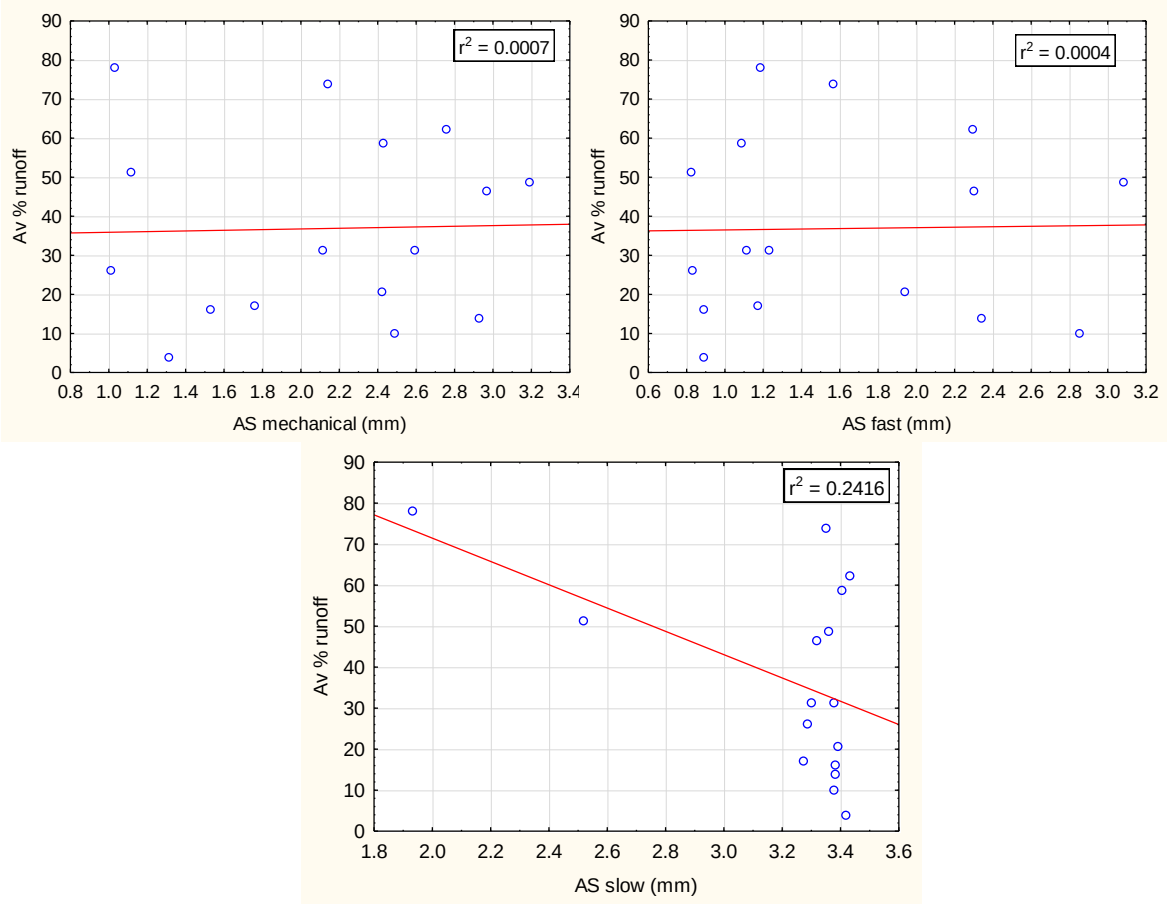

Figure 6. Biplot and linear fit between % Runoff and aggregate stability. Data from Defra project SP0519 (Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration). Experimental details can be found in the SP0519 project report.

Power analysis and sampling size.
For aggregate stability, the power analysis is based on data obtained from the Defra project SP0519 in which aggregate fractions were associated with degrees of stability (very unstable, unstable, medium, stable and very stable, which are taken as qualitative categories of aggregate stability; Table 5). Three types of aggregate stability test were considered using various wetting conditions and energies (fast wetting (AS fast); slow wetting (AS slow); and mechanical energy applied after pre-wetting (AS mechanical). The power analysis is based on the differences between these categories (Figure 7). The high variability in aggregate stability as reported in the literature suggests a very high sampling intensity is required to detect changes in space and time.

Table 5. Classification of aggregate stability based on mean weight diameter (MWD; after Le Bissonnais, 1996)

MWD 0.4 mm	Very Unstable
MWD 0.4 - 0.8 mm	Unstable
MWD 0.8 - 1.3 mm	Medium
MWD 1.3 - 2.0 mm	Stable
MWD >2.0 mm	Very Stable

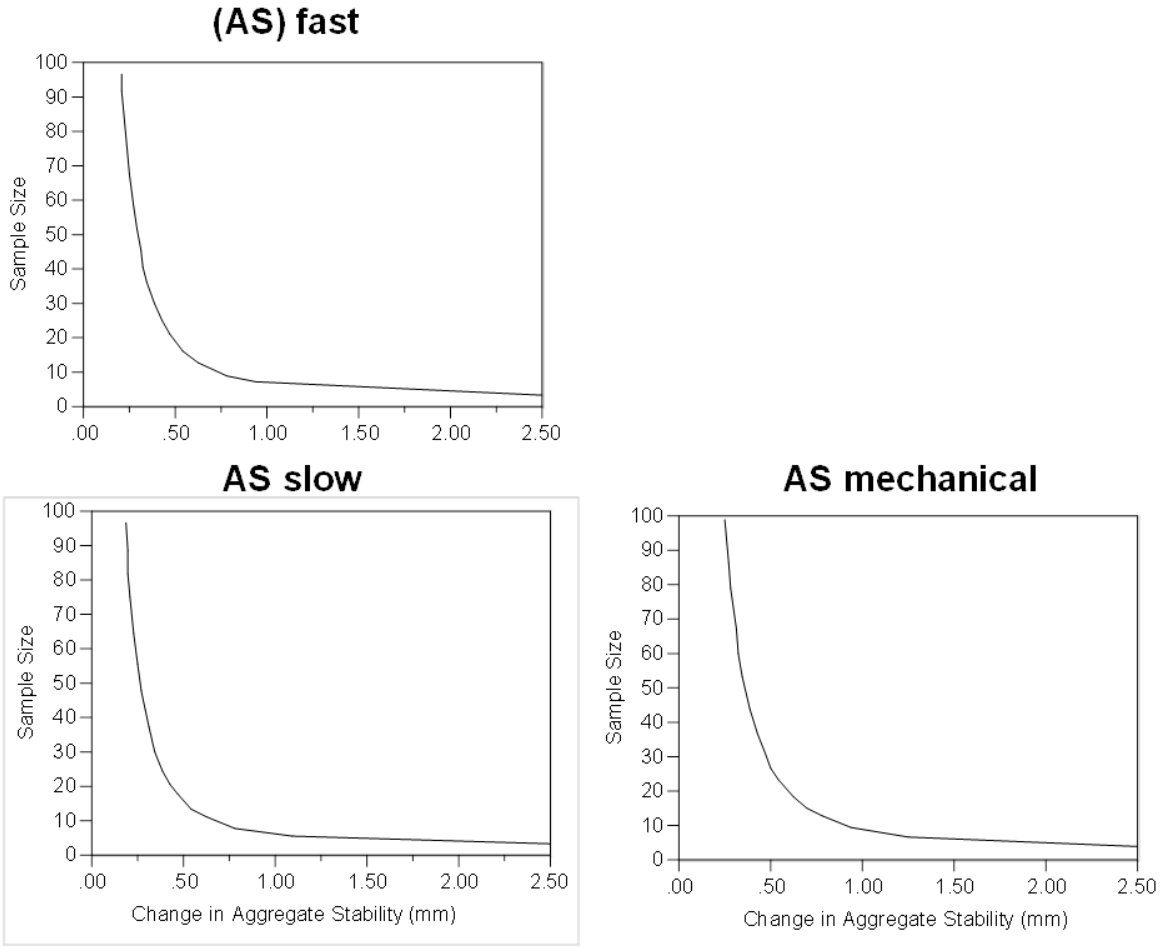

Figure 7. Power analysis of three different measurement techniques to determine aggregate stability. Data from Defra project SP0519 (Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration).

3.4.4. Rate of Erosion

Defra project SP1303 (Brazier et al., 2012) noted that whilst there has been a great deal of erosion monitoring in the UK historically, it has not been placed within an unbiased sampling framework. The project proposed a sampling design for a cost-effective, national erosion monitoring scheme. It should be noted that the data used in the analysis were drawn only from more erodible (cultivated) land use types, as they were the only available data to investigate water erosion over time. As similar datasets do not exist for gross erosion from all pathways (water, wind, tillage and soil loss by co-extraction with harvested crops), this analysis could not be performed at this level of detail. Brazier et al. (2012) note that in the future should these datasets become available, such analysis could be undertaken.

Table 6. Results of the power analyses to detect specified change; 0.1 is 10% and 1 is 100% (from Defra Project SP1303 Final report)

	Power (p=0.05) to detect specified change Simple Random Sampling				
Total Sample Size	0.1	0.25	0.5	0.75	1
50	0.05	0.1	0.22	0.38	0.53
100	0.06	0.15	0.4	0.65	0.83
150	0.07	0.21	0.55	0.82	0.94
200	0.08	0.26	0.67	0.91	0.98
250	0.09	0.32	0.77	0.96	1
300	0.1	0.37	0.84	0.98	1
350	0.11	0.42	0.89	0.99	1

400	0.12	0.46	0.93	1	1
500	0.14	0.55	0.97	1	1
600	0.16	0.63	0.99	1	1
700	0.18	0.7	0.99	1	1
800	0.2	0.75	1	1	1
900	0.22	0.8	1	1	1
1000	0.24	0.84	1	1	1

According to Brazier et al. (2012), a common target power is 80%. The results show that a total sample of 300 would be adequate to achieve this power to detect a 50% increase in erosion rate (two-date comparison). Between 900 and 1000 samples would be needed to detect a 25% increase with the same power. A 10% increase is not detectable as a two-year comparison with 1000 samples, and clearly many more would be needed.

In any case, what constitutes a meaningful change in erosion rates still requires data on the impacts of erosion on soil functions in England and Wales, and will be dependent on highly variable factors such as specific crop (rooting habit, crop demands - water, nutrients); soil properties (water holding capacity; nutrient status) and external inputs (manufactured fertilisers; irrigation).

Monitoring soil erosion by remote sensing (satellite, airborne or ground based) assumes erosion features produce detectable changes in the electromagnetic radiation recorded by the remote sensor (Milton and Webb, 1987; Milton et al., 1995), which must be distinguishable from radiometric distortions arising from the sensor (Collins and Walling, 2004). At present, most small scale monitoring (e.g. using satellite imagery) is at odds with the spatial scale of erosion processes, local risk factors and mitigation measures. The new generation of sensors such as IKONOS may be more suitable, with spatial resolutions appropriate for erosion studies (e.g. <4 m). Remote sensing shows great potential for erosion monitoring, but image processing algorithms have to be better at considering pixel-to-pixel interactions (Dr. Karen Anderson, Exeter University, pers.comm.).

3.4.5. Depth of soil

Detecting changes in soil depth over space and time poses a number of challenges to monitoring, which must take into account any uncertainty in measurement; variability in observed distributions; expected rate of change; and spatial variability. Monitoring soil depth is further complicated, because definition of ‘depth of soil’ is debatable (for example, see distinction of ‘critical’ and ‘effective’ soil depth in Work Package 2 report).

Power analysis and sampling size.

In the case of soil depth as a potential SQI, we restricted our analysis to consider a particular stratum or type of soil which is vulnerable to changes in soil depth i.e. those which are denoted as shallow soils in LandIS (Soil Survey of England and Wales). This also allows for the fact that data come from a depth limitation of 150cm in the original survey. We obtain the measure of spatial variability in depth from the soil profile database and use this to calculate the sample numbers required to determine a change in soil depth. The results from the power analysis are represented in Figure 8, which also shows the spatial coverage of the shallow soils in England and Wales.

3.4.6. Soil Sealing

Over time, monitoring the change in the proportion of sealed soils will allow assessment of changes in soil functions. For example, the water regulating function of soil is lost by surface sealing. This increases flood risk due to higher runoff coefficients from paved surfaces. The extent of the built environment can be estimated from high resolution satellite imagery (<1 m ground resolution) and aerial photography. Both are capable of including narrow corridors, such as road and rail systems, as well as providing accurate estimates of residual soil areas within the built environment. The utility of remote sensing data can be improved through integration with other datasets, e.g. OS MasterMap or soil maps, enabling sealed or unsealed areas to be resolved at a finer spatial scale. However, as reported in Wood et al (2005), there

are few quantified data demonstrating the effect of soil sealing on soil function, which limits detailed analysis of data.

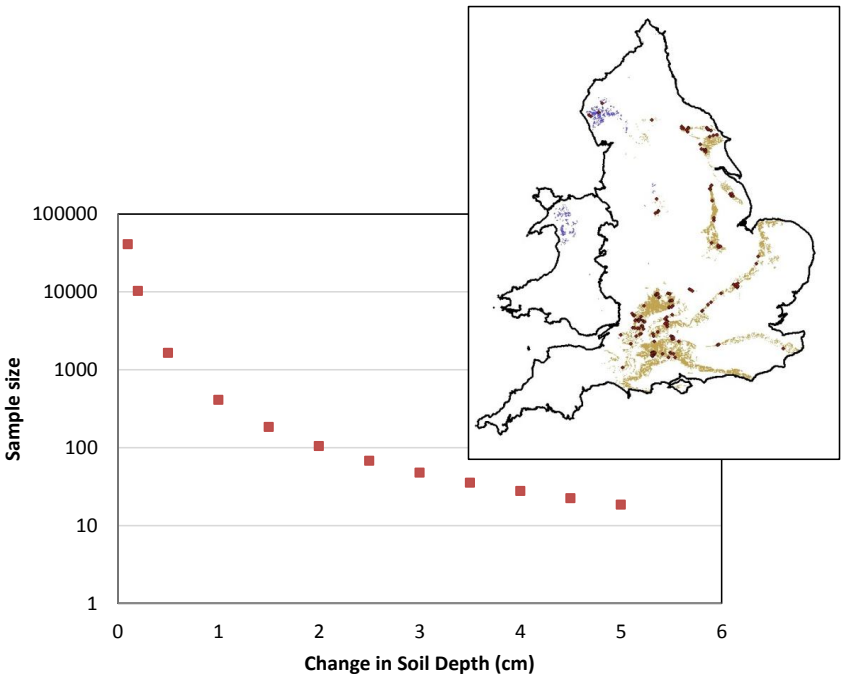

Figure 8. Results from the power analysis for shallow soils in England and Wales. Insert shows the spatial coverage of the data points i.e. the distribution of shallow soils. Note that the y-axis is on a logarithmic scale

3.4.7. Visual Soil Evaluation

The main objective of visual soil evaluation (VSE) is to assess the effects of cultural operations on soil structure looking at the intrinsic quality of the soil. Visual soil evaluation (VSE) is based on the qualitative or semi-quantitative evaluation of soil properties and SQIs e.g. morphological, physical, biological and chemical, which are visible or possible to distinguish without laboratory analysis (Houšková, 2005). VSE is used to assess soil quality by comparing the state of the soil against a reference sample (i.e. either a photograph or a soil sample known to be in optimal condition). For example, the New Zealand Visual Soil Assessment (VSA (NZ)) method (Shepherd, 2008) considers soil texture, soil structure, soil porosity, soil colour, number and colour of soil mottles, earthworm (number and size), rooting depth, surface ponding, surface crusting/cover and soil erosion (wind/water).

One criticism of VSE techniques is the challenge of quantifying the findings, thereby providing comparable data in space and time (which is essential for an effective monitoring programme). However, a number of studies have linked VSE findings to quantifiable soil properties. Also, the scores for a number of VSE methods have been found to be significantly correlated to corresponding lab-based methods (e.g. Shepherd et al., 2002; reported in Boizard et al., 2005; Mueller et al., 2009a; 2009b; Figure 9). In the evaluation by Boizard et al. (2005) the Peerlkamp method was the only one with a sufficient number of results to enable a statistical evaluation to be made of the differences between the topsoil structure of the plots. However, the number of replicate samples depends on the time allowed to undertake the analysis.

Mueller et al. (2012) found that compaction status of soils with clay contents > 30% could not be reliably determined either by dry bulk density measurements or penetrometer readings. However, they found that visual observations could determine structural differences in these soils.

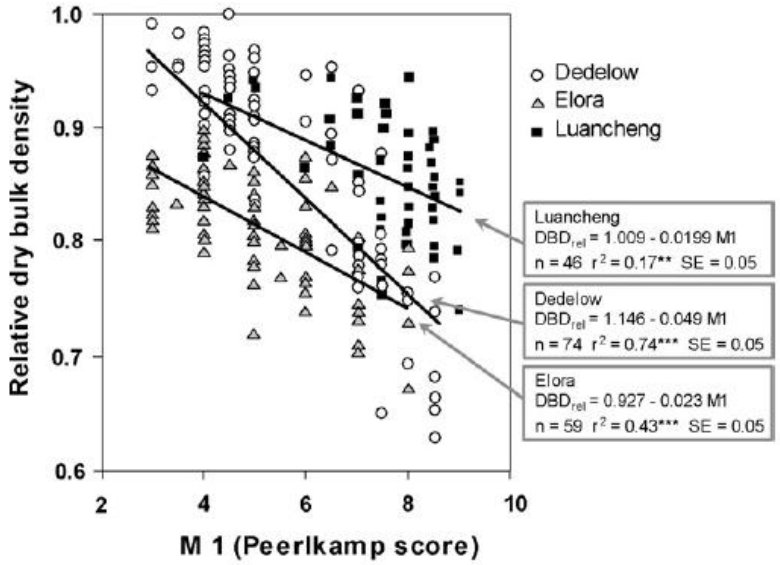

Figure 9. Correlation between Peerlkamp score and relative dry bulk density (taken from Mueller et al., 2009a)

Another uncertainty surrounding VSE outcomes is the continuity in results between different surveyors / monitors (reliability). The VSA (NZ) method has been validated as a robust method whereby laypeople with little or no background in soil science could use the method and come up with similar answers to an 'expert' (Figure 10; Boizard et al., 2005).

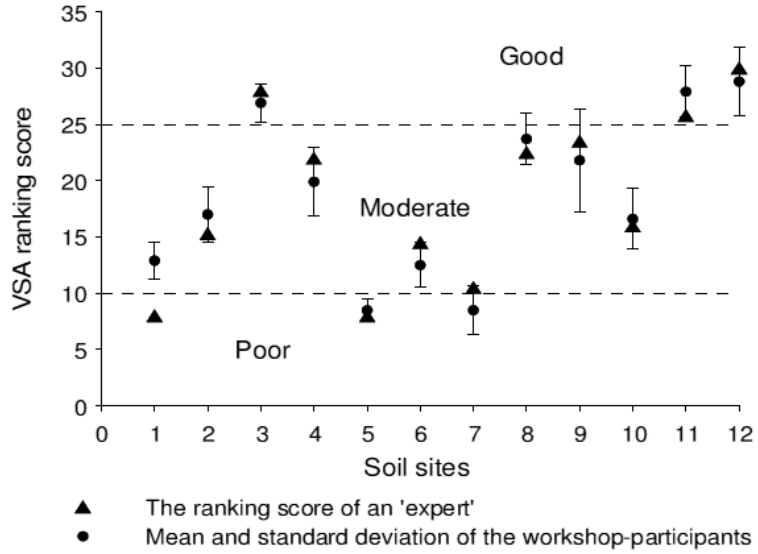

Figure 10. VSA of the condition of 12 soils under arable cropping – A comparison of 'expert' and workshop participant rankings (taken from Boizard et al., 2005).

It is now recognised that the use of good reference material (e.g. photographs) in combination with well-defined descriptions of several soil properties, which can be used to assign a soil structural quality score, provides a more robust and consistent classification system that enhances the reproducibility of the results (Mueller et al., 2012). While the reproducibility of visual features can be, to some extent, aided by good visual reference material, the reproducibility of tactile observations (e.g. soil texture) is more dependent on subjective descriptions. However, Hodgson et al. (1976) demonstrated that with experience and the use of reference material against which observers can 'calibrate' themselves, it is possible to

produce a confident estimate of soil texture for a wide range of soils. In their study, they found that 76% of the variation in field estimates of silt content and 85% of the variation of clay estimates could be predicted by hand texturing.

In summary, semi-quantitative VSE methods provide a value or description against which temporal changes in score and rankings (the proportion of soils in 'good', 'moderate' or 'poor' condition) can be gauged and that can be recorded as an on-going reference. The logistics and practicalities of carrying out VSE are discussed in the Work Package 2 report.

3.5 Integration of physical SQIs

Each candidate physical SQI was considered independently, but we also considered the relationships between the candidate SQIs. There is evidence that combining the measurements of physical (and biological and chemical) SQIs improves the relationship between the SQIs, soil processes and soil functions. In justifying the use of bulk density / packing density as a meaningful SQI (WP1), we are aware of empirical evidence suggesting better prediction of air capacity by combining bulk density and clay content (i.e. packing density) (Figure 12).

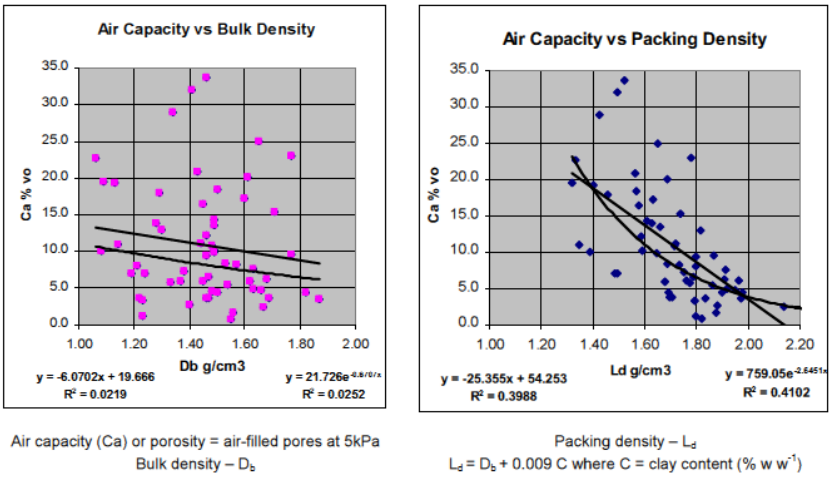

Figure 12. Improving the relationship between air capacity and measures of bulk / packing density (from Huber et al., 2008)

A similar exercise was done here where data were available (i.e. PD, BD, aggregate stability and depth), with the *a priori* reasoning that a number of the physical SQIs would be inter-dependent and therefore exhibit spatial clustering. However, the resulting cluster analysis of the data showed no spatial patterns which reflects the complexity of relationships between the SQIs and paucity of data. In any case, any relationship between the parameters would have to be expressed in terms of soil processes and functions for it to be meaningful.

This project has been focussed on physical properties as soil quality indicators, without explicit reference to biological or chemical SQIs. According to Karlen et al. (2003) and Arshad and Martin (2002), soil quality assessment must reflect biological, chemical and physical properties, processes and their interactions (Table 7). Taking this more holistic view, Karlen et al. (1997) note the interdependence among SQIs and that the concept of soil quality should be "an umbrella concept for examining and integrating relationships and functions among various biological, chemical and physical parameters that are measured and important for sustainable agricultural and environmental systems." They suggest that "field, farm and watershed-scale evaluations of soil quality require a transition from an experimental mode that contributes to an understanding of soil quality to more interdisciplinary approaches".

Table 7. Interrelationships of key soil quality indicators (Arshad and Martin, 2002).

Selected indicator	Other soil quality indicators affecting the selected indicator
Aggregation	Organic matter, microbial activity (especially fungal), texture
Infiltration	Organic matter, aggregation, electrical conductivity, exchangeable sodium percentage

Bulk density	Organic matter, aggregation, topsoil depth, electrical conductivity, biological activity
Microbial biomass and / or respiration	Organic matter, aggregation, bulk density, pH, texture, electrical conductivity
Available nutrients	Organic matter, pH, topsoil depth, texture, microbial parameters (mineralisation and immobilisation rates)

These interrelationships have been demonstrated above in section 3.5.2. and in Fact Sheet 2, Work Package 2 Report (Soil water retention characteristics), where basic soil properties (bulk density, texture and organic C) were used to predict soil water retention characteristics (Dexter's S, drainable porosity, plant available water and relative field capacity) through pedotransfer functions. Even so, we need to relate these relationships to soil processes and functions. Shukla *et al*. (2004) carried out step-wise regression analysis with corn grain yield as the dependent variable and measured soil attributes as the independent variables (Table 8).

Table 8. Linear regression analysis for total dry corn grain yield (Yg, Mg ha^{-1}) as dependent variable and measured soil attributes as independent variables (P<0.009)

	Equation	R^2
One parameter model		
	Y_g = 3.753 + 0.007 WSA	0.33
Two parameter model	Y_g = 3.717 2 0.424 AWC + 0.008 WSA	0.34
	Y_g = 3.353 10.009 WSA – 0.422 MWD	0.34
	Y_g = 14.321 + 0.006 WSA – 1.435 pH	0.34
Three parameter model	Y_g = 23.569 + 0.009 WSA – 0.906 MWD – 2.808 pH	0.37
	Y_g = 24.061 + 0.007 WSA – 2.809 pH – 2.449 EC	0.36
where: AWC – available water (cm); WSA – water stable aggregates (g kg^{-1}); MWD – mean weight diameter (mm); EC – electrical conductivity (dS m^{-1})		

The criticism with this approach is that a) regressions give no explanation of why combining these soil properties improves prediction of soil functioning (here, yield); b) the relationships and equations would vary for different soil functions (e.g. provisioning v. regulation); c) there are few equivalent data for England and Wales linking soil attributes (i.e. physical SQIs) to soil functions; d) this approach takes no account / makes no allowance of how a change in one or more attributes over time (which is at the core of a soil monitoring programme) may change the interrelationships between soil attributes; e) the current England and Wales database on physical soil attributes is too limited and contains too much variability to derive rigorous regression equations. In any case, the resulting R^2s (i.e. the degree of variation accounted for) in Table 8 are low.

It has been demonstrated that for statistical rigour, the sampling design of each SQI is based on the detectable / meaningful change in that property (i.e. power analysis). As a result, different SQIs will require different sampling designs, which undermines the concept of having multiple, integrative SQIs, unless the largest sampling size is taken for all. Given the cost implications, we conclude it is impossible to design and implement a rigorous sampling scheme for multiple SQIs. Another limitation of integrative SQIs is error propagation when using more than one SQI. Error in one or more input variables (e.g. measurement / sampling error) means the resulting integrative SQI may not be robust (Murray Lark, pers.comm.).

3.6 Conclusions to Data Analysis and Modelling

Data on the physical SQIs selected by the logical sieve process in WP1 are limited in spatial and temporal extent for England and Wales. This has limited the degree of analysis and modelling. Where data are available, power analysis was used to understand the variability of the indicator as given by the observed distributions. This process determines the SQIs ability to detect a particular change at a particular confidence level, given the 'noise' or variability in

the data (i.e. a particular power to detect a change of 'X' at a confidence level of 'Y%' would require 'N' samples).

The paucity in data has limited the specification of a robust sampling design required to detect changes in the SQI that are associated with a meaningful change in any soil process and/or function. In any case, there is little scientific evidence to define what is meant by a 'meaningful change' in any given SQI and this will vary for different soil types, land covers and soil functions. Attempts were made to stratify detectable changes in packing density and soil depth by land cover and soil type, but no relationships were found. If this had been the case, we would need to relate these changes to associated changes in soil processes and soil functions, but the evidence base is very weak to do this. Schipper and Sparling (2000) identify the challenge: "a standardised methodology may not be appropriate to apply across contrasting soils and land uses. However, it is not practical to optimise sampling and analytical techniques for each soil and land use for extensive sampling on a national scale".

Soil hydrological relationships are key to soil functioning, especially in water regulation (availability to plants and avoidance of both flooding and drought; Merrington et al., 2006). Here, the analysis of available data gave promising results regarding the prediction of SQI values from easy to measure soil properties (bulk density, texture and organic C), using pedotransfer functions. These measurements also allow estimates of packing density which are also related to soil hydrological properties (e.g. air capacity; Huber et al., 2008). Expanding the evidence base (space and time) should be possible with the development and use of rapid, cost-effective techniques using NIR sensors to gain measurements of bulk density, texture and packing density.

More evidence is needed as to how aggregate stability affects soil processes and thus soil functions. We have found an equivocal relationship with water regulation (runoff generation), but this was affected by the method of measurement (low or rapid wetting or mechanical disturbance of the aggregates) for example. There are insufficient data to assess a 'meaningful' change in aggregate stability i.e. how a change in that property affects processes and thus functions. Gathering such data would rely on better, more cost-effective, standardised measurement techniques.

Defra project SP1303 (Brazier et al., 2012) used power analyses to estimate the number of monitoring locations required to detect a statistically significant change in soil erosion rate on cultivated land. On the basis of this analysis, the project proposed a cost-effective framework to monitor (and model) soil erosion in England and Wales, with an emphasis on constructing a statistically sound approach to locating sampling sites for soil erosion monitoring. However, what constitutes a meaningful change in erosion rate still requires data on the impacts of erosion on soil functions.

At present there is insufficient quantified evidence for statistical rigour to be applied in determining a sampling strategy for visual soil evaluations. Although, some studies have begun to investigate how VSE might be moved to a quantified scale. The use of remote sensing to detect changes in surface sealing has potential, although the spectral signatures received are not direct measurements of soil quality in terms of physical properties and their influence on soil processes and functions. Wood et al. (2004) notes that in general, remote sensing techniques are most useful when considering indicators that relate to soil quantity. These techniques have limited utility for those indicators that relate to soil condition (quality). In any case, as reported in Wood et al (2005), there are few quantified data demonstrating the effect of soil sealing on soil function, which limits detailed analysis of data.

The evidence base is poor: data on meaningful (i.e. what degree of change affects soil processes and functions) and detectable (i.e. what sample size is needed to detect the meaningful signal from the variability or noise in the signal) changes in physical SQIs are lacking at present to underpin the development of a rigorous and reliable soil monitoring programme.

4. SYNTHESIS AND POLICY IMPLICATIONS (details in Work Package 3 report)

Soil policy should be demonstrably effective. This requires that indicators are available that can reliably measure progress towards targets linked to policy objectives that are either directly related to intended policy outcomes or that allow interpretation of progress towards them.

4.1 Policy background and drivers

Physical SQIs are important data for decision-making because they are indicators of the physical functioning of the soil that supports services including plant growth for food production, attenuation of water flows in catchments to reduce flood risks and retention of water for periods of drought. The following issues are strongly linked to the monitoring of physical SQIs (see Work Package 3 report for details):

- Food security is an increasingly important policy issue (see Foresight, 2011; Global Food Security strategic plan 2011-2016 (2011), requiring better protection for agricultural soils
- Expansion of the built environment and the performance of residual soil resources in the built environment, such as their capacity to attenuate surface water flows and reduce risk of flooding.
- Climate change adaptation in terms of food production (yield and quality of produce), land use change, flood prevention and drought tolerance. This includes protecting and enhancing stores of soil carbon
- Future energy requirements may also impact on soil quality
- Bio-security is a persistent policy issue of high priority. Soil can act as a reservoir and transport media for pathogens, including E coli O157, cryptosporidium and prions. Understanding how pathogens are dispersed from sources to receptors requires information about how the pathogen is partitioned between water and soil and then how the soil landscape responds to infiltration or the mobilisation of sediment through soil erosion.

4.2 Current policy

There is a substantial body of policy in place that is aimed at safeguarding UK soil resources, supported by a range of implemented policy measures, as well as policy aimed at addressing other issues but which requires soil-related actions. Notably, the European Thematic Strategy for the Protection of Soil (EC, 2006) which identifies a range of threats to soil resources, including erosion, decline in soil organic matter and compaction. The Common Agricultural Policy (CAP) takes account of the Thematic Strategy through the inclusion of mandatory soil management requirements under Cross Compliance linked to Single Farm Payments and via Agri-Environment Schemes (including Environmental Stewardship) under national Rural Development Plans. Cross Compliance requirements, codified within definitions of good agricultural and environmental condition (GAEC) include measures to control erosion and compaction and therefore their efficacy should be supported by physical SQIs.

Inevitably, the European Commission will seek more information on the status and trends in soil quality, including in relation to compaction. The revision / extension of cross-compliance requirements in the new CAP agreement is expected to include strengthening of soil protection measures. This will require monitoring to demonstrate that these measures are effective, including the mitigation of soil degradation processes. Therefore indicators relevant to compaction and erosion will become increasingly important.

Policies driven by the Water Framework Directive (WFD) consider the importance of land and soil management on surface water quality, storm flows and aquifer re-charge. Monitoring schemes are needed to target, implement and evaluate the success of these policies. Physical SQIs that relate to changes in infiltration (soil water retention characteristics), runoff (packing density and soil sealing) and erosion (rate of erosion and aggregate stability) will be important in this evaluation. Rate of soil erosion, aggregate stability, water retention characteristics and packing density will also be important in model based predictions used to inform transfer of contaminants attached to soil particles and sources of diffuse pollution of surface water.

At the national level, a number of overarching policy statements have been published, including:

- The Natural Environment White Paper, The Natural Choice (Defra, 2011a)
- The Scottish Soil Framework (Donelley, 2009)
- Welsh Soil Action Plan (WAG, 2008a)

The relevance of physical SQIs monitoring to the above policy statements is discussed in the Work Package 3 report.

4.3 Evaluation of policy relevance of physical SQIs

As demonstrated in the Work Package 3 report, physical SQIs are highly relevant to a wide range of existing and emergent policy issues of importance. This suggests that the absence of agreed and well-defined SQIs is likely to be a barrier to policy development and its subsequent implementation.

All 7 candidate indicators from WP2 provide useful information about soil conditions but they vary in the ease with which the information can be interpreted. The relationship between physical (and other) SQIs and soil functional performance and how this influences ecosystem services' delivery is complex and important gaps remain in even the realisation of a conceptual model for these inter-relationships let alone their quantification (Figure 13). The underpinning processes for delivery of some ecosystem services are better understood than for others.

It is possible to interpret physical SQIs such as bulk density with provisioning and regulation services. However, it is more difficult to relate qualitative visual soil evaluation with rates of ecosystem service delivery. This suggests that the selection of priority physical SQIs should exclude from a national monitoring scheme those physical SQIs that do not have an established role in the parameterisation of mechanistic models of ecosystem services delivery. Otherwise such SQIs are likely to be ineffective for assessing achievement of soil policy outcomes i.e. changes in the performance of soil as a supporting medium for ecosystem services. On the other hand, this also raises the question of whether individual quantitative SQI can completely be related to ecosystem services, given the number of variables.

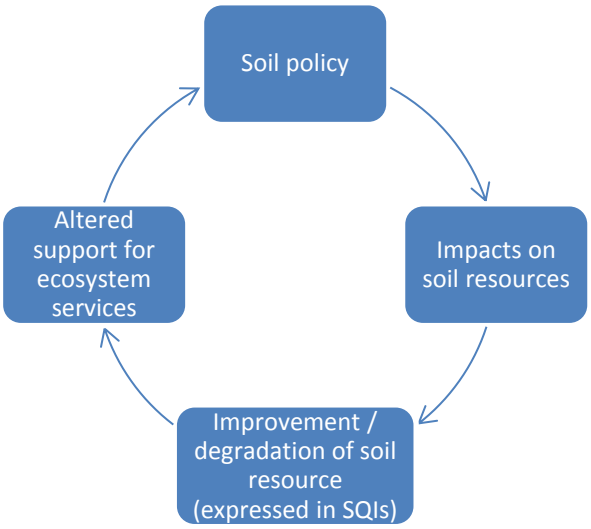

Figure 13. Interaction of soil policy, soil resources and ecosystem services

4.4. Exploring whether physical SQIs could be incorporated into soil monitoring frameworks at the national scale.

In this section, we consider how a soil monitoring programme that includes one or more of the candidate physical SQIs identified in WP2 might be implemented. A number of international monitoring programmes are reviewed in the Work Package 3 report to demonstrate how

physical SQIs are incorporated into national monitoring schemes elsewhere. In the UK a number of monitoring schemes exist (full analysis is given in Work Package 3 report):

- The Countryside Survey
- The National Soil Inventory (NSI)
- Environmental Change Network (ECN; http://www.ecn.ac.uk/)
- Intensive Monitoring of Forest Ecosystems in the UK
- Geochemical Baseline Survey of the Environments (G-BASE)

4.4.1. Choosing a monitoring scheme

How samples are collected will impact on the way in which the information can be used. For example, gridded sampling enables unbiased estimates, while stratified sampling introduce a form of bias because these sites are selected due to an underlying preference. Stratified sampling is often established with a predetermined question in mind, but as a consequence may be a less effective sample design if the question changes in the future. Gridded systems are not established with any predetermined question and therefore are more versatile if the question changes at some future point. The use of gridded sampling is an efficient way to ensure spatial coverage. However, this approach may not be as efficient at sampling extreme values. Stratified sampling may be effective at determining extreme values, as it can be focussed within areas where such values are expected (e.g. erosion monitoring is only targeted at soils / land use combinations known to erode; see Defra project SP1303, Brazier et al., 2012).

The frequency with which samples are collected also varies between monitoring schemes. The most commonly used sampling interval is 5 years although it is recognised that sampling interval will be dependent on the parameter being measured and the size of anticipated, measured or meaningful changes. This relates to the 'signal to noise' ratios for each SQI. This reflects the difficulty in measuring changes in soil status due to the high spatial and temporal variation in rates of change in soil properties. Also, these changes may be out of time with any soil policy change. This presents challenges in ascertaining trends that can feed into policy development or be used to gauge the effectiveness of soil protection policies.

In exploring possible options for monitoring physical SQIs in the future, the following have been considered (See Work Package 3 report for details):

1. Devise a national monitoring scheme based on the physical SQIs discussed in Work Package 2.

The design of a scientifically and statistically robust monitoring scheme, based on power analyses is discussed in the Work Package 2 report. Variability in the data and the magnitude of detectable change in the SQI that reflects a meaningful change in soil function will determine sample size. But these relationships are different for the different candidate SQIs, as reported in the Work Package 2 report. Also, the main hindrance in setting up such a scheme is the uncertainty regarding when the change in the value of the SQI represents a meaningful and significant change in soil function (i.e. the reliability of the SQI). Analysis of the limited data / literature available suggests different SQIs will require different sampling strategies. Also, for any given SQI, the sampling strategy might vary with land use, climate and the soil function in question. It is unlikely that a standardized methodology would be appropriate across contrasting soils and land uses. One approach could be to take the largest sample size suggested by the power analysis, and apply this to all SQIs being considered, which would represent over-design in the rest of the SQIs. Schipper and Sparling (2000) argue that it is not practical to optimize sampling and analytical techniques for each soil and land use for extensive sampling on a national scale. There would be substantial set up, surveying and analytical costs associated with such a scheme too.

2. Add physical SQIs to current suite of SQIs measured in the Countryside Survey (CS).

The Countryside Survey has been carried out at regular intervals since 1978 and includes the measurement and monitoring of a number of SQIs. Bulk density is the only physical SQI included in the dataset currently, but this could be expanded to include texture (% clay content) for estimates of packing density, as well as other point-sampled physical SQIs (i.e.

soil water retention characteristics, aggregate stability, depth, sealing and visual soil evaluation). The justification of this option would include:

- The relatively low cost of making additional measurements as part of an established survey.
- Physical SQIs could be integrated with biological and chemical SQIs already measured at CS sites.
- Data are available from previous surveys to capture changes over time (monitoring)
- According to the Defra Evidence Plan, soil monitoring is currently "aligned with the Countryside Survey but requires further development in order to address specific policy needs. Development of indicators for soil monitoring has been taking place over recent years and the final piece of work needs to be done to design what an enhanced soils package for Countryside Survey would look like. This will need to be done before the next round of Countryside Survey, and in the context of possible developments in the future shape of Countryside Survey."

The drawbacks of this option would include:

- Limited number of sites (629) which may not be sufficient to detect meaningful change in one or more of the physical SQIs (the adequacy of the sample size will depend on a) what a 'meaningful' change is in terms of signal to noise ratio (variability) and b) how a change in any given soil property indicates a change in soil functioning)
- Sampling regime is based on a stratified sample, to ensure that all major land covers and habitat types are represented.
- The survey was not designed to monitor physical SQIs *per se.*
- According to the Defra Soils Evidence Plan (2011b) "any future Countryside Survey would be at risk without funding from Defra and / or the Natural Environmental Research Council (NERC). In addition, the soil component of the survey is dependent on the nature of the survey. For example, the use of non-expert volunteers to collect samples."

3. National Soil Inventory (NSI) resampling

The original NSI represented over 6000 sites on a gridded sampling regime. The justification for resampling any number of these sites would include:

- The national scale coverage is unbiased
- It represents the greatest density of soil survey sites
- The number of sites would enable changes to be detected more reliably than where fewer sites are used.
- The gridded survey means the results can be used whatever the policy question being asked (unlike a stratified survey)
- The gridded survey means resurveying only a subsample of the original 6217 sites would still ensure national coverage
- Data are available from both the original and resurveyed sites to capture changes over time (monitoring)
- Soil data can be linked with additional data held in LandIS, such as Hydrology of Soil Type (HOST), flood vulnerability, runoff risk, soil hydrological information and available water content

The drawbacks of this option would include:

- No planned resampling of NSI
- Gridded sampling may not represent all land use / soil type combinations. It may under- or over-represent some. So, depending on the policy question being asked, resampling may require stratification.
- Costs of resampling
- The survey was not designed to monitor physical SQIs *per se.*

4.5. Conclusion to WP3 - Selection of suitable physical soil quality indicators (SQIs) to be used for soil monitoring in England and Wales

Seven physical SQIs have been identified that can be related to soil processes, soil functions and delivery of ecosystem goods and services. As such, all SQIs have direct relevance to current and likely future soil and environmental policy. However, soil properties are influenced by many factors and it is not usually possible to link particular changes to particular policy activities. The relationship between physical (and other) SQIs and soil functional performance and how this influences ecosystem services' delivery is complex and important gaps remain in even the realisation of a conceptual model for these inter-relationships let alone their quantification. Soil monitoring can be used to determine the overall effectiveness of soils policies in reducing soil degradation, even if it cannot be used to evaluate the effectiveness of individual measures.

Meaningful and detectable changes in physical SQIs may be out of time with any soil policy change. This presents challenges in ascertaining trends that can feed into policy development or be used to gauge the effectiveness of soil protection policies.

Soil monitoring programmes should be tailored to available resources. Whether existing monitoring programmes can be adapted to incorporate additional measurement of physical SQIs should be explored.

5. PROJECT CONCLUSIONS

5.1 The logical sieve approach

The physical SQIs defined by Loveland and Thompson (2002) and subsequently evaluated by Merrington et al. (2006), were revisited in the light of new scientific evidence, SQI selection criteria, sampling techniques and monitoring methodologies. A logical sieve (Ritz et al., 2009) was used as a decision-support tool to identify a prioritised list of potential SQIs, based on a formalised method for assessing the relative strengths, weaknesses and suitability of each indicator for national scale soil monitoring (Black et al., 2008).

The logical sieve is flexible to accommodate the agenda of a range of stakeholders. New challenge criteria (e.g. policy relevance) can be added as they arise. As the output of the logical sieve is determined by the questions being asked of it, and by the weightings (if any) ascribed to different components of the sieve (e.g. the provisioning function is given more importance / weighting than the cultural function), it does not produce an unequivocal and definitive list of meaningful physical SQIs. Whilst this could be seen as a flaw in the approach, it helps demonstrate that there is no one definitive answer to the question "what is a meaningful physical SQI?". As Sojka and Upchurch (1999) point out "It is quite possible that a single, affordable, workable soil quality index is unachievable". Different consensus arises as to which physical SQIs are most appropriate, because of the different definitions of the role and function of the soil system as brought about by multiple users with different agenda.

By emphasising the current key soil functions (i.e. provisioning and regulating), 18 candidate physical SQIs were identified. This list was further reduced to seven SQIs on the basis of the scientific evidence, duplications, overlaps and doubles counting (Table 9). Justification for selecting these SQIs has been restricted to qualitative (narrative) information, or at best, limited empirical data. All can be related to soil processes, soil functions and delivery of ecosystem goods and services and thus have direct relevance to current and likely future soil and environmental policy. Of the seven SQIs, soil depth and surface sealing are regarded by many as indicators of soil quantity rather than quality. VSE is not suited to soil monitoring in the strictest sense, as its semi-qualitative basis cannot be analysed statistically. Bulk/packing density, aggregate stability and soil water retention characteristics can be sampled at a point; rate of erosion requires a larger sampling support.

Table 9. Summary of candidate physical SQIs

Physical SQI	Positives	Limitations
Bulk density / packing density	• Already part of the Minimum Data Set (Robinson et al., 2010) and measured in the Countryside Survey and derived by pedotransfer function in NSI national soil	• Limited monitoring (change) data to date. • Power analysis shows the number of samples needed to

	inventories. • New methodologies (e.g. NIR sensing) show promise for rapid, cost effective measurements. • Pedotransfer functions can be used to estimate packing density from easy to measure soil properties (bulk density, texture and organic C) • As a measure of compaction, links directly with soil degradation process (Thematic Strategy for Soil Protection).	detect a change, but it is not known what change is significant in terms of affecting soil processes and functions. Significant change will vary for different soils / land uses / function.
Soil water retention characteristics	• Soil hydrological relationships are key to soil functioning, especially in water regulation (availability to plants and avoidance of both flooding and drought). • Analysis of available data has given promising results regarding the prediction of values of SQIs from easy to measure soil properties (bulk density, texture and organic C), using pedotransfer functions. These measurements also allow estimates of packing density which is also related to soil hydrological properties (e.g. air capacity; Huber et al., 2008).	• Mechanistic relationships between soil physical properties, soil processes, soil functions and delivery of ecosystem goods and services need development
Rate of erosion	• Defra project SP1303 (Brazier et al., 2012) used power analyses to estimate the number of monitoring locations required to detect a statistically significant change in soil erosion rate on cultivated land in England and Wales. • Links directly with soil degradation process (Thematic Strategy for Soil Protection). Pilot study to be run in Defra project SP1311 (following proposals in Defra project SP1303)	• Tends to be stratified sampling (sites known to be prone to erosion; see SP1303/SP1311) • What constitutes a meaningful change in erosion rates still requires data on the impacts of erosion on soil
Aggregate stability	• Indicates physical, biological and chemical soil quality. • New methodologies (e.g. laser granulometry) show promise for rapid, cost effective measurements.	• Lack of data on spatial and temporal variation at the national scale. • Lack of standard technique although Defra project SP0519 addresses this point. • Analysis of data from various soil types revealed no apparent link with soil processes (runoff, through flow and erosion) and thus soil hydrological behaviour. • Insufficient data on 'meaningful' change in aggregate stability i.e. how a change in that property affects processes and thus functions.
Depth of soil	• Links with soils ability to store and regulate water flow. • Relevance to flood regulation and drought tolerance.	• Indicates soil volume / quantity rather than quality • Requires estimates of bulk density to be meaningful. • Highly variable and significant changes likely only over long time spans
Sealing	• Lends itself to remote sensing i.e. sampling unnecessary. • Policy relevant in terms of land use change	• Indicates soil quantity rather than quality Wood et al. (2004) • few quantified data demonstrating the effect of soil sealing on soil function
Visual Soil Evaluation	• Indicates physical, biological and chemical soil quality	• Semi-quantitative, which challenges suitability for

	• Technique is popular and trusted by many in the soil science community • Some studies have begun to investigate how VSA might be moved to a quantified scale. Some attempts at more detailed quantification of the process show promising results	monitoring. • insufficient quantified evidence for statistical rigour to be applied in determining a sampling strategy

5.2 Data availability and analysis

A robust soil monitoring programme needs to analyse soil data in terms of uncertainty in their measurement; variability (spatially and temporally) in their observed distribution; and the expected rate of change in soil properties that affects soil processes and functions. Whilst a baseline is needed (i.e. the current state of soil), it is the rate of change and the implications of that change in terms of soil functioning that are key to effective soil monitoring. Power analysis was used to understand the variability of indicators as given by observed distributions. This process determines the ability to detect a particular change in the SQI at a particular confidence level, given the 'noise' or variability in the data (i.e. a particular power to detect a change of 'X' at a confidence level of 'Y%' would require 'N' samples).

However, the evidence base is poor: data on the physical SQIs selected by the logical sieve process are limited in spatial and temporal extent for England and Wales. This has limited the degree of analysis and modelling possible. Scientific evidence of 'what is meaningful?' (i.e. what degree of change in the SQI affects soil processes and thus functions) and 'what is detectable?' (i.e. what sample size is needed to detect the meaningful signal from the variability or noise in the signal) is lacking at present. This constrains the design and implementation of a scientifically and statistically rigorous and reliable soil monitoring programme. Evidence that is available suggests that what constitutes meaningful change will depend on soil type, current soil state, land use and the soil function under consideration.

Priority cannot be given amongst the seven SQIs, because the evidence base for each varies in its robustness and extent (although strengths and weaknesses are summarised in Table 9). Lack of data (including uncertainty in measurement and variability in observed distributions) applies to individual SQIs; attempts at integrating more than one SQI to improve associations between soil properties and processes / functions are only likely to propagate errors.

Some technological advances in soil measurements (Work Package 2 report) can be used to expand the evidence base (in space and time) in a rapid, cost-effective manner. This includes the use of NIR sensors to gain measurements of bulk density, texture and packing density. Also, analysis of available data and use of pedotransfer functions has given promising results regarding the prediction of SQI values from relatively easy to measure soil properties (bulk density, texture and organic C).

5.3 Options for a national soil monitoring programme

Establishing a consensus on a set of standard conditions to be used for evaluating soil quality at the national scale is difficult, as soil quality is dependent on the soil's primary function, which is site and time specific (Karlen and Stott, 1994). Schipper and Sparling (2000) recognise the challenge: "a standardised methodology may not be appropriate to apply across contrasting soils and land uses. However, it is not practical to optimise sampling and analytical techniques for each soil and land use for extensive sampling on a national scale". How this dilemma is to be reconciled is beyond the scope of the present project, but does warrant further investigation. Soil monitoring programmes should be adaptable to answer the different requirements of stakeholders (which will evolve over time), ensuring they can make best use of collected data to establish the state of national soil resources. A gridded sampling strategy is preferred to a stratified one, as it allows for future policy (and associated questions) to be accommodated.

The number of samples needed for a statistically robust monitoring programme will depend on the SQI and soil function in question, land use, soil type and other site-specific factors. In other words, a different sampling regime is required for different geographical areas and

different SQIs, if the monitoring is to be statistically robust. Compromises will have to be made to design and implement a rigorous sampling scheme for multiple SQIs.

In terms of monitoring frequency, monitoring cycles tend to be over long time frames (5 – 15 years apart; Defra, 2011b).This reflects the difficulty in measuring changes in soil status due to the high spatial and temporal variation in rates of change in soil properties; changes occur either very rapidly or very slowly, so again a standardised monitoring methodology may not be appropriate. Soil properties are influenced by many factors and it is not usually possible to link particular changes to particular policy activities, not least because physical changes may not be at a rate that is synchronised with developments in soil / environmental policy. Soil monitoring can be used to determine the overall effectiveness of soils policies in reducing soil degradation, even if it cannot be used to evaluate the effectiveness of individual measures. This presents challenges in ascertaining trends that can feed into policy development or be used to gauge the effectiveness of soil protection policies.

Whether existing monitoring programmes can be adapted to incorporate additional measurement of physical SQIs should be explored. This would include whether the existing proposed sampling support would be sufficient to detect meaningful change in the SQI. As noted above, lack of data means there is uncertainty as to the definition of 'meaningful change'. The challenge is also to decide whether carrying out soil monitoring that is not statistically robust is still valuable in answering questions regarding current and future soil quality.

5.4 Future work

The relationship between physical (and other) SQIs and soil functional performance and how this influences ecosystem services' delivery is complex. Important gaps remain, even in the realisation of a conceptual model for these inter-relationships, let alone their quantification. Better understanding of the mechanisms involved is required. This will include investigating integrative physical, biological and chemical SQIs (e.g. as manifest in aggregate stability and VSE) and how these properties (and changes in them) reflect soil processes and functions.

The scientific robustness of physical SQIs depends on the availability of spatial and temporal data, as these reflect the variability of each property (signal to noise ratio), which in turn determines the sampling strategy required to detect significant change. Whether that change is meaningful depends on the evidence relating soil properties to soil processes and soil functions. The evidence base is poor: data on meaningful (i.e. what degree of change affects soil processes and functions) and detectable (i.e. what sample size is needed to detect the meaningful signal from the variability or noise in the signal) changes, and the extent to which these will vary for different soil types, land covers and soil functions are lacking at present. This constrains the proposal of a rigorous and reliable soil monitoring programme. New methodologies (e.g. NIR sensing or in-situ soil properties; laser granulometry for aggregate stability testing) show promise for rapid, cost effective measurements.

At present there is insufficient quantified evidence for statistical rigour to be applied in determining a sampling strategy for VSE. Some studies have begun to investigate how VSE might be moved to a more detailed, quantified scale to improve the reliability and robustness of this method of soil quality evaluation.

Soil monitoring programmes should be tailored to available resources. Whether existing monitoring programmes can be adapted to incorporate additional measurements of physical SQIs should be explored further. Detailed analysis of existing data has given promising results regarding the prediction of values of SQIs from easy to measure soil properties (bulk density, texture and organic C), using pedotransfer functions. However, what constitutes a meaningful change in each SQI still requires further investigation.

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