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Supplementary material for this article is available [online](#)

## Abstract

Soil is the most important natural resource for life on Earth after water. Given its fundamental role in sustaining the human population, both the availability and quality of soil must be managed sustainably and protected. To ensure sustainable management we need to understand the intrinsic functional capacity of different soils across Europe and how it changes over time. Soil monitoring is needed to support evidence-based policies to incentivise sustainable soil management. To this aim, we assessed which soil attributes can be used as potential indicators of five soil functions; (1) primary production, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) soil biodiversity and habitat provisioning and (5) recycling of nutrients. We compared this list of attributes to existing national (regional) and EU-wide soil monitoring networks. The overall picture highlighted a clearly unbalanced dataset, in which predominantly chemical soil parameters were included, and soil biological and physical attributes were severely under represented. Methods applied across countries for indicators also varied. At a European scale, the LUCAS-soil survey was evaluated and again confirmed a lack of important soil biological parameters, such as C mineralisation rate, microbial biomass and earthworm community, and soil physical measures such as bulk density. In summary, no current national or European monitoring system exists which has the capacity to quantify the five soil functions and therefore evaluate multi-functional capacity of a soil and in many countries no data exists at all. This paper calls for the addition of soil biological and some physical parameters within the LUCAS-soil survey at European scale and for further development of national soil monitoring schemes.

## 1. Introduction

### 1.1. Policy drivers for soil protection

Soil is a natural resource which is essential for human existence on our planet. Given its fundamental role, both the availability and quality of soils must be managed sustainably. The need for legal measures in soil protection was recognised already in the 19th century, when the first national laws explicitly mentioning soil protection were adopted in Europe (Hungarian National Assembly 1879, Hungarian National Assembly 1894). Both the scientific understanding of the functions supplied by the soil system, as well as society's appreciation of soil-based ecosystem services, have evolved since (Keesstra *et al* 2016).

At EU-level, the European Commission remains committed to the objective of soil protection through the EU Soil Thematic Strategy and the 7th Environment Action Programme (Publications Office of the European Union 2013) with the objectives that by 2020 'land is managed sustainably in the Union, soil is adequately protected and the remediation of contaminated sites is well underway'. Member States (MSs) are urged to 'increase efforts to reduce soil erosion and increase organic matter content, to remediate contaminated sites and to enhance the integration of land use aspects into a coordinated decision-making framework, involving all relevant levels of government, supported by the adoption of targets on soil and on land as a resource'.

Environmental policies in the area of water, climate change, biodiversity and chemicals are equally relevant to protecting, preserving or improving soil functions. Both the 2030 Climate and Energy Framework (EC 2014) and the COP21 Paris agreement (specifically the 4/1000 initiative) (UN 2015), highlight the importance of enhancing the carbon sequestration potential of soils (particularly agricultural soil). The EU Biodiversity Strategy encourages MSs to map ecosystems and their services, including the role played by soils by 2020 (EC 2011).

Soil protection is increasingly seen as an important element also in other EU policy sectors. The recent review by Vrebos *et al* (2017) clearly shows that EU policies influence soil functions both directly and indirectly. This has been taken into account in the soil pilot of the Mapping and Assessing of Ecosystem Services (MAES) project (MAES Soil pilot 2016).

### 1.2. Soil multi-functionality

As the interface between the mineral and biosphere, water and air, the soil performs many vital ecosystem functions. The five overarching functions which we consider in this paper, following many other studies (e.g. Schulte *et al* 2014), are: 1. Production of food, feed, fibre and (bio) fuel; 2. Water purification and regulation; 3. Carbon sequestration and climate regulation; 4. Soil biodiversity and habitat provision; 5. Recycling

of (external) nutrients/agro-chemicals. These ecosystem functions have been termed soil functions (SFs) by several authors (EC 2006, Ritz *et al* 2009, Schulte *et al* 2014), and they can be adopted in assessments of ecosystem services of soils (Dominati *et al* 2010, Rutgers *et al* 2012, Robinson *et al* 2014). With increasing scarcity of our land (Banwart 2011), we require that most soils deliver more than one SF in any given time and space. Soils indeed have the capacity to deliver several of these SFs in tandem, but based upon the landscape in which the soil is found and therefore the intrinsic soil properties, combined with management of the soil, the delivery of these functions may vary.

### 1.3. Current extent of soil monitoring networks

To understand the potential of our soils to deliver these soil functions and enable the formation of evidence-based policies to incentivise sustainable soil management, it is essential to monitor the variation in the capacity of different soils across Europe to provide the five major functions and how that changes over time. Soil monitoring is the systematic determination of soil properties that can detect and record spatial and temporal changes (FAO/ECE 1994) and a soil monitoring network (SMN) is a set of sites/areas where this periodic assessment is carried out and documented (Morvan *et al* 2008). Monitoring of the soil resources has been implemented to facilitate the effective management of the soil and to support the delivery of the multiple soil functions. The focus of a SMN is on soil features that can be readily measured and can be used to detect changes over time. Previous research has already reviewed existing SMNs in Europe for assessing soil quality through the assessment of a minimum set of attributes, e.g. in the ENVASSO project for soil threats (Morvan *et al* 2008) and the Forest Soil Condition Database, which include physicochemical and hydraulic properties for forest tier II sites only across Europe (Fleck *et al* 2016). They indicated that the suitability of existing sites for monitoring relies on two factors: firstly, existing sites must have GPS locational accuracy and site georeferencing relevant to the scale of the sampling method and secondly, at least two (preferably more) measuring campaigns must have been conducted at the site or planned for the near future. Surveys or inventories that are measured only once can also be taken as a starting point towards soil monitoring, and are therefore also considered in this paper. Although Morvan *et al* (2008) provide a clear overview of available SMNs throughout Europe, they only provided sampling density for a very limited set of attributes.

### 1.4. EU-wide soil monitoring network

In addition to national SMNs, an EU-wide monitoring effort is undertaken by the statistical office of the European Union (Eurostat). Eurostat undertakes a regular survey to monitor the situation of land use, land cover and changes over time across the

European Union (EU). This survey is known as Land Use and Coverage Area frame Survey (LUCAS) (Eurostat 2012). In 2006, the interval of the survey was fixed to three years. Since 2008, the legal basis for LUCAS has been provided through its inclusion in Eurostat's annual and multi-annual work program and budget. The sampling is based on a regular grid across the EU defined as the intersection points of a  $2 \times 2$  km grid covering the territory of the EU, resulting in around 1 000 000 georeferenced points. Each point has been classified in accordance with seven land cover classes using orthophotos or satellite images. Of these points, approximately 270 000 points are visited in the field by surveyors to assess the validity of the remote sensing observations and to collect additional information that cannot be assessed remotely.

In 2009, the scope of the survey was extended by including a topsoil component (i.e. the uppermost 20 cm of soil). The aim of the LUCAS soil component was to create a harmonised and comparable dataset of physical and chemical properties of topsoil across the EU to monitor the impact of land related policies on soil condition and to support new policy development (Tóth *et al* 2013). The soil component is carried out on approximately 10% of the visited points (c. 27 000 samples). The latest LUCAS survey was carried out between March and October 2015 where surveyors visited a total of 273 401 points (again soil sampling was only carried out at 10% of the sites). Additionally, soil samples were collected from Albania, Bosnia-Herzegovina, Croatia, former Yugoslav Republic of Macedonia, Montenegro and Serbia while Switzerland also decided to collect soil samples according to the LUCAS methodology and sampling protocols in order to make their national soil monitoring programme concurrent and compliant with that of the EU. A next survey for 2018 ( $n=1000$ , with 100 grassland sites where also vegetation diversity will be sampled) is currently being planned with a view to include analysis of soil biodiversity, bulk density, organic pollutants and depth of peat (Fernández-Ugalde *et al* 2016). This wealth of data becomes available to support assessments of the state and trends of soil functions. A few examples of the analyses of the large LUCAS dataset are already published (Tóth *et al* 2014, Ballabio *et al* 2016, Tóth *et al* 2016), but these analyses are so far limited to the trends in soil properties. The next step forward should be focused on the trends in the provision of soil functions instead of looking at the measured basic soil attributes.

To analyse the gap in soil function assessment within SMNs, this paper first provides an assessment of soil attributes which can be used as potential indicators of five soil functions (primary production, water purification and regulation, carbon sequestration and climate regulation, habitat for biodiversity and recycling of nutrients). Secondly, we assessed to which extent these attributes are included in existing soil monitoring schemes, soil surveys and large scale/detailed agricultural studies at country level across Europe. We also

discuss the need for spatial and methodological harmonisation to assure reliable comparisons of data and suggest potential solutions for European scale monitoring of soil functions for future application.

## 2. Materials and methods

### 2.1. Attribute selection for soil monitoring

In an effort to quantify five SFs (primary production, water purification and regulation, carbon sequestration and climate regulation, habitat for biodiversity and recycling of nutrients (Schulte *et al* 2014)), we created a model which defines the contribution of various soil attributes to the delivery and capacity of a specific SF (figure 1). The attributes provide the key data to facilitate the quantification of the SFs. Hence they do not necessarily represent mechanistic links; plausible or statistical links are also considered. A soil attribute can be described as a characteristic or set of characteristics of the soil, which can be measured, estimated, or modelled. Subsequently, this information can be used to quantify the performance of a SF.

This framework was first tested for all SFs by the EU Horizon 2020 funded 'LAND Management: Assessment, Research, Knowledge base (LANDMARK)' project consortium. Potential attributes were listed, for which data, expert judgements or models could be collected, albeit not always at the scale of Europe. Linking information to a SF was further supported by creating the possibility to aggregate several attributes together and subsequently making the link to the soil function more tangible. It must be stressed that the procedure was primarily developed to derive transparent and traceable weighting factors for the soil attributes to be used in a model for quantification of SFs individually. As a default four integrated attributes were defined, i.e.:

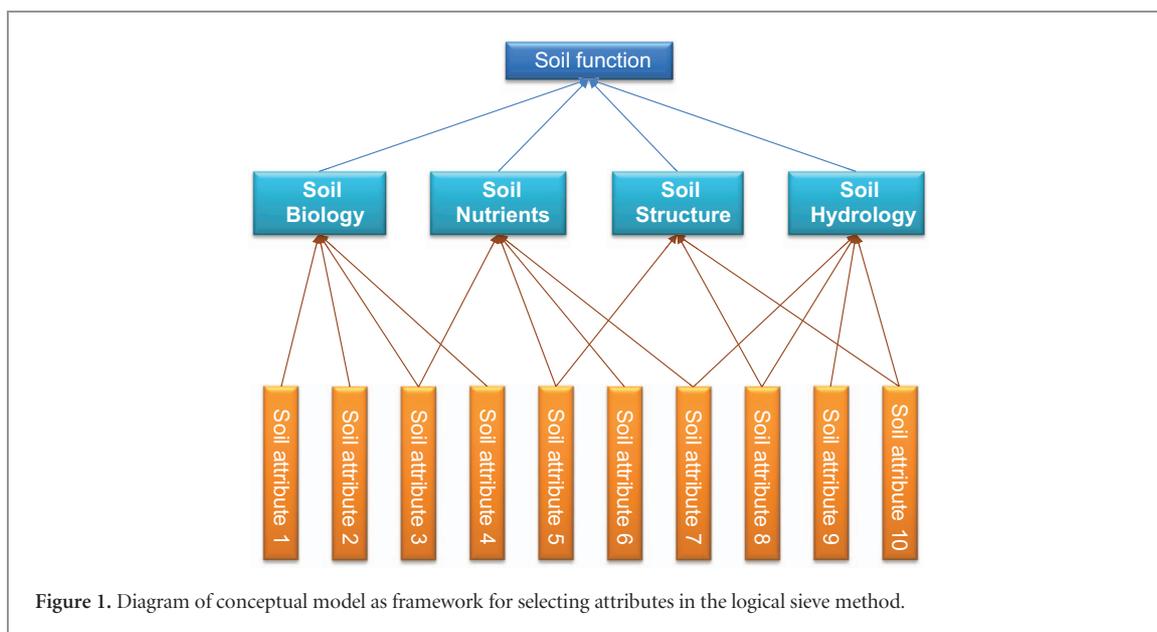
Soil biology: Information on the diversity, biomass and activity of soil organisms.

Soil nutrients: Status, trends, turnover, and availability of nutrients for plants and soil organisms (C, N, P, K, with extensions to micronutrients).

Soil structure: All information on soil structure and density, ranging from mesoscale (coarse fractions, soil particles, organic matter, air and water-filled space) to macroscale (soil layers, terrain, slope).

Soil hydrology: All processes and elements that contain information on the hydrological status of the soil, such as humidity and the flows of water.

The created set of potential attributes consisted of both single and some aggregated attributes, and many of these attributes contain important information for all five SFs. Note that each of the (aggregated) attributes can be quantified by a suite of methods, but the assessment of ways to harmonise these methods is beyond the scope of this paper. We adopted the 'logical sieve-method' described by Ritz *et al* (2009) to rank the attributes on perceived importance.



A questionnaire (appendix A available at [stacks.iop.org/ERL/12/124007/mmedia](http://stacks.iop.org/ERL/12/124007/mmedia)) was sent out to all Landmark consortium members, which cover a wide array of disciplines (including pedology, soil biology, soil chemistry, agronomy, botany), following the protocol set by Ritz *et al* (2009). In total 33 attributes, selected by the Landmark consortium members were scored on relevance and sensitivity towards four integrated attributes (biology, nutrients, structure and hydrology) for each of the five SFs separately. The integrated attributes aided in steering the usability of the information provided by the attributes towards the SFs. A weighting factor for each of these integrated attributes towards the SFs was also included in the questionnaire. The sum of the weighting factors for the integrated attributes is always one. By default (equal weights) the scores are 0.25 for each integrated attributes. If one attribute was judged as more important than another, the weight for that factor was increased (e.g. to 0.5) at the cost of the weights of (one of) the other 3 integrated attributes. Attribute **relevance** (i.e. how important is the information held by an attribute for the assessment of a SF) was scored from 0: not relevant, to 5: highly relevant, whereas attribute **sensitivity** (i.e. how easily the value of an attribute changes) was scored as 0: not sensitive, 1: sensitive to climate, 2: sensitive to land use, 3: sensitive to soil type, 4: sensitive to disturbance with significant stress, 5: sensitive to disturbance with little stress. Relevance/sensitivity was only left unscored if the relevance or sensitivity of an attribute was unknown by the respondent. The scores for relevance and sensitivity of the attributes for each integrated attribute and the weighting factor of the importance of the integrated attributes for each SF were used to calculate a score for the attributes for each SF using the formula (equation 1):

$$X = \sum \frac{R + S}{2} W \quad (1)$$

in which  $X$  = score for the attribute for the specific soil function,  $R$  = relevance value of attribute to the integrated attributes,  $S$  = sensitivity value attribute to the integrated attributes and  $W$  = weighting factor of the importance of the integrated attributes for each SF (fraction; sum of weighing factors for each SF is 1) of the integrated attribute to the soil function. Using the scores of the attributes for the separate soil functions, a final weighted score ( $F$ , equation 2) was calculated as

$$F = \frac{\Pi(X)}{n} \quad (2)$$

in which  $\Pi(X)$  is the product of the scores of the attribute over all SFs for which it was scored and  $n$  represents the number of SFs for which the attribute was scored. Multiple approaches are possible for calculating a final score, for example taking the average of the scores for the individual SFs as final score. But doing so, the number of SFs the attribute is scored for is not taken into account. Reversely, by taking the sum or product of the individual scores, the final score depends too much on the number of studies it's scored for, and attributes that score high for only one or two SFs are ranked very low. Hence, we used an intermediate method, by applying the product of the scores for each SF and subsequently dividing by the number of SF it was scored for, emphasizing attributes that both scored high for many SFs, as well as attributes that scored high for only one or two SFs. Based on these scores the attributes were ranked and this ranking can be used to select attributes for inclusion in a SMN. The number of attributes included in a SMN can then be based on for example the necessary information resolution or available budget. The procedure of calculating final scores was made as simple as possible, to avoid a false sense of precision based on the rough scoring from the questionnaires.

**Table 1.** Top 30 of soil attributes resulting from the logical sieve. Presented are the scores from the logical sieve per soil function, and the final scores on which the attributes were ranked. In bold the three highest scores per soil function.

Attribute/SF	Primary productivity	Water regulation	C sequestration	Biodiversity	Nutrient cycling	Final score
Organic C/N/P/K	<b>2.89</b>	<b>3.47</b>	<b>2.88</b>	3.24	<b>3.42</b>	64.2
pH	2.38	2.57	2.66	3.14	<b>3.31</b>	33.7
Bulk density	<b>2.62</b>	3.20	2.69	2.70	2.63	31.9
C:N ratio	2.25	2.36	2.63	2.58	<b>3.13</b>	22.5
C mineralisation rate	2.12	2.36	3.01	2.62	2.80	22.1
Texture	2.55	2.49	2.49	3.13	2.18	21.6
Rooting depth	2.00	2.57	2.47	2.97	2.72	20.5
Microbial biomass	2.31	2.47	<b>3.47</b>	<b>3.40</b>		16.8
Drainage class	2.26	<b>3.54</b>	2.74	2.50		13.7
Soil temperature	1.90	2.04	2.21	2.43	2.59	10.8
Salinity	2.07	1.97	1.94	2.19	2.52	8.74
CEC	1.72	2.08	2.12	2.18	2.37	7.87
WHC	2.37	2.09	2.45	2.22		6.76
Groundwater table	1.84	2.42	2.27		2.54	6.42
Fe/Al	1.58	1.94	2.18	1.97	2.40	6.31
Earthworm community		3.23	1.64	<b>3.49</b>		6.16
Clay mineralogy	1.92	1.73	2.62	2.73		5.95
Soil slope	1.62	2.41	2.12	2.06		4.27
Bacterial community				<b>3.46</b>		3.46
Soil moisture	<b>2.78</b>		2.42			3.37
Microarthropod community				3.21		3.21
Fungal community				3.19		3.19
Top-layer infiltration capacity					3.11	3.11
Air-filled porosity					2.99	2.99
Field capacity days					2.96	2.96
Nematode community				2.96		2.96
Wilting point days					2.85	2.85
Enchytraeid community				2.75		2.75
Soil frost days	1.76	1.55	2.01	1.98		2.70
Redox state					2.60	2.60

## 2.2. Assessment of current soil monitoring networks

After establishing the ranked list of attributes we investigated the incorporation of these attributes in existing monitoring schemes throughout Europe. A standard Excel spreadsheet was sent to Landmark consortium members and contacts from 18 European countries requesting detailed information on national SMNs (including long-term field experiments and extensive soil surveys), their sampling designs, measured parameters and analytical methods. For a number of countries no SMNs existed (Greece, Spain), or we were not able to get information on these.

## 3. Results

### 3.1. Attribute selection for soil monitoring

For the questionnaires we sent out to provide scores for relevance and sensitivity of the selected attributes, we received 37 responses by 17 individual experts, i.e. experts were asked to fill in questionnaires for more than one soil function in case they judged their expertise as meaningful. The majority of selected attributes was scored for all SFs, whereas for some SFs additional attributes were listed and scored (table 1). Organic C/N/P/K was given high scores for all SFs, which is shown by the high individual scores and in the resulting highest final score. Also pH and bulk density were judged as highly relevant and sensitive attributes to quantify soil functions. Low scores were given to soil frost days, soil slope and clay mineralogy, whereas a number of attributes such as bacterial community, and

top layer infiltration capacity received only high scores for respectively biodiversity and nutrient cycling, and thereby ended up lower in the combined ranking.

### 3.2. Current extent of soil monitoring networks

After establishing the list of attributes we investigated the incorporation of measuring these attributes in existing monitoring schemes throughout Europe. We received input by contacts from 18 European countries with detailed information on national SMNs (including long-term field experiments and extensive soil surveys), their sampling designs, measured parameters and analytical methods (table 2). For a number of countries no SMNs existed (Greece, Spain), or we were not able to get information on these.

For each of the countries analysed, the density of monitoring sites was plotted for each of the attributes and presented for biological attributes (figure 2), chemical attributes (figure 3) and soil physical attributes (figure 4). Although the results of the assessment are spatially incomplete, they still provide sufficient overview of the supply of monitoring schemes at the scale of Europe. Some of the highly ranked attributes in table 1 are measured regularly in many SMNs, such as organic C, pH, texture, whereas only a few SMNs include a wide range of biological, chemical and physical soil attributes. Within the biological attributes, only organic C content was measured regularly (but only in the topsoil in many cases), while the other attributes were generally heavily underrepresented. Within the list of chemical attributes, contents of N, P and K were

**Table 2.** Existing soil monitoring schemes in European countries.

Country	Start year of monitoring campaign	National sampling strategy		Description of the site					Site sampling strategy		Reference
		Type*	Number of monitoring sites	Vegetation	Geology (parent material)	Slope	Exposure	Fixed depth/pedological horizon	Depth of sampling	Replicates/composites	
Austria	1986	2	10000	yes	yes	yes	yes	fixed depth	various,	composite	(BORIS 2014)
Southern Belgium	2004	2	850	yes	yes	yes	yes	fixed depth	0–20 cm	composite	(Colinet <i>et al</i> 2016)
Southern Belgium	2014	5	120	yes	yes	yes	yes	fixed depth	Various	both	(Colinet 2017)
Southern Belgium	2015	1	120	yes	no	no	no	fixed depth	0–20 cm	composite	NA
Bulgaria	2003	2	10	yes	yes	yes	yes	fixed depth	60–80 cm	composite	(Dinev <i>et al</i> 2008)
Bulgaria	2005	2	397	no	yes	no	no	fixed depth	–	replicate	NA
Switzerland	1985*	3	112	yes	yes	yes	yes	fixed depth & horizons	various	composite	(Gubler <i>et al</i> 2015)
Germany	1985	2	789	yes	yes	yes	yes	horizon	0–30 cm	composite	(Kaufmann-Boll <i>et al</i> 2012)
Germany	2010*	2	3200	yes	yes	yes	yes	fixed depth	0–100 cm	composite	(Kaufmann-Boll <i>et al</i> 2012)
Germany	various	2	45	yes	yes	yes	yes	–	–	–	(Lanthaler 2008)
Germany	1961	2	500	no	no	no	no	fixed depth	0–100 cm	–	(Kaufmann-Boll <i>et al</i> 2012)
France	2000	2	2240	yes	yes	yes	no	fixed depth	0–50 cm	composite	(Arrouays <i>et al</i> 2002)
France	1991	5	19	yes	yes	yes	yes	horizon + fixed depth	soil profile + 0–15 cm	individual + composite	(Nicolai <i>et al</i> 2016)
France	2000	5	8	yes	yes	yes	yes	horizon + fixed depth	soil profile + 0–15 cm	individual + composite	(Stone <i>et al</i> 2016)
France	2010	2	13	yes	yes	yes	yes	horizon + fixed depth	soil profile + 0–15 cm	individual + composite	(Pères <i>et al</i> 2011)
GB	2007	4	2955	yes	yes	yes	no	fixed depth	0–15 cm	individual	(Emmet <i>et al</i> 2010)
GB	1971	4	1648	yes	no	yes	no	fixed depth	0–15 cm	individual	(Wood <i>et al</i> 2015)
Hungary	1992	3	1236	yes	yes	yes	yes	fix depth	0–90 cm	composite	(Várallyay 2009)
Iceland	2007	2	600+	yes	no	yes	yes	fixed depth	0–30 cm	?	(Hellsing <i>et al</i> 2016)
Iceland	2005	1	1000	yes	yes	yes	yes	horizon	0–30 cm	?	(Snorrason 2010)
Iceland	1999	4	1106	yes	no	yes	no	fixed depth	0–10 cm	composite	(Magnússon <i>et al</i> 2009)
Iceland	2001	4/3	158	yes	no	no	no	fixed depth	0–10 cm	composite	(Elmarsdóttir 2009)
Ireland	1995	2	1310	no	no	no	no	fixed depth	0–10 cm	composite	(Fay <i>et al</i> 2007)
Ireland	2012	2	227	yes	yes	yes	yes	horizon	>80 cm	individual	(Creamer <i>et al</i> 2014)
Ireland	2015	2	40	yes	yes	yes	yes	horizon	>80 cm	composite	(Teagasc 2017)
Ireland	2006	5	61	yes	yes	yes	no	fixed depth	0–25 cm	composite	(Schmidt 2015)
Italy	1986	7	14	yes	no	no	no	fixed depth	0–60 cm	replicates	(Mazzoncini <i>et al</i> 2016)
Italy	1993	7	256	yes	no	no	no	fixed depth	0–60 cm	replicates	(Sapkota <i>et al</i> 2012)
Italy	2001	7	175	yes	no	no	no	fixed depth	various	replicates	(Mazzoncini <i>et al</i> 2010)
Netherlands	1993	4	~300	yes	no	no	no	fixed depth	0–10/0–20 cm	composite	(Rutgers <i>et al</i> 2009)
Netherlands	1984–2004	1	1,387,000	no	yes	no	no	fixed depth	various	composite	(Reijneveld <i>et al</i> 2009)
Netherlands	1984–2004	1	>280,000	no	yes	no	no	fixed depth	various	composite	(Reijneveld <i>et al</i> 2010)
Portugal	2015	3	100	yes	no	no	no	fixed depth	0–10 cm	replicates	NA
Scotland	1978–88	2	195 (183 with soil)	yes	yes	yes	yes	horizon	>80 cm	individual	(Chapman <i>et al</i> 2013)
Slovenia	1989–2007	2	422	yes	yes	yes	yes	fixed depth	0–30 cm	composite	(Zupan <i>et al</i> 2008)
Sweden	1995	4	2034	yes	no	no	no	fixed	0–20, 40–60 cm	composite	(Eriksson <i>et al</i> 2010)

Types of sampling: 1: random sampling, 2: systematic sampling, 3: judgmental sampling, 4: stratified pattern with random sampling, 5: stratified pattern with systematic sampling, 6: stratified pattern with directed sampling, 7: nested pattern with random sampling, 8: nested pattern with systematic sampling. Reports for SMNs in Belgium and Portugal not yet available.



regularly measured, as well as soil pH. Within physical attributes only soil texture showed a high sampling density in many SMNs. In addition to the monitoring density of individual attributes, we also looked at the total number of attributes measured per category (biological, chemical, physical) within the participating countries (figure 5). Chemical aspects are well covered, whereas biological and physical aspects need a higher sampling resolution for proper representation of the soil functions.

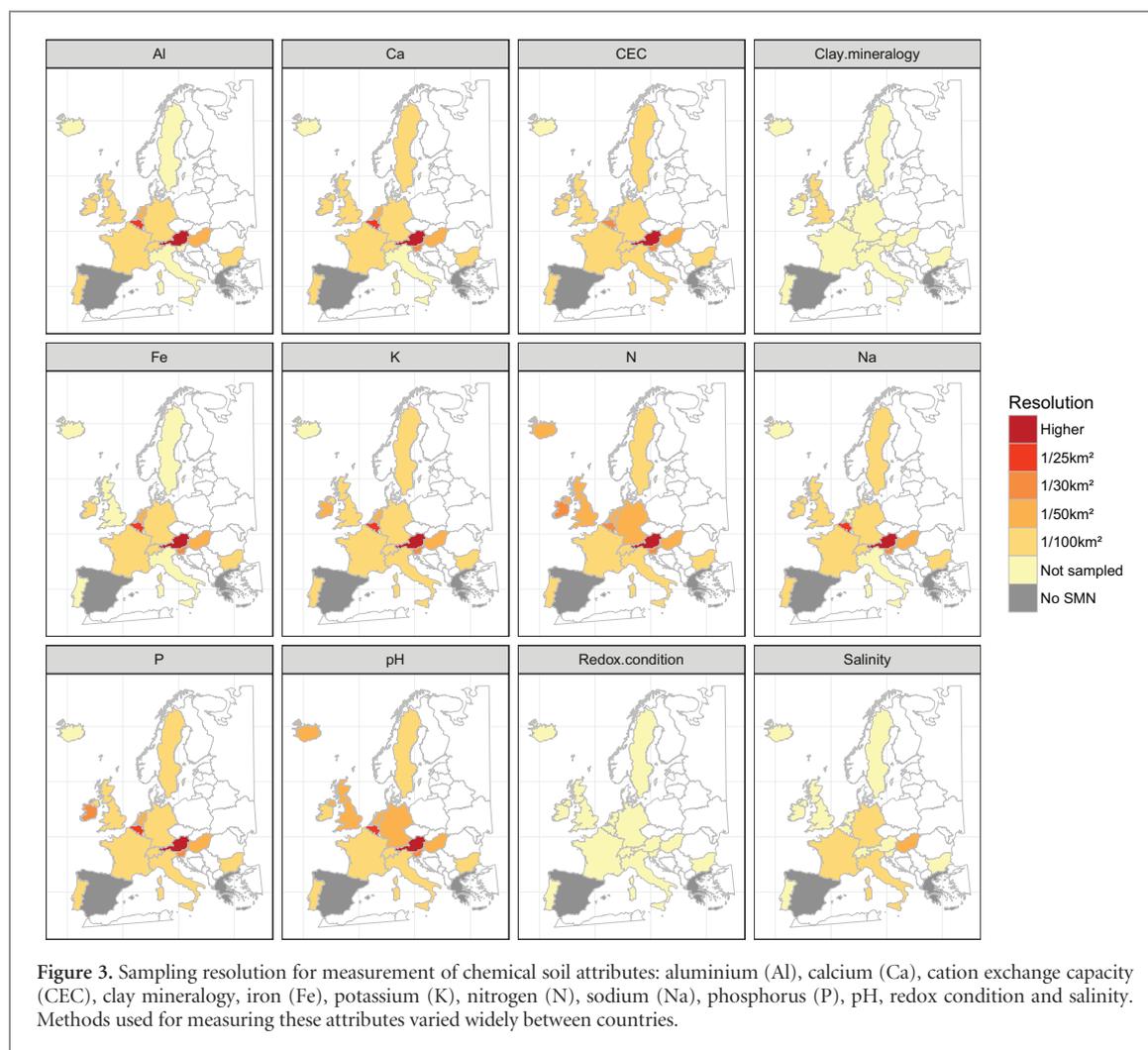
An important point that emerges when comparing the various SMNs in table 2 and figures 2–5 is the large variation between SMNs in number of sites, site selection and included attributes, showing a clear lack of harmonisation between SMNs.

The comparison of the national SMNs also clearly indicated the lack of harmonisation (sometimes even between different SMNs within the same country) in

the methods used to measure the specific attributes (appendices B, C, D). For example, a well-known basic attribute such as pH is measured in various ways, including in KCl or CaCl<sub>2</sub> solution or in water, providing values that are difficult to compare. The same applied for a number of other attributes, including (but not limited to) organic carbon content, phosphorus content, texture and bacterial and fungal biomass.

#### 4. Discussion

To manage the potential of our soils to deliver soil functions at different spatial scales and assess the impact of current and upcoming EU Directives and Regulations, we need to monitor the delivery of these functions. To this aim, we assessed which soil attributes can be used as potential attributes of the five soil functions



(primary production, water purification and regulation, carbon sequestration and climate regulation, soil biodiversity and habitat provisioning, and recycling of nutrients) and linked the list of attributes to the existing national and EU-wide soil monitoring networks. This revealed the extent to which these attributes are currently measured. The overall picture highlighted a clearly unbalanced dataset, in which predominantly chemical soil parameters were included, and soil biological and physical attributes were severely underrepresented. In addition, even when specific attributes, such as pH or P content, were measured in several national SMNs, a wide range of different methods is being used, limiting the comparability. Harmonisation of soil sampling and analyses in the countries across Europe is therefore a key feature of a coordinated EU-wide SMN. We therefore also assessed the potential of an EU-wide soil monitoring network such as the LUCAS survey for monitoring the provision of soil functions.

#### 4.1. Suitability LUCAS survey for monitoring soil functions

When comparing the attributes measured in the national SMNs, and particularly the methods used to assess these attributes in the set of SMNs, a clear lack

of harmonisation emerges. Combined analysis of data from different datasets/countries is thereby very challenging. One of the clear advantages of data generated by EU-wide monitoring of soil in comparison with the national SMNs is the central organisation, and the creation of a harmonised methodology (in which the soil analysis is carried out by a single laboratory). However, in the current LUCAS-soil survey prioritisation has been given to chemical-physical measures such as C, N, P, K, pH and texture (similar to many of the national SMNs). The main limitation of the current, and previous sampling rounds in the LUCAS survey when it comes to the relation of the measurements with soil functions (table 1), is the lack of important biological soil parameters included in the sampling, such as C mineralisation rate, microbial biomass and earthworm community, but also bulk density. Hence, quantifying the five soil functions at the same time and in the same location, which is needed from the perspective of soil multi-functionality, requires additional parameters to be included in the sampling design. Another point of concern is the current limitation to sampling the topsoil, as it has been shown that subsoils cannot be neglected for all soil functions, especially for the function of carbon sequestration and climate regulation (Torres-Sallan *et al* 2017). However, these concerns are

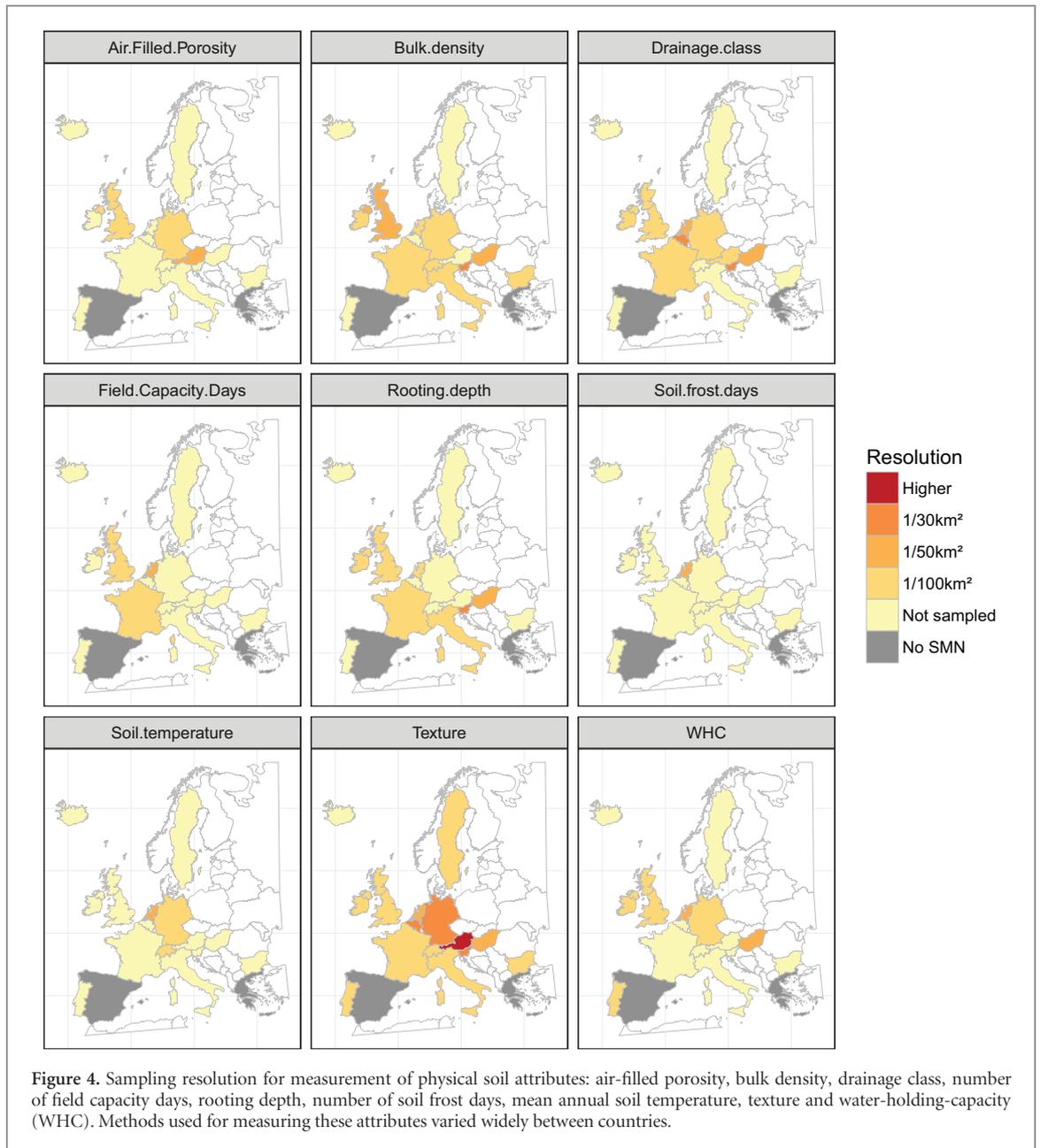


Figure 4. Sampling resolution for measurement of physical soil attributes: air-filled porosity, bulk density, drainage class, number of field capacity days, rooting depth, number of soil frost days, mean annual soil temperature, texture and water-holding-capacity (WHC). Methods used for measuring these attributes varied widely between countries.

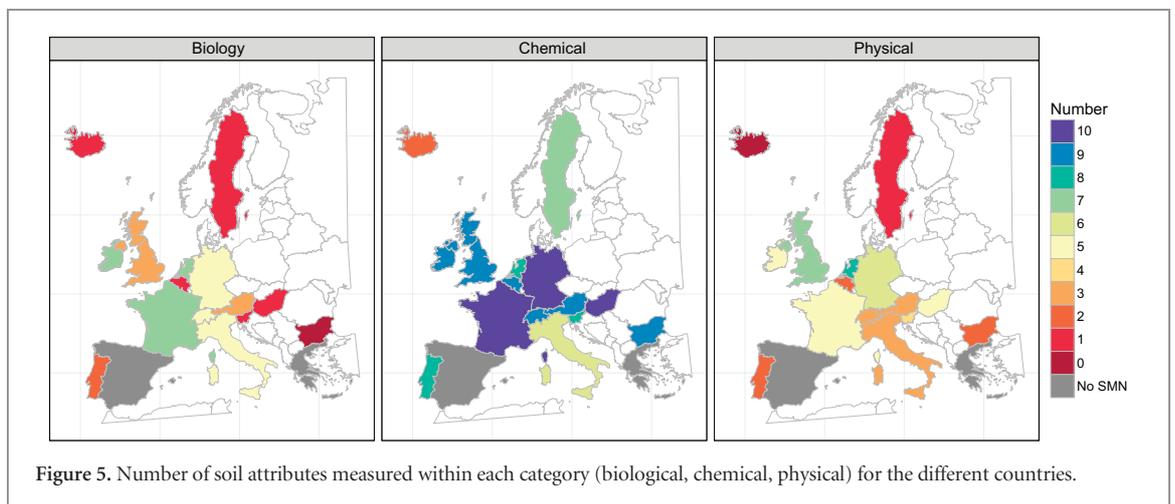


Figure 5. Number of soil attributes measured within each category (biological, chemical, physical) for the different countries.

taken into account for the next survey in 2018, thereby strengthening the usability of the database for the monitoring of soil functions impacted by current and future EU policies.

#### 4.2. Sampling resolution for EU-wide of monitoring soil functions

When implementing a SMN for monitoring soil functions at a larger spatial scale, one of the most important decisions to be made is the spatial resolution at which the SMN should be laid out. Earlier estimates yielded a suitable sampling grid of  $16 \times 16$  km for soil monitoring studies in Ireland (O'Sullivan *et al* 2017) and France (Arrouays *et al* 2002). The issues that are presented on the scale of Ireland and France, are certainly also important when considering EU-wide soil monitoring, to allow for both national and European use of the monitoring network. Also the ENVASSO project (Morvan *et al* 2008) and the recent review of Arrouays *et al* (2012) pointed out that a  $16 \times 16$  km grid delivers a good resolution to be representative for soil type/land cover combinations at the European scale. However, this only applies when the area is covered by a homogenous land use and soil type. In the French SMN (RMQS), this problem was circumvented by only sampling sites representative for the dominant soil type/land use combination for the specific grid cell (Arrouays *et al* 2002), but this is not representative for the variation within the grid cells. In the stratified Dutch SMN (BISQ) the focus was on the farm level in which only farms covering a single soil type were included (Rutgers *et al* 2009), thereby covering all dominant soil type/land use combinations. Currently in the 2015 sampling round, the LUCAS soil data collection is working on a resolution of 27 000 sites at nearly 4.5 million km<sup>2</sup>, yielding a resolution of approximately 166 km<sup>2</sup>. As this more dense than the estimated minimal  $16 \times 16$  km grid size based on the Irish SMN recommendations, the LUCAS monitoring network is certainly sufficiently dense for quantification of soil functions, but only if the sampling points are located homogeneously and representatively throughout the biogeographical zones in the EU.

### 5. Conclusions

To manage the potential of our soils to deliver soil functions at different spatial scales, including a European scale, and the impact of current and upcoming policy documents, we need to monitor the delivery of these functions. To this aim, we assessed which soil attributes can be used as potential attributes of the five soil functions (primary production, water purification and regulation, carbon sequestration and climate regulation, soil biodiversity and habitat provisioning, and recycling of nutrients) and linked the list of attributes to the existing national and EU-wide soil monitoring networks. From this work, three main conclusions can be drawn:

- Current SMNs form an unbalanced dataset, in which predominantly chemical soil parameters are included, but soil biological and physical attributes severely under represented.
- A wide range of different methods is being used in the different SMNs for measuring attributes. Harmonisation of soil sampling and analyses in the countries across Europe is therefore a key feature of a coordinated EU-wide SMN.
- Although the previous and current LUCAS surveys had limitations in resolution, spatial cover and sampled attributes, the planned survey broadens the scope for using the LUCAS database in the context of monitoring soil functions at the European level.

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