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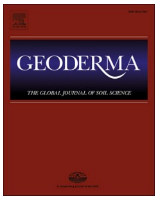

Comparing LUCAS Soil and national systems: Towards a harmonized European Soil monitoring network

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ABSTRACT

A recent assessment states that 60–70% of soils in Europe are considered degraded. Protecting such valuable resource require knowledge on soil status through monitoring systems. In Europe, different types of monitoring networks currently exist in parallel. Many EU Member states (MS) developed their own national soil information monitoring system (N-SIMS), some being in place for decades. In parallel in 2009, the European Commission extended the periodic Land Use/Land Cover Area Frame Survey (LUCAS) led by EUROSTAT to sample and analyse the main properties of topsoil in EU in order to develop a homogeneous dataset for EU.

Both sources of information are needed to support European policies on soil health evaluation. However, a question remains whether the assessment obtained by using soil properties from both monitoring programs (N-SIMS and LUCAS Soil) are comparable, and what could be the limitations of using either one dataset or the other.

Conducted in the context of European Joint Programme (EJP) SOIL, this study shows the results of a comparison between N-SIMS and LUCAS Soil programs among 12 different EU member states including BE, DE, DK, EE, ES, FR, DE, HU, IT, NL, PL, SE and SK. The comparison was done on: (i) the sampling strategies including site densities, land cover and soil type distribution; (ii) the statistical distribution of three soil properties (organic carbon, pH and clay content); (iii) two potential indicators of soil quality (i.e. OC/Clay ratio and pH classes). The results underlined substantial differences in soil properties statistical distributions between N-SIMS and LUCAS Soil in many member states, particularly for woodland and grassland soils, affecting the evaluation of soil health using indicators. Such differences might be explained by both the monitoring strategy and sampling or analytical protocols exposing the potential effect of data source on European and national policies. The results demonstrate the need to work towards data harmonization and in the light of the Soil Monitoring Law, to carefully design the

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future of soil monitoring in Europe taking into account both LUCAS Soil and N-SIMS considering the significant impact of the monitoring strategies and protocols on soil health indicators.

1. Introduction

European soils, as an essential and non-renewable natural resource on a human scale, are under threat. According to recent estimates, approximately 60 % of European soils are in a somewhat anthropogenically degraded state (Veerman et al., 2020). As most member states (MS) of the European Union (EU) do not have a national law to protect their soils fully, the European Commission has on November 21st, 2021 approved and published the EU soil strategy for 2030 (Commission, 2021). Shortly after, the so-called Soil Monitoring Law (SML), which is the proposal for a Directive of the European parliament and of the Council on Soil Monitoring and Resilience (Commission, 2023) was published on July 5th, 2023. The SML will ask MS to monitor and report the status of their soils. It provides a legal framework of setting up a soil monitoring system, assessing soil health and implementing sustainable soil management. However, soil health assessment relies on the existence and accessibility of data from soil monitoring, the quality of acquired data linked to sampling and analytical protocols and their representativeness of the diversity of soil types and land uses.

Soil monitoring is defined as a systematic determination of soil variables used to record their temporal and spatial changes (FAO/ECE, 1994). Nevertheless, monitoring strategies can differ in many different aspects as reported by de Gruijter et al. (2012):

1. Target quantities (e.g. soil organic carbon (OC) content or soil OC stock, and changes or trends therein, in layers at various depths);
2. Domains of interest (e.g. nationwide or focused on specific forms of land use);
3. Sampling strategy (random, targeted or convenience);
4. Sampling density (e.g. grid distance in case of orthogonal grid samples);
5. Inference method (design-based or model-based);
6. Sample support (number, configuration and dimensions of the aliquots taken at the sampling locations, sampling instrument (e.g. spade, soil auger);
7. Method for laboratory analyses;
8. Method for determining stock of elements.

In the EU, many MS have already established ongoing national soil information monitoring systems (N-SIMS), which vary in all aspects between MS (Bispo et al., 2021), hampering a direct comparison across MS. A more homogeneous soil monitoring system is the LUCAS Topsoil monitoring network (LUCAS Soil), which was first conducted by the Joint Research Center of the European Commission in 2009 (2012 for Bulgaria and Romania) (Orgiazzi et al., 2018). Sampling campaigns in the LUCAS Soil monitoring network have been repeated three times, i.e. in 2015, 2018 and 2022. The LUCAS soil campaigns were modified in several ways, i.e. both the number of sites (with substantial increases in the 2018 and 2022 campaigns) and the soil properties included. For almost 15 years, N-SIMS and LUCAS Soil have been performed side by side without the attempt to comprehensively compare them across different MS. Given the objective of the SML proposal, comparing the national and the European-scale LUCAS Soil monitoring networks (e.g. regarding representativeness of their key results), is highly relevant for the ongoing debate on the soil monitoring strategy to assess soil health.

Indeed, soil health assessment rely on indicators and their associated reference values or thresholds need to be based on robust and representative datasets in order to support sound policy decisions. The data from both N-SIMS and LUCAS Soil can provide relevant information, but the question remains whether N-SIMS and LUCAS Soil datasets could be combined and if the data on soil properties are consistent between networks at a national level. Different results will have an impact on soil indicator values and soil health assessment through the definition of reference values or thresholds which could affect policies objectives and action needed. Thus, this comparison between the European and national soil datasets is essential for future efforts to combine and utilize data from multiple monitoring systems since the SML proposal explicitly suggest that « *in order to alleviate the burden, Member States should be allowed to take into account the soil health data surveyed under the enhanced LUCAS Soil.* ».

The objectives of the present research work conducted as a part of the Working Package 6 of the European Joint Programme SOIL were: (i) to compare soil monitoring strategies between LUCAS Soil and N-SIMS in 12 MS, related to sample site density and the representativeness in relation to land cover and dominant soil types; (ii) to compare the outcome of the statistical distribution of three soil properties (soil texture through clay content, organic carbon concentration (OC) and pH) for both LUCAS Soil and N-SIMS; (iii) to evaluate the impact of using LUCAS Soil or N-SIMS datasets on potential soil indicators for the assessment of soil health; and (iv) to discuss the strengths and weaknesses of LUCAS Soil and N-SIMS, their complementarity and possible ways to harmonise them.

2. Material and methods

2.1. Description of monitoring networks and analytical methods

2.1.1. National soil information monitoring systems (N-SIMS) and LUCAS Soil program

Twelve EU MS were involved in this study: Belgium (BE), further divided into two regions, i.e. Flanders (BE.F) and Wallonia (BE.W), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), France (FR), Hungary (HU), Italy (IT), The Netherlands (NL), Poland (PL), Sweden (SE) and Slovakia (SK). A brief description of the N-SIMS considered in the study is presented in Table 1. No phase sampling has been done in N-SIMS programs therefore the campaign years considered are supposed to represent the population. Further details on the monitoring systems are reported in the Supplementary Material.

LUCAS Soil is a monitoring programme designed in 2009 and extended from the EUROSTAT's survey on land cover (Orgiazzi et al., 2018). The soil sampling procedure consists of a composite sample of 3–5 subsamples taken over a surface of 12 m^2 at 0 – 20 cm depth (for the 2009, 2015 and 2018 campaigns) and at 0–30 cm (for the 2022 campaign). The strategy to select the sampling locations varied between campaigns. According to Tóth et al. (2013) (see the supplementary material), the LUCAS Soil sampling design for 2009 was a 10 % subsample of the 200,000 LUCAS Survey georeferenced sites leading to a total of 20,000 LUCAS Soil sampling sites across the EU. Four terrain geographical covariates (altitude, slope, curvature and aspect, all derived from the Shuttle Radar Topography Mission digital elevation model) and land use (derived from CORINE Land Cover [CLC] 2000) were compiled to construct about 20,000 strata (Tóth et al., 2013). The LUCAS Soil sites within a stratum were used as primary sampling units in a two-stage random sampling. The number of sites selected was first proportional to both the surface area of each MS and the percentage of each type of land use and cover in each MS, according to the classes proposed by the CLC-2000 dataset. However, a choice was then made to reduce the number of forest soils by a third and to transfer it to arable lands and grasslands (Tóth et al., 2013). In addition, the final selection of LUCAS Soil sites sampled within a stratum among the proposed triplets (i.e. a group of three LUCAS Soil points having common properties) was left to the discretion of the local surveyors (see Tóth et al., 2013). Some sites planned to be resampled during several campaigns, showed discrepancies in sampling locations across the three surveys (2009, 2015 and 2018) as 80 % of the revisited sites in 2015 could have been taken up to 10 m from the initial sampling site location (Jones et al., 2020). Consequently, given the sampling surface of 12 m^2 and the spatial heterogeneity of soils, revisited sites that were not exactly located at the same place can introduce an additional variability in some of the soil properties. Finally, as soil heterogeneity was not considered in the monitoring strategy, the representativity of LUCAS Soil sites could vary greatly depending on the MS (Tóth et al., 2013).

2.1.2. Soil analytical methods

Different sets of analyses have been performed on the soil samples from LUCAS Soil depending on the sampling campaign (Orgiazzi et al., 2018) including: coarse fragments, particle-size distribution, pH (H_2O and $CaCl_2$), OC, carbonates, extractable phosphorus, total nitrogen, extractable potassium, cation exchange capacity, hyperspectral properties and trace elements. Most of those analyses were performed for the 2009, 2015 and 2018 campaigns (Orgiazzi et al., 2018), however particle-size distribution analysis was not performed on the revisited sites. Some analyses such as bulk density, which is required for an accurate estimation of soil OC stocks, were only integrated from 2018′s campaign, and furthermore only for 10 % of the sampling sites (Orgiazzi et al., 2018).

Methods used for analyses in the different N-SIMS of OC, pH (H_2O) and particle size distribution have been reported by each MS and are presented in Table 2. Similar analytical methods were used for pH (H_2O) and OC (ISO 10694.1995) in most of the MS and LUCAS Soil program (Table 2). Only BE.F measured pH using exclusively the KCl method (ISO 10390:2005). For cropland sites in Estonia, pH measured in KCl was converted into pH measured in H_2O (Kabała et al., 2016). Particle size distribution analysis was conducted using ISO 11277(1998) by DE, EE, ES, IT and SK, similarly to the LUCAS Soil program of 2009. For LUCAS Soil campaigns undertaken in 2015 and thereafter, laser diffraction method was used (ISO 13320:2009) which was also used by BE.F and PL. National methods (mostly with pipette methods) were used by BE.W, DK, FR, HU, NL and SE. Various particle size distribution determination methods lead to various cut-off limits especially between silt and sand (see Table S1), however the cut-off limit for clay content, used in this study was 0.2 μm for all LUCAS Soil and N-SIMS programs.

2.2. Comparison procedure

The comparison of N-SIMS with LUCAS Soil was done separately for each MS included in the study.

2.2.1. Monitoring strategy

The comparison of the monitoring strategies integrated the spatial distribution of the samples across each MS through the calculation of the coverage area (km^2) per site, called site coverage area (SCA) calculated by dividing the total area of the MS by the number of sites. The spatial density of sites was calculated using a square grid of 10 km x 10 km and expressed in number of sites per km^2 at the national scale; maps are reported in Table S2. Land cover distribution was assessed by calculating the proportion of sites sampled by each program (i.e. LUCAS Soil or N-SIMS) for each main land cover type (i.e. cropland, grassland, woodland, artificial land and other). Those proportions were then compared to the reference land cover distribution in each MS (national reference such as Corine Land Cover or LUCAS survey distribution which corresponds to the observed distribution in the field using the 2 km x 2 km grid,

Table 1
Description of the national soil information monitoring systems (N-SIMS) with land cover monitored, topsoil sampling depth and years of N-SIMS and LUCAS Soil considered for the comparison.

Country (ISO code)	N-SIMS Land Cover	N-SIMS Topsoil sampling depth	N-SIMS campaign years considered	LUCAS Soil campaign considered (year)	Reference
Belgium Flanders (BE.F)	Cropland, grassland, woodland, shrubland, bareland, wetland	Soil profile (0–10-30 cm)	2021–2022	2018	Oorts et al., 2023
Belgium Wallonia (BE.W)	Agricultural land (cropland, grassland)	0–15 cm or 0–25 cm	2018	2018	Genot et al., 2012
Germany (DE)	Cropland, grassland, permanent crops	Soil profile (0–10-30 cm)	2011–2018	2015	Poeplau et al., 2020
Denmark (DK)	Agricultural land mainly	0–25 cm	2009	2009	Taghizadeh-Toosi et al., 2014Harbo et al., 2023
Estonia (EE)	Agricultural land (mainly cropland)	Soil profile (0–10-30 cm)	2007–2012	2009	https://kese.envir.ee/
	Woodland	Soil profile (0–10-30 cm)	2008	soil profile (0–80 cm	https://icp-forests.org/data/fm_start.php
Spain (ES)	Cropland, Grassland	0–20 cm	2001–2007	2009	Rodríguez Martín et al., 2016
France (FR)	Cropland, grassland, woodland, shrubland, wetland	0–30 cm	2000–2010	2009	Arrouays et al., 2022, Jolivet et al., 2022
Hungary (HU)	Agricultural land, woodland, special land cover	0–30 cm	1992 – present	2009	TIM, 1995
Italy (IT)	All land covers	Soil profile (0–10-30 cm)	2003—2013	2009	Costantini et al., 2014
The Netherlands (NL)	Artificial Land, Bareland, Cropland, Grassland, Shrubland, Woodland	0–30 cm	2018	2018	Knotters et al., 2022
Poland (PL)	Agricultural land (cropland, grassland, permanent crops)	0–20 cm	2017—2022	2018	private resources of IUNG-PIB
Sweden (SE)	Cropland, (majority of grassland)	0–20 cm	2011–2017	2015	Adler et al., 2022
	Woodland, shrubland, wetland, permanent grasslands/pastures	0–30 cm	2007–2018	2015	Ågren et al., 2024
Slovakia (SK)	Cropland, Grassland	0–10 cm	2007	2009	Fiala et al., 1999, Hrivňáková, 2011

Table 2
Description of the analytical methods used to measure OC, pH (H_2O) and particle size distribution in LUCAS Soil and N-SIMS programs ordered by MS.

Soil property	OC			pH (H2O)		Particle size distribution		
Method	ISO 10694.1995 (combustion)	Turin method	National methods	ISO 10390.1994 (1:5 suspension of soil in H_2O)	Other method: (1:2.5 suspension)	ISO 11277.1998 (Sieving, sedimentation)	ISO 13320:2009 (Laser diffraction)	National methods (pipette)
LUCAS Soil	X			X		X (2009)	X (2015 and after)	
BE.F	X			/			X	
BE.W	X			X				X[f]
DE	X			X		X		
DK	X			X				X
EE	X			X		X		
ES	X			X		X		
FR	X			X				X[f]
HU			X[b]		X[c]			X[g]
IT	X			X		X		
NL		X[a]		X				X[h]
PL	X			X			X	
SE	X			X (crops)	X (forest)			X (crops)
SK		X			X	X		

[d]: 1:2.5 KCl, UN/BCE Meted 91035A.
[e]: 1:2.5 KCl, MSZ-08–0206/2–1978.
[a] : NEN 5753.
[b] : MSZ-08–0210:1977.
[c] : MSZ-08–0206/2–1978.
[f] : NF X 31–107.
[g] : MSZ-08–0205-1978.
[h] : density fractionation, NEN 5753 Soil.

(Palmieri et al., 2011)). Finally, the comparison of dominant soil classes distribution was done using the European Soil Database (ESDB) and the WRB reference system (Panagos, 2006; Van Liedekerke et al., 2006; Panagos et al. 2012). Dominant soil type was extracted at each site for both N-SIMS and LUCAS Soil and the final distribution of soil types were compared to the reference surface distribution based on ESDB at the national scale.

2.2.2. Soil properties

For each MS involved, the comparison was done using the campaign of LUCAS Soil closest in time to the campaign of N-SIMS data considered in the study (Table 1). Consequently, DK, EE, ES, FR, HU, IT and SK compared the data with LUCAS Soil campaign 2009, DE and SE with LUCAS Soil 2015 and BE.F, BE.W, NL and PL with LUCAS Soil 2018. In BE.W, EE (croplands), IT and SK, a subselection of the data collected during a period comparable to LUCAS Soil campaigns was made (Table S1). Due to the variation of some soil properties in the soil profile, a mass-weighted average was used to estimate each soil property at 0 – 20 cm for N-SIMS for which soil samples were collected along the soil profile (e.g. 0 – 10 cm, then 10 – 30 cm). This was the case for BE.F, DE, EE and IT. A similar calculation was done of the Swedish forest soil samples including both the O horizons and mineral soil layers.

2.2.3. Soil assessment indicators

To evaluate the impact of using datasets from N-SIMS or LUCAS Soil, a case of possible indicators of soil degradation has been made. The OC/Clay ratio has been proposed by some authors (Johannes et al., 2017; Prout et al., 2021), as an indicator of the soil structural state and its ability to store carbon. The threshold of OC/Clay $> 1/13$ has been suggested in the SML proposal as the criterion for healthy soils (for agricultural soils, excluding *"unmanaged and natural soils")*. Therefore, this ratio was tested on cropland and grassland soils from N-SIMS and LUCAS Soil, considering a soil as *degraded* under 1/13, *moderately degraded* between 1/10 and 1/13, *good* between 1/8 and 1/10, and *very good* above 1/8. Though we acknowledge that the OC/Clay ratio may not be a relevant indicator for all soils (Poeplau and Don, (2023), Rabot et al. (2024)), we used this ratio as an example of the impact of the dataset chosen on the results of this indicator, currently suggested in the SML proposal to assess whether soils are degraded concerning soil OC loss. As a second indicator, we used pH H_2O classes and we compared the proportion of sites falling in the different classes depending on the dataset used. The classes considered in the comparison were adapted from Baize (1993) as follows: below 4.8; between 4.8 and 5.5; between 5.5 and 6.3; between 6.3 and 6.8 and above 6.8.

2.3. Statistics analysis

The first step consisted of producing descriptive statistics for OC (g kg^{-1}), clay content (g kg^{-1}), and pH (H_2O or $CaCl_2$ depending on data availability). For each of those soil properties, range (min – max), median and mean values were calculated by land cover and based on data from each program (LUCAS Soil and N-SIMS) for all included MS. We also ran, in a second step, a nonparametric Mann-Whitney test to analyse if the distributions of the samples collected from the two survey designs (i.e.N-SIMS and LUCAS Soil) were comparable. A nonparametric test was selected as soil properties were not normally distributed.

All statistics and data treatment were done using R software (R Core Team, 2023). To enable a common comparison of the N-SIMS with the respective LUCAS Soil data for each MS, a unique script was developed using Rsoftware and implemented using Rmarkdown package (Allaire et al., 2023). This script is available on GitHub at the following address: https://nicolassaby.pages.mia.inra.fr/ejpsoilwp6lucas/. Differences between distribution of variables were statistically assessed using package *stats* (R Core Team, 2023). The distribution of variables was assessed using Skewness and Kurtosis tests using the package *psych* (Revelle, 2023). The figures were done using package *ggplot2* (Wickham, 2016) and maps were done using package *tmap* (Tennekes, 2018).

3. Results

3.1. Comparing the monitoring strategies

3.1.1. Sampling and soil properties selection and methods

Among the N-SIMS considered, different sampling strategies were employed. Some MS adopted different monitoring strategies between land covers. This is the case for EE and SE with two different N-SIMS for agricultural land and forest (Table 1). In six MS, i.e. BE.F, ES, FR, HU, IT and NL, all land covers are considered whereas BE.W, DE and PL mostly monitored agricultural lands (croplands and grasslands). In DE and SK, agricultural soils and forest soils are monitored in a similar way but by different authorities. As the soil properties data of forest soils for those two MS were not available, the current analysis comparing dominant soil type distribution and soil property values was restricted to agricultural soils monitored by the participating organisations.

Regarding soil sampling depth, BE.W, ES, PL and SE (agricultural soils) sampled topsoil (from 0 – 10 cm to 0 – 25 cm) whereas ten MS also sampled deeper soil layers including BE.F, DE, DK, EE, FR, HU, IT, NL, SE (forest soils) and SK (see Table S1) Some soil properties were measured in almost all N-SIMS (Table S1) such as OC, particle size distribution (sand, silt, clay), pH (either H_2O, $CaCl_2$, or KCl dilutions) and total nitrogen (forest soils only in EE). Many MS also monitored other soil properties such as nutrients (P, K), bulk density, carbonate content and available cations (e.g. Ca^{2+}, Mg^{2+}). Some MS have extended the monitoring with specific properties such as trace elements (EE, ES, FR, NL, PL, SE and SK) or even pesticide residues (EE, FR). Most of those soil properties have also been measured in LUCAS Soil campaigns (Table S1), except for bulk density that was measured only in 10 % of the sites during the 2018′s campaign (see section 2.1.1).

3.1.2. Site coverage area and spatial distribution of site density

The results of site coverage area (SCA) in km^2 for all LUCAS Soil campaigns and the N-SIMS of each MS are presented in the Fig. 1. Site coverage area is usually lower in N-SIMS (SCA mean value of 96 km^2 among the MS) compared to LUCAS Soil campaigns (SCA mean value of 197 km^2). The largest differences between SCA of N-SIMS and all LUCAS Soil campaigns were observed in Belgium (both BE.F and BE.W) with N-SIMS site coverage are being 102 times and 31 times smaller than LUCAS Soil (2018) SCA for BE.W and BE.F respectively (Fig. 1). Moreover, in Belgium, the SCA drastically decreased over the different LUCAS campaigns with a very high SCA for BE.F for the LUCAS Soil 2009 campaign compared to all the sampling campaigns of the other MS. Wide differences in site coverage areas for N-SIMS and LUCAS Soil were also observed in IT and PL with N-SIMS SCA being 11 times smaller than 2009 LUCAS Soil and 5 times smaller than LUCAS Soil 2022. A rise in the number of samples of LUCAS Soil 2022 campaign resulted in SCAs comparable to N-SIMS for DK, HU and NL (Fig. 1). Moreover, the increase of sites in LUCAS Soil 2022 resulted in smaller SCA for DK and SK compared to N-SIMS and previous LUCAS Soil campaigns. In ES, comparable SCA were observed already from LUCAS Soil 2015 whereas in EE and FR the SCA in the N-SIMS were lower than LUCAS Soil campaigns by a half and a third respectively.

The spatial distribution of site density at the national scale, expressed in number of sites per km^2, of N-SIMS and LUCAS Soil campaigns considered in the comparison of soil properties (i.e. 2009, 2015 or 2018) are presented in the Table S2 (supplementary material). For the considered campaigns, LUCAS Soil spatial site density (in number of obs./km^2) was much lower than N-SIMS in the majority of the MS with the spatial site density of LUCAS Soil being 30 times lower than N-SIMS for BE and PL, 10 times lower for IT, 5 times for DK, NL and SE and 2 times for SK and HU (Table S2). In addition, the distribution of LUCAS Soil samples appeared to be more heterogeneous than N-SIMS, showing some regions with high-density sampling whereas other regions almost have no sampling sites. This is the case for the MS showing comparable spatial site densities between N-SIMS and LUCAS Soil such as DE, EE, ES and FR (see Table S2). Differences in the spatial distribution of locations are particularly evident in ES and FR, where the N-SIMS is based on a square grid, therefore covering the territory homogeneously, while the sites of the LUCAS Soil campaigns were unevenly distributed across the territory.

As the sampling strategy of LUCAS Soil campaigns (before 2022) excluded the areas above altitude 1000 m in 2009 (Tóth et al., 2013) and 1500 m in 2015 and 2018 (Gallego et al., 2015), areas with lower sampling density could be observed in mountainous regions. This was the case for SK where most of the LUCAS Soil sampling sites were clustered in the flat area in the south-west of SK, but also in DE and SE with lower spatial site density in mountainous areas. In IT, sites in both N-SIMS and LUCAS Soil were unevenly distributed, however N-SIMS had a much higher spatial site density including several sampling sites

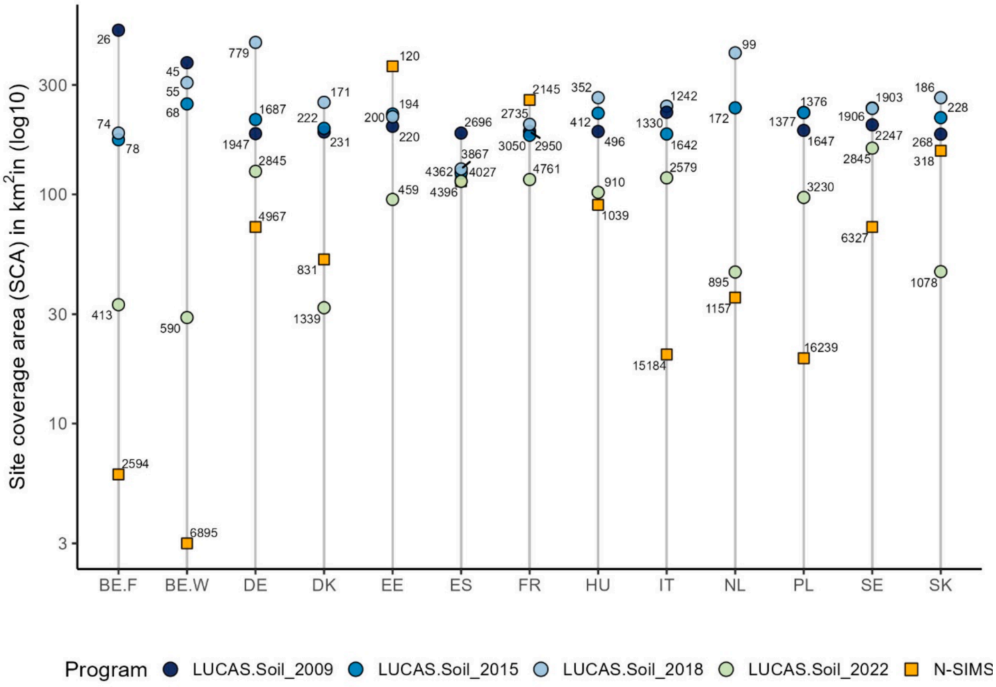


Fig. 1. Site coverage area in km^2 of monitoring program campaigns (i.e. LUCAS (2009, 2015, 2018 and 2022) or N-SIMS) for each MS. The total number of sites sampled in each MS is indicated in the labels next to each monitoring program symbol.

located in the Appennine and Alpine regions that LUCAS Soil did not cover. In LUCAS Soil 2022 campaign, however, an increase of sampling sites in those mountainous areas was observed.

Higher spatial heterogeneity of LUCAS Soil sampling locations was also observed in less mountainous MS such as in BE.F, NL and PL (Table S2). In BE.F, LUCAS Soil showed a higher sampling density towards the borders. The N-SIMS in BE.F had a much higher spatial site density rate than LUCAS Soil (Table S2), despite a higher number of sites located in the eastern part of BE.F linked to sampling method (GRTS) taking into account the land cover. In PL, LUCAS Soil showed a more clustered distribution compared to the N-SIMS, with lower spatial site densities in the north-west and south-west of PL, mostly by the sea and in the mountains, but also in the areas mostly occupied by agriculture in the north-central PL. In NL LUCAS Soil samples were concentrated in the central and northern parts of NL, leaving large areas at East, North and South with few sampling locations (Table S2). Finally, fewer differences in the heterogeneity of spatial site density distribution were observed for DK and HU.

3.1.3. *Land cover distribution*

The distribution of main land cover categories for LUCAS Soil campaigns and N-SIMS has been reported by each MS and compared with a reference value of land cover obtained from LUCAS Survey or national data (BE.F, DE, FR, IT, NL, and PL). In BE.F, DE, EE, FR, IT and NL, the distribution of land cover from N-SIMS was closer to the reference values of the MS, whereas croplands were oversampled in LUCAS Soil campaigns at the expense of the other land cover categories (Fig. 2). In BE.F croplands represent only 31 % of the territory in the reference but 65 % and 80 % of all the LUCAS Soil 2018 and LUCAS Soil 2022 samples were collected under croplands. Grasslands in BE.F cover 32 % of the territory but only 12 % and 11 % of the sampling sites were under grassland in LUCAS Soil 2018 and LUCAS Soil 2022 respectively. In DE, both LUCAS Soil 2015 and N-SIMS oversampled croplands (i.e. 50 % and 45 % respectively) compared to the reference of 36 %. Conversely, woodlands were undersampled by LUCAS Soil (24 %) compared to the reference of 30 % and oversampled by N-SIMS (38 %). In LUCAS Soil 2022, croplands were oversampled in DE by up to 70 % at the expense of woodlands and grasslands (Fig. 2). In IT and FR, woodlands cover almost 30 % of the area but represented only 11 % and 14 % of LUCAS Soil 2009 sampling sites, respectively. In BE.F, woodlands and other land covers (Bareland, Shrubland and Wetland) were also undersampled in the LUCAS 2022 soil campaign whereas they had a higher proportion of sites in the N-SIMS compared to the reference, due to the method used to allocate sampling sites being based on the minimum detectable difference for a change in carbon stocks (Sleutel et al., 2021). In NL, both LUCAS Soil campaigns (2018 and 2022) sampled around 50 % of the sites under croplands when the reference is around 30 %, at the expense of forest soils (Fig. 2); furthermore, the N-SIMS sampling covered more grasslands (46 %) than the reference value (38 %) and LUCAS Soil (2018) campaign (33 %). Even though the proportions of woodland in N-SIMS and LUCAS Soil 2018 in NL were similar, the large difference in the site coverage areas (Fig. 1) between the N-SIMS and LUCAS Soil resulted in a higher number of woodland samples for N-SIMS (150) compared to LUCAS Soil 2018 (13 sites). In EE, woodlands were oversampled in N-SIMS (80 %) compared to 47 % of the sites in LUCAS Soil and the reference value of 52 %. In LUCAS Soil 2022, the proportion of woodland sites has been reduced by 18 % compared to LUCAS Soil 2009, consequently being much lower than the woodland coverage in the reference (Fig. 2). Croplands represented 25 % and 41 % of the samples in EE from LUCAS Soil 2009 and 2022 respectively compared to 19 % in N-SIMS being closer to the reference value of 12 %. EE had only one site dedicated for grassland soil monitoring although grasslands cover 21 % of the area in EE, grasslands were therefore poorly represented in N-SIMS compared to LUCAS Soil monitoring (Fig. 2).

In DK, ES and HU, cropland areas constituted around 70 % of the sampling sites for both programs, at the expense of woodlands and/or

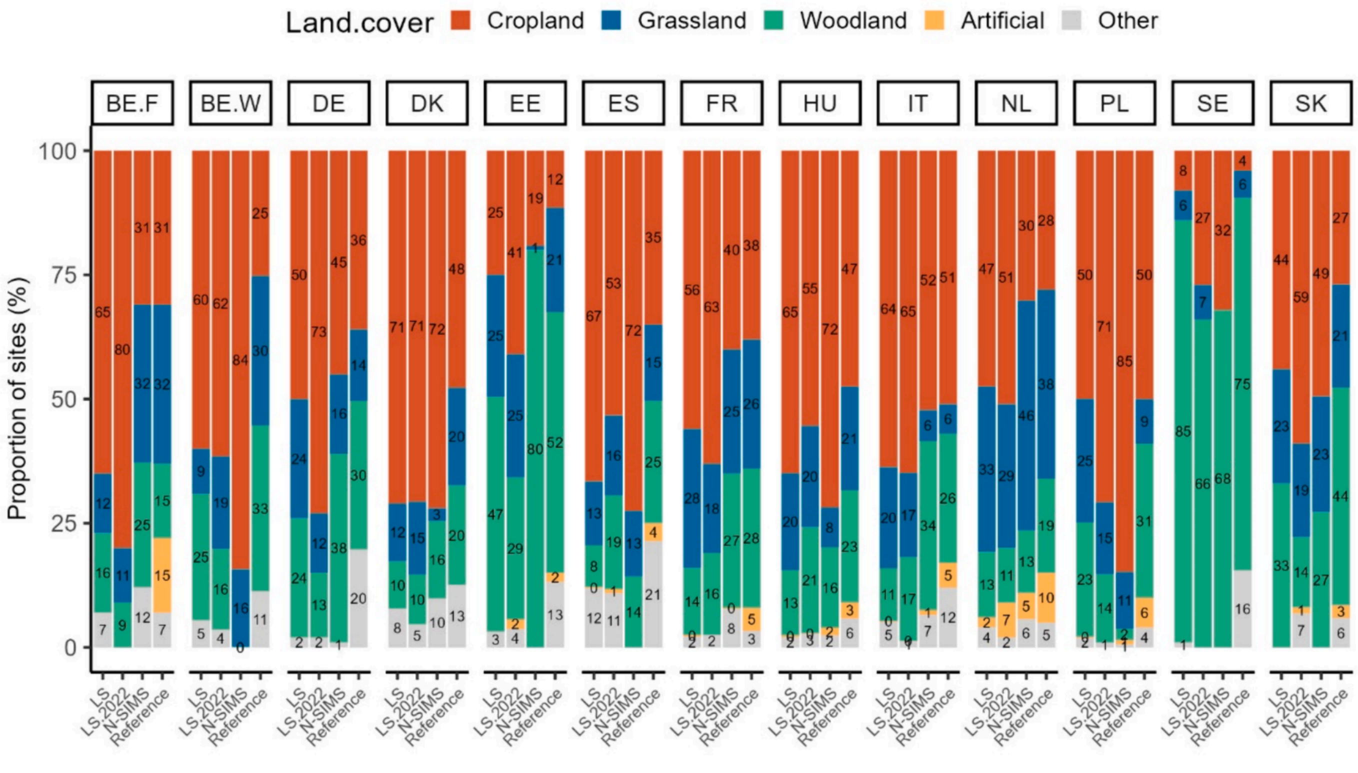


Fig. 2. Distribution of main land cover of sampling points by MS and monitoring program with: LS: Lucas Soil campaigns before 2022; LS.2022: Lucas Soil campaign 2022; N-SIMS: National SIMS; Reference: the reference values of land cover national distribution based on Lucas Survey or national statistics if significantly different as for (BE.F, DE, FR, IT, NL, PL). The proportion of sites (%) for each land cover and monitoring program is reported in each bin.

grasslands, when the reference cropland distribution was approximately 50 % for DK and HU and 35 % for ES. However, N-SIMS campaigns for DK and HU integrated 16 % of sites under woodlands (i.e. 129 sites for DK and 168 sites for HU), which is closer to the reference values compared to LUCAS Soil campaign including 22 (10 %) and 65 woodland sites (13 %) in DK and HU respectively. In SK, both LUCAS Soil (2009) and N-SIMS sampled around 50 % of croplands when the reference value was of 27 % for croplands. The land cover distribution of LUCAS Soil 2022 sampling sites was more closely aligned with their reference values in ES and HU. On the contrary, LUCAS Soil 2022 campaign in SK shifted the distribution of cropland and woodland substantially further away from the reference land cover compared to the previous LUCAS Soil campaign (Fig. 2).

In BE.W, PL and SE, LUCAS Soil land cover distributions were closer to the reference values. In BE.W, 80 % of the 110,000 sampling sites from the entire N-SIMS (only 6895 data points from 2018 were selected for the comparison) were under cropland compared to LUCAS Soil sampling integrating 60 % of cropland and 25 % of woodland. However, despite a distribution of LUCAS Soil closer to the reference in BE.W, the much lower total number of LUCAS Soil sites (55 sites, Fig. 1) resulted in a low number of sites under forests (14 sites). In PL, the distribution of LUCAS Soil 2018 sites was closer to the national reference compared to N-SIMS with most of the sites from LUCAS Soil (2018) being located within cropland (50 %), grassland (25 %), and woodland (23 %). As the PL N-SIMS was designed to monitor agricultural areas, a higher proportion of the sites were located within cropland (85 %) and grasslands (11.5 %). Despite a large difference in the proportion of woodland sites (Fig. 2), the absolute number of woodland sites was similar between LUCAS Soil and N-SIMS with respectively 324 and 344 sites, respectively, due to a higher number of N-SIMS sampling sites (Fig. 1). In LUCAS Soil 2022 in PL, a higher proportion of sites were under croplands (71 %), diverging from the reference distribution. In SE, most of the soils sampled by both LUCAS Soil and N-SIMS programs were woodland, representing respectively 85 % and 68 % of the total number of sites which is close to the 75 % woodland coverage of SE as reported in Fig. 2. Croplands were oversampled in N-SIMS campaign representing 32 % of the total number of sites (i.e. 6327) compared to the national reference value according to LUCAS Survey of 4 % and the LUCAS Soil percentage of 8 %. The increased focus on agricultural land in the LUCAS Soil 2022 campaign clearly increased this proportion of the soil samples, leading to a sample distribution between forests and agricultural lands similar to the N-SIMS.

The difference in grassland distributions in SE is linked to a problem with what is defined as 'grassland' in the LUCAS Survey for SE. The reported reference proportion of grasslands and croplands according to both LUCAS Survey and LUCAS soil sampling are similar (around 6–7 %, Fig. 2) whereas the national statistics of grasslands (excluding croplands) are only 1 % while the proportion of cropland is around 7 %. Although these differences may appear small, it might have a large impact on calculations based on land cover, e.g. OC. The difference in classification is due to the fact that the vast majority of grasslands in SE are temporary three-to-four-year leys within a crop rotation.

3.1.4. Dominant soil types

The distribution of dominant soil types in each program (i.e. N-SIMS and LUCAS Soil) were compared to the reference value from the European soil data base (ESDB) using the World Reference Base classification (WRB, 1998), except for BE.F where it was compared to the reference values from the regional soil map (WRB, 2014). The results showed that the distribution of dominant soil types from LUCAS Soil diverged more from the reference values than N-SIMS in eight MS (BE.F, DK, EE, ES, FR, HU, IT, and NL) (Fig. 3). In DE and SK, the distribution of dominant soil types was similar between LUCAS Soil and N-SIMS, whereas the soil type distribution of LUCAS Soil was closer to the reference value compared to N-SIMS in BE.W, PL and SE.

Cambisols were oversampled by LUCAS Soil for BE.F (+6.2 percentage points (pp)), DK (+3 pp), EE (+3.8 pp), ES (+10.3 pp), FR (+3 pp) and IT (+6.2 pp), compared to the reference values of 20.9 % (BE.F), 7.2 % (DK), 9.4 % (EE), 45.9 % (ES), 42.4 % (FR) and 67 % (IT). The difference compared to reference values was lower for N-SIMS with + 0.4 pp for BE.F, −0.3 pp for DK, +2.3 pp for EE, +6.4 pp for ES, −0.5 pp for FR and + 5.5 pp for IT. In SE and PL, we observed that the oversampling of Cambisols by N-SIMS of + 16.2 pp and + 3.6 pp respectively, was higher than that of LUCAS Soil (+7.3 pp and −0.45 pp) as compared to the reference values of 9.9 % and 12.8 % for SE and PL respectively. On the contrary, Cambisols were undersampled in DE (−4 pp for both programs), SK (−8.8 pp for N-SIMS and −7.4 pp for LUCAS Soil) and in HU (LUCAS Soil −2.2 pp compared to N-SIMS+0.5 %). In BE.W, Cambisols were undersampled by N-SIMS (−25.3 pp) compared to LUCAS Soil (−1.4 pp) for a reference value of 34 %. However, the large discrepancies between the total number of sites (Fig. 1) resulted in 610 Cambisols sampled by N-SIMS in 2018 which was higher than the 17 Cambisols sampled by LUCAS Soil 2018.

To a lower extent, Luvisols were oversampled by LUCAS Soil in DE (+4.4 pp), EE (+5.8 pp), FR (+2.8 pp), BE.F (+2.1 pp) and IT (+4.7 pp) compared to the reference values of 19.4 %, 18.7 %, 15.5 % and 11 % respectively when N-SIMS differences were of + 2.8 pp (DE),-2 pp (EE), −0.1 pp (FR), −0.2 pp (BE.F) and −1.1 pp (IT). In PL, both programs oversampled Luvisols by 3 pp. In BE.W Luvisols were oversampled by N-SIMS by + 27 pp compared to the reference value of 57 %. On the opposite, Luvisols were slightly undersampled by LUCAS Soil in DK (−2.9 pp) and HU (−5.1 pp) compared to N-SIMS (−1.2 pp, +3.5 pp) when reference values were 36.8 % (DK) and 19.6 % (HU). In NL, Luvisols representing 5.1 % of the territory were undersampled by LUCAS Soil (–4.1 pp) compared to N-SIMS (+2.4 pp).

Podzols were undersampled by LUCAS Soil in BE.F (−3.8 pp), FR (−3.1 pp) and NL (−10.7 pp) compared to N-SIMS (+3.8 pp in BE.F; +0.3 pp in FR; −5 pp in NL) when the reference values were 11.9 %, 5.5 % and 38 % respectively. In SE, Podzols were undersampled by N-SIMS (−19.8 pp) and by LUCAS Soil (–10 pp) compared to the reference values of 78 %. However, the number of Podzols sampled by N-SIMS (i.e. 3682) was higher than LUCAS Soil's (1301 sites). In IT, no Podzols were sampled by LUCAS Soil, while Podzols constituted 1.8 % of the soils in the territory. Particularities in dominant soil type representativeness could be observed in some MS, with Fluvisols being oversampled by LUCAS Soil in the NL (+15.2 pp) compared to N-SIMS (−1.7 pp) with respect to the reference values of 31 %. Fluvisols were oversampled by N-SIMS in SK (+5.5 pp) compared to LUCAS Soil (+3 pp). Gleysols, representing 31 % of EE soils were undersampled by −5.4 pp in LUCAS Soil compared to N-SIMS (−1.3 pp). In addition, Histosols known to have a high content of organic matter were underrepresented in EE by both programs with a slightly higher difference in LUCAS Soil (−3.9 pp) compared to N-SIMS (−2.4 pp) when the reference was 15.7 %. In BE.F, Technosols were undersampled in LUCAS Soil (−13.4 pp) compared to N-SIMS (−4.6 pp) and Albeluvisols were overrepresented by + 6.3 pp in LUCAS Soil 2018 (−1.3 pp for N-SIMS). Finally, Leptosols covering respectively 18 % and 10 % of ES and IT were undersampled by both programs with a larger difference in LUCAS Soil with −11.3 pp and –8.5 pp for ES and IT respectively (Fig. 3) compared to N-SIMS (−7.5 pp for ES and –2.6 pp for IT).

The LUCAS Soil campaign 2022 resulted in an improvement in the representativeness of the dominant soil types in most of the MS (see Figure S1, supplementary material). In BE.F, the differences between LUCAS Soil distribution and the reference values decreased except for Luvisols that were slightly overrepresented. In DE and IT, LUCAS Soil 2022 was closer to the reference values than LUCAS Soil (2015 and 2009 for DE and IT respectively). In ES and HU, differences with the reference values decreased for Leptosols and Regosols for ES, and Luvisols for HU, while overrepresentation of Cambisols increased in both MS. In NL, Podzols and Fluvisols distributions in LUCAS Soil 2022 were closer to the reference values but Histosols became undersampled (−1.9 pp). In FR, the differences of LUCAS Soil 2022 with the reference values were

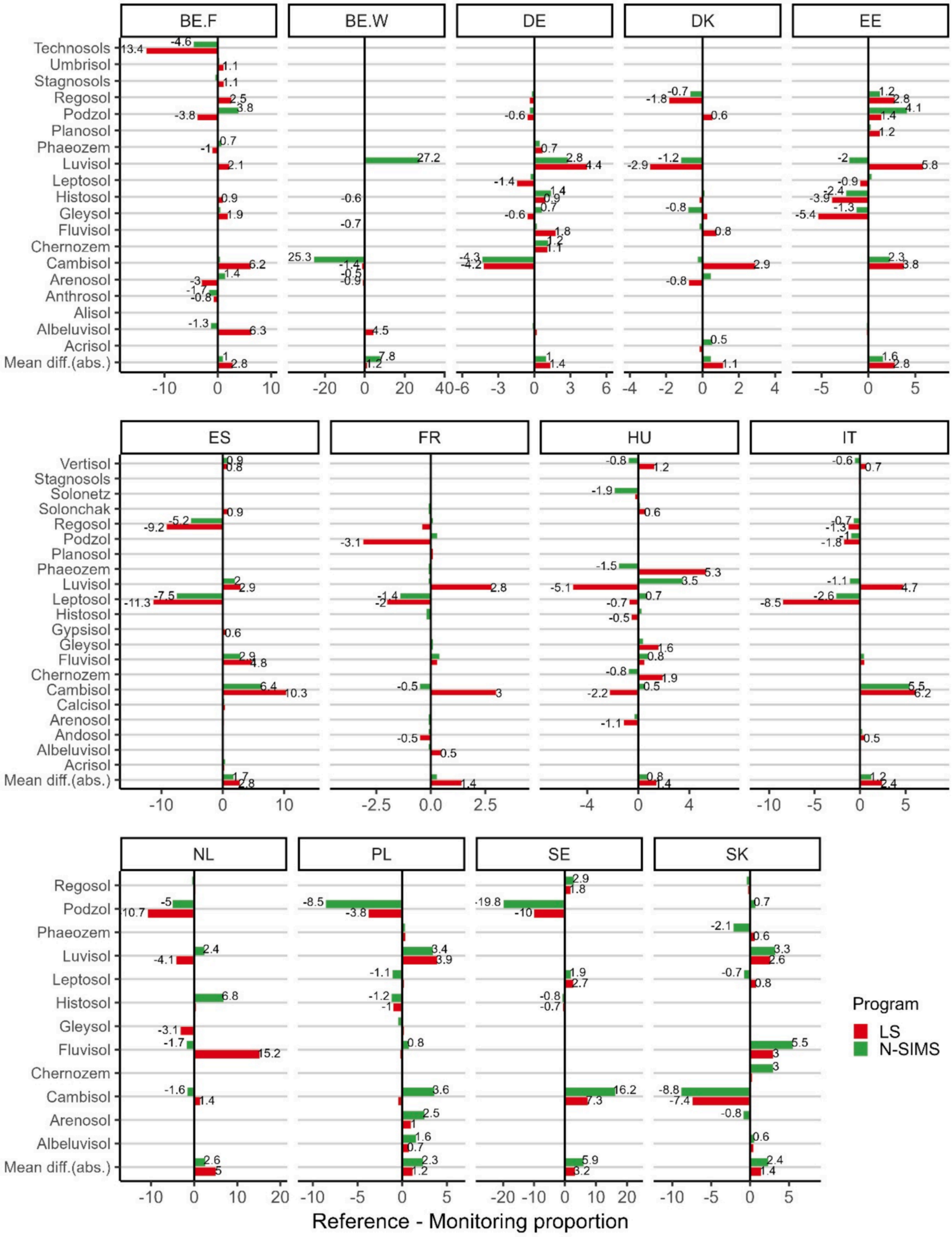


Fig. 3. Difference (in percentage points (pp)) between reference values of the distribution of soil types across the MS from the European soil database (ESDB) (except for BE.F where a regional reference soil map was used) using WRB classification and the distribution in N-SIMS (in green) and LUCAS Soil (LS in red) samples. (BE.F and BE.W: Belgium Flanders and Wallonia; DE: Germany; DK: Denmark; EE: Estonia; ES: Spain; FR: France; IT: Italy; HU: Hungary; NL: The Netherlands; PL: Poland; SE: Sweden; SK: Slovakia). The mean value of absolute pp difference for all soil types by program (LS, N-SIMS) is represented as “Mean diff. (abs.)”.

similar than LUCAS Soil campaign (2009). However, in EE, PL, SE and SK, soil type distribution from LUCAS Soil 2022 (Figure S1) departed from the reference values compared to previous LUCAS Soil campaigns (Fig. 3). In EE and PL, Luvisols oversampling increased at the expense of Podzols for both MS and additionally of Histosols for EE. However, the minor undersampling of Gleysols decreased in EE. In SE, LUCAS Soil 2022 representation of soil types was closer to N-SIMS with an increase in the undersampling of Podzols and oversampling of Cambisols. Finally, in SK, undersampling of Cambisols increased in LUCAS Soil 2022.

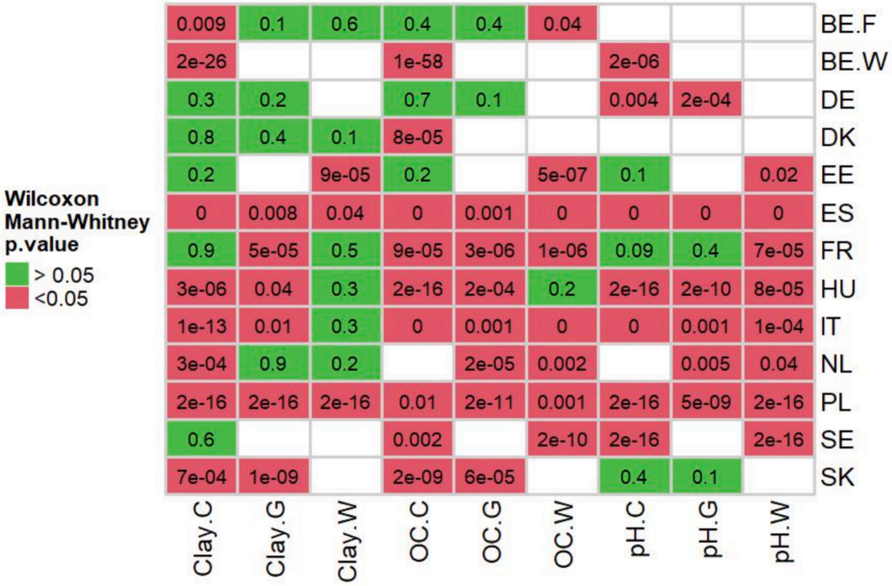
3.2. *Soil properties comparison*

Selected soil properties (clay, OC and pH) were compared between and N-SIMS LUCAS Soil nearest campaign in time (Table 1) for each MS and land cover (i.e. croplands (C); grasslands (G); woodlands (W)), concerning the distribution (Wilcoxon-Mann-Whitney test). Despite results varying between MS, the clay content was generally comparable among the two programs, especially in woodlands (Fig. 4). On the other hand, observations of OC and pH from the two programs showed significant differences for most of the MS and land covers. In ES and PL, all of the considered soil properties showed significant differences in their distributions among the two programs, while in BE.F most properties were comparable, except for clay content in croplands and OC content in woodlands.

Most of the differences in the distributions of OC content between LUCAS Soil and N-SIMS were observed in woodlands and grasslands (Fig. 4). As shown in the Fig. 5A, the LUCAS Soil OC had significantly higher median values than N-SIMS in approximately 60 % of the cases as in woodlands in BE.F (42.1 g kg^{-1} in LUCAS Soil vs 27.2 g kg^{-1} in N-SIMS), EE (71 g kg^{-1} vs 20.5 g kg^{-1}), ES (40.2 g kg^{-1} vs 20.9 g kg^{-1}) and FR (34.5 g kg^{-1} vs 26.9 g kg^{-1}) and in grasslands in HU (22.5 g kg^{-1} vs 9.5 g kg^{-1}) and SK (23.4 g kg^{-1} vs 12.6 g kg^{-1}). On the other hand, lower values of OC in woodlands were observed in LUCAS Soil compared to N-SIMS in IT (28.8 g kg^{-1} vs 43 g kg^{-1}), and in grassland in BE.W (25 g kg^{-1} vs 40 g kg^{-1}) and in all three land cover categories considered in NL (C: 15.5 g kg^{-1} in LUCAS Soil vs 64 g kg^{-1} in the N-SIMS; G: 32 g kg^{-1} vs 47.9 g kg^{-1}; W; 20.3 g kg^{-1} vs 49 g kg^{-1}).

The widest differences in clay contents were observed in grasslands in HU and SK (Fig. 5B) where LUCAS Soil clay content was significantly higher than N-SIMS (230 g kg^{-1} vs 80 g kg^{-1} in HU and 270 g kg^{-1} vs 143 g kg^{-1} in SK). Similarly, significantly higher median values of clay content in LUCAS Soil were observed in several MS showing low range of median clay contents such as PL, in all land covers considered (G: 80 g kg^{-1} vs 17 g kg^{-1}; W: 40 g kg^{-1} vs 12 g kg^{-1}; C: 70 g kg^{-1} vs 24 g kg^{-1}), in NL grassland (G: 60 g kg^{-1} vs 24 g kg^{-1};), in DK grasslands (G: 90 g kg^{-1} vs 50 g kg^{-1}) and in EE woodlands and croplands (W: 90 g kg^{-1} vs 43 g kg^{-1}; C: 130 g kg^{-1} vs 99 g kg^{-1}). These results were supported by statistically significant differences in distributions of clay content in woodlands in EE and PL (Fig. 4). This trend was also observed, at a lower extent, in MS with more clayey soils such as ES (G: 150 g kg^{-1} vs 170 g kg^{-1}; C: 240 g kg^{-1} vs 210 g kg^{-1}), IT (G: 270 g kg^{-1} vs 258 g kg^{-1}; C: 300 g kg^{-1} vs 257 g kg^{-1}), SE (C: 225 g kg^{-1} vs 220 g kg^{-1}) and SK (C: 260 g kg^{-1} vs 229 g kg^{-1}). Differences in clay content distributions were statistically significant for ES, IT and SK (Fig. 4). Additionally, some MS showed an opposite trend with lower clay content in LUCAS Soil compared to N-SIMS, including BE.F (W: 65 g kg^{-1} vs 104 g kg^{-1}; G: 100 g kg^{-1} vs 150 g kg^{-1}; C: 150 g kg^{-1} vs 178 g kg^{-1}), HU (W: 120 g kg^{-1} vs 150 g kg^{-1}; C: 260 g kg^{-1} vs 290 g kg^{-1}) and ES in woodlands (W: 150 g kg^{-1} vs 170 g kg^{-1}). Those differences were supported by statistically significant differences in clay content distribution in croplands in BE.F and HU and in woodlands in ES (Fig. 4). Finally, similar clay contents were observed between LUCAS Soil and N-SIMS in all land covers in BE.W, DE and FR and in croplands and woodlands in DK and NL (Fig. 5B). However, despite the close median values of clay content between LUCAS Soil and N-SIMS in the late cited MS, statistical differences in clay content distributions were observed in grasslands in FR, and croplands in BE.W and NL (Fig. 4).

The distributions and the median values of pH_{H2O} in LUCAS Soil and N-SIMS were significantly different in most of the cases (Figs. 4 and 5C). BE.F measured pH using the $CaCl_2$ method and was therefore not considered in the median comparison (i.e. Fig. 5C). Significantly higher pH values in LUCAS Soil compared to N-SIMS were observed in all land covers in NL (C: 7.5 vs 6.2; G: 5.8 vs 4.8; W: 4.2 vs 4), in woodlands in EE and FR (5.6 vs 4.9 in EE; 5.6 vs 4.9 in FR) and in grasslands in ES (6.7 vs 5.8). This trend was also observed in woodlands in HU and SE, at a lower extent (6.4 vs 6.2 in HU; 4.4 vs 4.3 in SE) but being statistically significant (Fig. 4). In six MS, including BE.W, ES, HU, IT, PL and SE, lower pH_{H2O} median values were observed in LUCAS Soil compared to N-SIMS



	Clay.C	Clay.G	Clay.W	OC.C	OC.G	OC.W	pH.C	pH.G	pH.W
BE.F	0.009	0.1	0.6	0.4	0.4	0.04			
BE.W	2e-26			1e-58			2e-06		
DE	0.3	0.2		0.7	0.1		0.004	2e-04	
DK	0.8	0.4	0.1	8e-05					
EE	0.2		9e-05	0.2		5e-07	0.1		0.02
ES	0	0.008	0.04	0	0.001	0	0	0	0
FR	0.9	5e-05	0.5	9e-05	3e-06	1e-06	0.09	0.4	7e-05
HU	3e-06	0.04	0.3	2e-16	2e-04	0.2	2e-16	2e-10	8e-05
IT	1e-13	0.01	0.3	0	0.001	0	0	0.001	1e-04
NL	3e-04	0.9	0.2		2e-05	0.002		0.005	0.04
PL	2e-16	2e-16	2e-16	0.01	2e-11	0.001	2e-16	5e-09	2e-16
SE	0.6			0.002		2e-10	2e-16		2e-16
SK	7e-04	1e-09		2e-09	6e-05		0.4	0.1	

Fig. 4. Results of statistical test Wilcoxon-Mann-Whitney for pH_{H2O}, clay content and organic carbon in croplands (C), grasslands (G) and woodlands (W) between the N-SIMS and LUCAS Soil observations for each MS (BE.F and BE.W: Belgium Flanders and Wallonia; DE: Germany; DK: Denmark; EE: Estonia; ES: Spain; FR: France; IT: Italy; HU: Hungary; NL: The Netherlands; PL: Poland; SK: Slovakia; SE: Sweden).

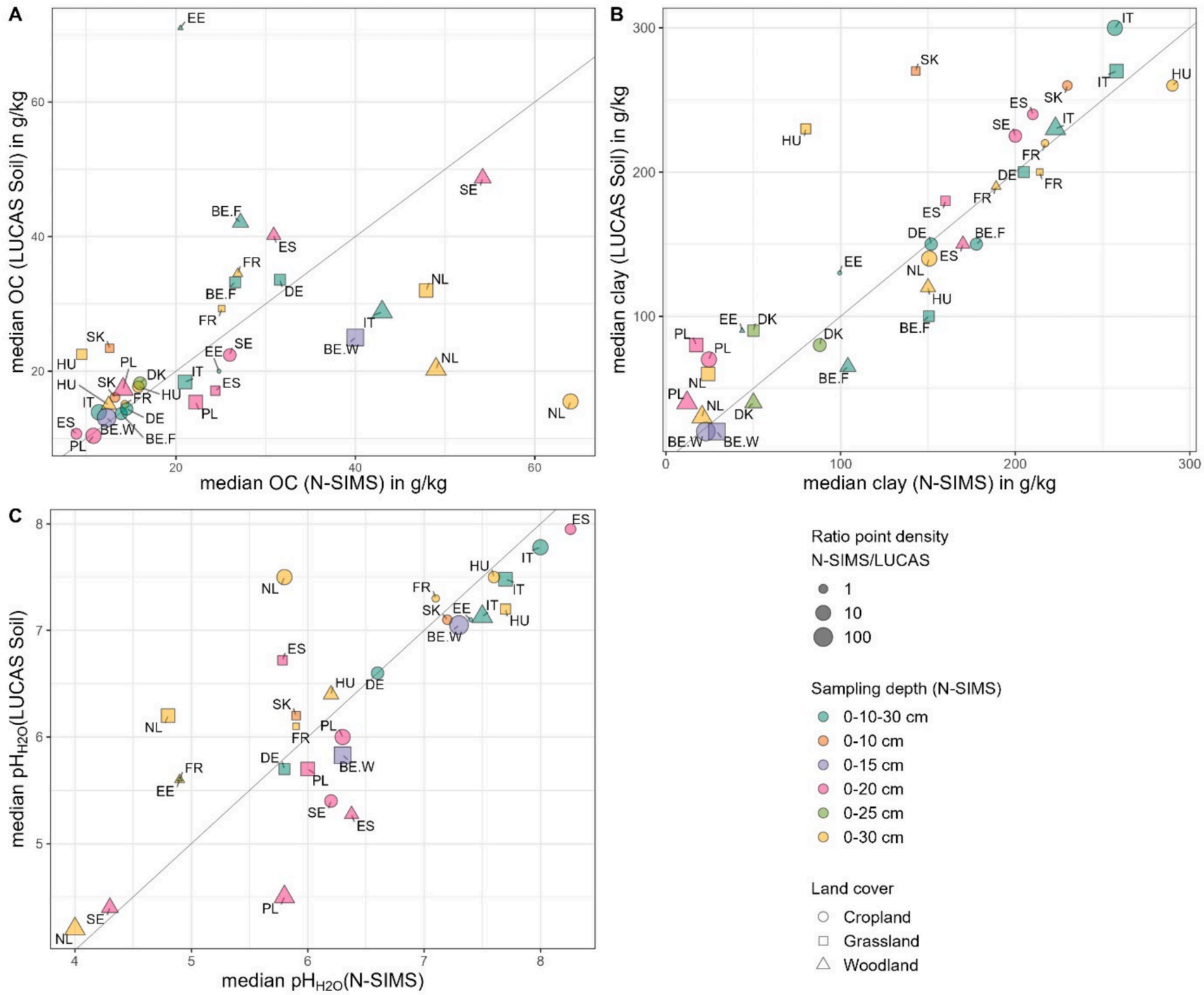


Fig. 5. Comparison of median values from N-SIMS and LUCAS Soil programs of organic carbon (A), clay content (B) and pH_{H2O} (C) for each country displayed by land cover (i.e. cropland, grassland and woodland), sampling depth of N-SIMS (colour) and site density ratio of N-SIMS over LUCAS Soil (size).

(Fig. 5C). The widest ranges within MS were observed in woodlands in PL and ES (4.5 vs 5.8 in PL; 5.3 vs 6.4 in ES) and in croplands in SE (5.4 vs 6.2) being statistically significant (Fig. 4). Slightly lower differences, but still statistically significant (Fig. 4), were found in croplands and grasslands in PL, IT (all land covers), in grasslands in HU or in croplands and grasslands in BE.W (Fig. 5C). Similar median values of pH_{H2O} between LUCAS Soil and N-SIMS were observed in croplands and grasslands in FR and SK, and in croplands in EE. Similar median values were also observed in DE and in croplands in HU (Fig. 5C), however with differences in pH distribution being statistically significant (Fig. 4).

3.3. Impact on soil health indicators

Two soil health indicators based on soil properties collected from LUCAS Soil or N-SIMS programme were calculated: OC/Clay ratio, suggested in the proposal of the SML, and pH_{H2O} classes distribution based on N-SIMS and LUCAS Soil data for each MS considering land cover differences.

The distribution of sites within the OC/clay ratio classes, described in 2.2.3, were substantially different for the MS, but the distribution of sites within the classes also varied between N-SIMS and LUCAS Soil (Fig. 6A). This discrepancy could be observed especially for grasslands in DE, ES, FR, HU and IT, with differences in OC/Clay ratio distribution being statistically significant (i.e. Wilcoxon test, $p\text{-value} < 0.05$). In BE.F, DE, ES, FR and HU, grasslands were better rated when using LUCAS Soil dataset as the proportion of soils considered as *very good* was higher in LUCAS Soil than N-SIMS. In FR and HU, 35 % and 11 % of grassland soils were considered as *very good* in N-SIMS respectively, while 61 % and 37 % achieved similar status in LUCAS Soil. For BE.F and DE, an increase by 20 and 14 percentage points, respectively, was observed between the proportions of *very good* rated grassland soils in LUCAS Soil and N-SIMS. In NL and PL, almost all the grasslands soils were rated as *very good* in N-SIMS (98 % and 99 % for NL and PL respectively), whereas a lower proportion was found in LUCAS Soil (81 % and 71 % respectively). Those differences can be linked to the observations of OC content being higher in LUCAS Soil as compared to N-SIMS for BE.F, DE, FR and HU, combined with a lower clay content in LUCAS Soil compared to N-SIMS for BE.F, DE and FR (Fig. 5). The opposite situation for NL and PL (lower OC content and higher clay content in LUCAS Soil) could explain the lower proportion of *very good* rated soils. Additionally, in BE.F and IT, the proportions of soils under grasslands considered as *degraded* were higher in LUCAS Soil (i.e. 11 % and 53 % in BE.F and IT respectively) than in N-SIMS (3 % and 42 %). This could be due to the higher clay content combined with the lower OC content in LUCAS Soil in IT (Fig. 5). However, in the case of BE.F, an opposite trend was observed (higher OC content and lower clay in LUCAS Soil) but the proportions of LUCAS Soil were based on less than half of the sites compared to N-SIMS which might explain the discrepancies (Fig. 1). No conclusion could be made

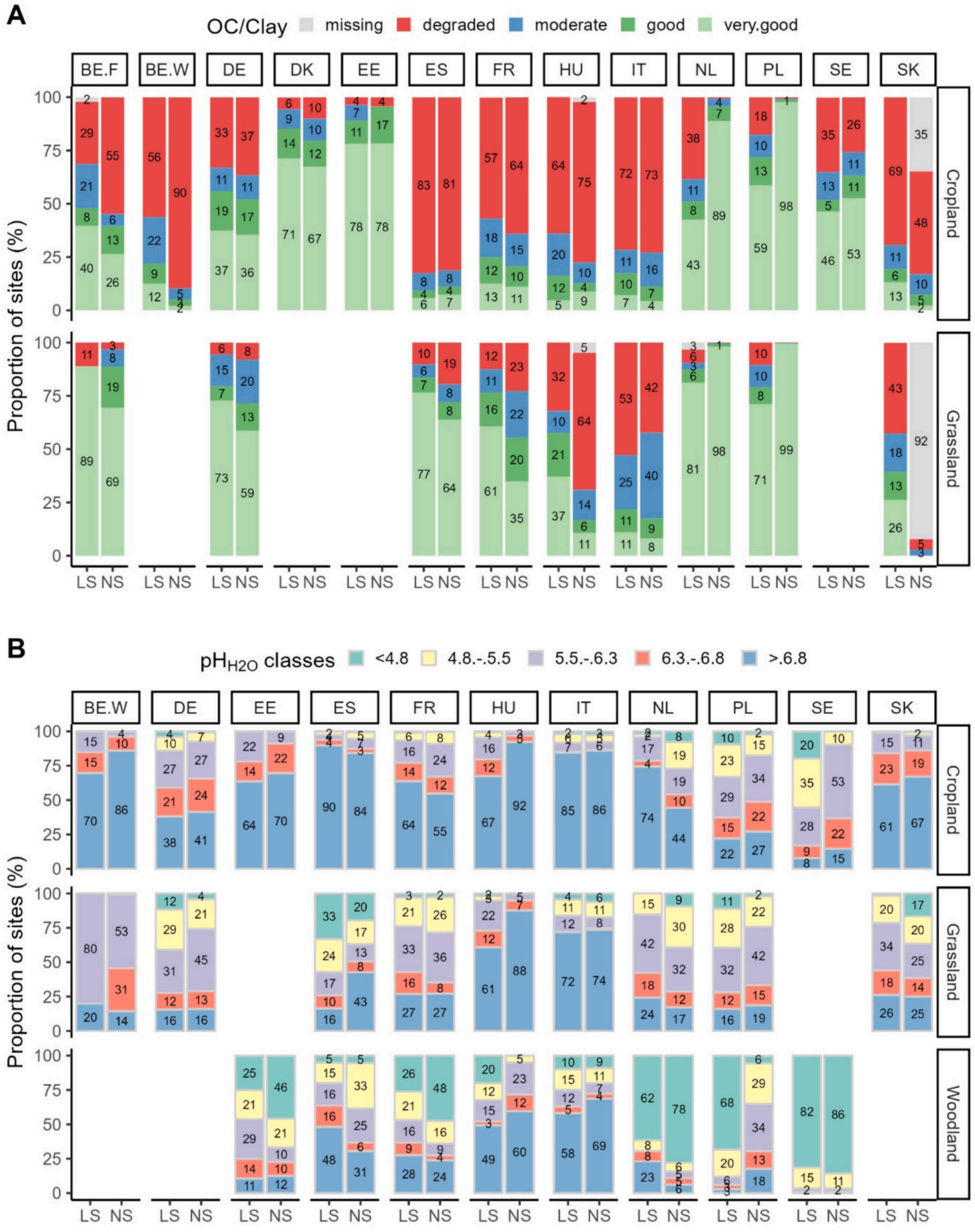


Fig. 6. Comparison of LUCAS Soil (LS) and N-SIMS (NS) results for organic carbon over clay ratio classes (A) and pH_{H2O} classes (B) displayed by MS (BE.F, BE.W, DE, EE, ES, FR, HU, IT, NL, PL, SE, SK) and land covers. BE.F and DK measured pH using $CaCl_2$ method and were not considered in the pH classes comparison. The proportion of sites (%) for each class in each monitoring programme (N-SIMS and LUCAS) is reported in each bin.

for SK as the majority of N-SIMS sites under grasslands did not simultaneously analyse OC and clay content, resulting in 92 % of missing values for the OC/Clay ratio (Fig. 6A).

Concerning croplands, the distribution of observations in the OC/Clay ratio classes was significantly different between LUCAS Soil and N-SIMS for BE.F, DK, ES, FR, HU, IT, NL and PL (i.e. Wilcoxon test, p-value < 0.05). The proportion of sites in the four OC/Clay ratio classes were not significantly different between LUCAS Soil and N-SIMS for DE (p-value: 0.061), EE (p-value: 0.28), SE (p-value: 0.061) and SK (p-value: 0.28). The widest differences of the distribution of observations between classes were observed in Belgium (BE.F and BE.W), where the proportion of *degraded* croplands soils reached 90 % and 55 % in N-SIMS for BE.W and BE.F respectively against 56 % and 29 % in LUCAS Soil. Those differences might be linked to the lower clay content in LUCAS Soil compared to N-SIMS for BE.F (Fig. 5). For BE.W, despite comparable median values of OC and clay content in cropland soils for LUCAS Soil and N-SIMS (Fig. 5A and B), the difference in the number of observations in N-SIMS (i.e. 240) compared to LUCAS Soil (i.e. 32) might explain the discrepancy between OC/Clay classes. In the case of FR and HU, the proportion of *degraded* cropland soils in LUCAS Soil was around 10 percent points less than in N-SIMS. In EE, IT and DK, the difference between proportions of OC/Clay ratio classes was less than 5 percent points. In SE, despite a non-statistically significant difference between LUCAS Soil and N-SIMS values of OC/Clay ratio distributions, the proportion of *degraded* soils in SE was 10 percent points higher for N-SIMS compared to LUCAS Soil and the proportion of *very good* cropland soils 10 % lower. Conversely, the class allocation of OC/Clay ratios and median values were similar for croplands in ES although the ranges were always much wider in N-SIMS than with LUCAS, which may be the source of the statistical difference. In NL, very large differences were found under cropland between LUCAS Soil and N-SIMS. This might be linked to the very low number of samples in LUCAS Soil in NL ($n = 99$) and, as mentioned before, the skewed land cover distribution in the sampling scheme (Fig. 2).

The Fig. 6B showed that pH class proportions were often not comparable among LUCAS Soil and N-SIMS, underlining the effect of different sampling designs on the distribution of this soil property. As shown by Fig. 6B, the pH class above 6.8 was the one showing highest similarities among programmes, while extremely acidic or intermediate pH classes showed greater discrepancies. High pH class (>6.8) constituted a major part of cropland soils in both programmes and in most of the MS (except PL and SE). Low discrepancies were observed for croplands, except in SE showing different pH classes distribution between LUCAS Soil and N-SIMS. Specifically, pH classes under 5.5 in croplands represented more than 50 % of LUCAS Soil samples against less than 10 % in N-SIMS (Fig. 6B) in SE. In HU, a higher proportion of acidic pH classes was also reported in LUCAS Soil whereas 92 % of N-SIMS observations were in the pH class above 6.8. On the contrary, the same acidic pH classes constituted a much lower proportion of LUCAS Soil samples (i.e. 4 %) compared to N-SIMS (27 %) in NL. In SE, the differences in pH classes distribution might partly be explained by the previously mentioned differences in land cover classification related to grassland and cropland. Woodlands and grasslands showed greater differences in the pH classes distribution compared to croplands. In grasslands, acidic pH class (<4.8) constituted a higher proportion of LUCAS Soil samples compared to N-SIMS in DE (12 % vs 4 %), ES (33 % vs 20 %), HU (2 % vs 0 %) and PL (11 % vs 2 %). Conversely, acidic pH class (<4.8) was less represented in LUCAS Soil compared to N-SIMS in grasslands in NL (0 % vs 9 %) and SK (1.6 % vs 17 %). A similar distribution between the two programmes was found in FR and IT grasslands (Fig. 6B). In BE.W, the number of grasslands sites greatly differed between LUCAS Soil (5 sites) and N-SIMS (118 sites). In this case (BE.W grasslands), estimating a proportion of sites among 6 pH classes and using 5 LUCAS Soil sites was not feasible. In woodlands, a different trend could be observed as a lower proportion of the most acidic pH classes (i.e. < 4.8 and 4.8–5.5) was less frequently represented in LUCAS Soil in EE (46 % vs 67 %), ES (20 % vs 38 %), FR (47 % vs 64 %) and NL (70 % vs 84 %). On the contrary, HU and PL woodlands showed a higher proportion of the most acidic pH classes in LUCAS Soil compared to N-SIMS (Fig. 6B), while IT and SE distributions were similar between LUCAS Soil and N-SIMS.

4. Discussion

4.1. Explaining differences in estimates of soil property distributions and their potential consequences

The current study demonstrates many differences in estimates of soil properties statistical distribution using the data collected by N-SIMS and LUCAS Soil programmes. Such differences might be explained by differences in the sampling design (i.e. spatial distribution of sampling sites, land cover and soil types considered), but also by the sampling protocols (i.e. field sampling and analytical methods). The bias induced by sampling design might be particularly important for smaller MS such as BE or NL where less than 100 samples were taken during the LUCAS Soil campaigns considered, being much lower than N-SIMS (see Fig. 1). Consequently, estimates of the statistical distribution of soil properties by land cover based on a low number of samples from LUCAS Soil would be less reliable compared to results from N-SIMS in these MS. Indeed, the large difference in numbers of samples between LUCAS Soil and N-SIMS in many MS might partly explain the drift in the statistical distribution of soil properties such as organic carbon and pH_{H2O} specifically. In addition, the low number of sites in LUCAS Soil 2009–2018 campaigns in several MS (e.g. (BE.F, BE.W, DK, HU, NL and SK) questions the robustness of the results presented in many derived products and papers based on the LUCAS Soil data (e.g. De Rosa et al., 2024).

The spatial distribution is also a key factor affecting the precision of the estimates of the soil properties statistical distribution, showing a more scattered pattern in LUCAS Soil campaigns compared N-SIMS in many countries, resulting in an oversampling or undersampling of some specific soil types. For example, Cambisols and Luvisols were oversampled whereas Podzols were undersampled in many MS. This could be related to the land cover distribution of soil monitoring programmes focused on agricultural soils associated with Cambisols and Luvisols at the expense of forests, associated with Podzols. Spatial distribution of sampling sites might be a major hypothesis explaining differences between soil properties in MS with comparable total number of samples such as FR, ES or SK. The difference in spatial distribution of sampling sites would also lead to various proportions of woodland types (e.g. broadleaved forests, coniferous forests etc.) or grassland types (pastures, age of the permanent grassland) sampled. These different sampling densities among land use potentially affect the results as vegetation is a key factor controlling soil organic carbon (Jobbagy and Jackson, 2000). It could also be one of the explanations of the differences observed in clay content in grasslands in HU and SK where similar number of samples were collected by LUCAS Soil and N-SIMS.

Overall, the discrepancies of estimated soil properties distribution between LUCAS Soil and N-SIMS were particularly noticeable for woodland and grassland soils in many MS. In addition to the sampling density effect, differences in sampling protocols such as soil depth might explain some divergences between LUCAS Soil and N-SIMS especially for OC content that can vary with small depth increments under forest and grassland topsoil. Indeed, the higher values observed for woodlands and grasslands in LUCAS Soil compared to N-SIMS values might be partly attributed to a potential methodological bias related to sampling depth differences in N-SIMS (Table1) compared to LUCAS Soil campaign (fixed depth 0–20 cm, extended in 2022 to 0–30 cm). The variation of OC with depth under grasslands and woodlands might also results in a shift in the results of LUCAS Soil 2022 as the soil depth has been changed to 0 – 30 cm, which affects the comparison with previous campaigns. However, the difference in sampling depth cannot be the only explanation of the observed discrepancies in OC content, as several MS such as ES, PL, or SE sampled at 0–20 cm depth like LUCAS Soil. In addition, the difference in sampling depth could not explain the lower OC content of LUCAS Soil samples compared to N-SIMS in NL that sampled at 0 – 30 cm and did not apply any correction (Fig. 5A). In the case of pH and clay content, the drift in soil properties between LUCAS Soil and N-SIMS was observed in many MS covering various soil depth, therefore sampling depth differences was likely not the only factor causing such differences.

Another possible source of discrepancy could be related to the sampling methods, including sampling configuration within the site, handling of litter and organic, and mixing of organic and mineral layers (Federer, 1982). The comparison of the sampling methods in Switzerland using spade for LUCAS Soil and gouge auger for N-SIMS conducted by Fernández-Ugalde et al., (2020) demonstrated that some discrepancies between OC of woodland soils could be attributed to the less rigorous litter removal of the spade method used in LUCAS Soil program. This study also showed that the soil sampling was uniform with depth (0 – 20 cm) for the gouge auger, but it varied between 15 and 20 cm for the spade method. This may partly explain why the sampling depth effect was not as pronounced as expected when comparing LUCAS Soil to N-SIMS using shallower depths.

Depending on the MS, discrepancies in soil pH and OC contents between LUCAS Soil and N-SIMS could be extreme (Fig. 5), both negatively and positively. Therefore, it will be difficult to combine LUCAS Soil and N-SIMS datasets both for national and for EU-scale applications. LUCAS Soil is of undisputed importance for the continental scale. However, due to different sampling strategies and analytical methods it is likely that national trends over time will also differ between LUCAS Soil and N-SIMS. For example, recent estimates of OC losses in Swedish agricultural soils based on three LUCAS Soil campaigns (De Rosa et al., 2024) were contradicting observed positive OC trends in cropland soils of the N-

SIMS of Sweden (Poeplau et al. 2015). This late example underlines that diverging results originating from N-SIMS and LUCAS Soil could impact the goals to reach in national and European policies such as carbon storage management in soils. In addition, this study also demonstrates the awareness needed regarding the source of soil data used to establish reference values as well as thresholds and targets. Indeed, the deviation in the statistical distribution of soil properties between LUCAS Soil and N-SIMS would impact soil health assessments, as illustrated in Fig. 6. This could then lead to potentially diverging conclusions about the state of soil health, impacting national policies and further actions taken. Nevertheless, there is a need to work on ways to combine the data already collected by LUCAS Soil and N-SIMS, and to develop the future of soil monitoring in Europe and taking the best of each program. Potential improvements on these two topics, based on the results of the present study, will be suggested in the following sections.

4.2. *The importance of defining the spatial sampling strategy*

4.2.1. *Consistency of national and pan-European site selection strategies*

N-SIMS strategies vary considerably with regards to the sampling design, the sampling protocol (e.g. the sample depth, the sampling itself (e.g. type of composite sampling)), the measured soil properties and the analytical methodologies, even if a common set of basic soil properties is measured in most of the considered N-SIMS. On the other hand, LUCAS Soil adopted the same field sampling protocol and analytical methodology in all the European MS. At a first glance, the sampling protocol of LUCAS Soil appears to be more consistent among MS. However, upon further inspection, the sampling density and the degree of inclusion of non-agricultural areas within LUCAS Soil can be very different among MS. Additionally, the sampling strategy for locating LUCAS Soil sites in the different campaigns (original, revisited and additional sites) is far from homogeneous for the first campaign or may have been influenced in the following campaigns by the willingness to monitor and map a specific soil property (i.e., OC).

The site coverage area varies substantially among N-SIMS, ranging from one site per 3 km^2 (in BE.W) to one site per 362 km^2 (in EE), while LUCAS Soil SCA has a narrower range among MS (from one site per 124 km^2 in ES (in 2015 campaign) to 520 km^2 in BE.F (2009 campaign) and has decreased noticeably in the last campaign in 2022 (one site per 29 km^2 in BE.W to one site per 159 km^2 in SE). However, the distribution of the sampling sites appears to be more geographically even in the N-SIMS. LUCAS Soil is configured as a European monitoring network and therefore we expected lower site density compared to the N-SIMS. The proportions of sites belonging to soil types or land cover categories were more similar to national statistics when using N-SIMS than when using LUCAS Soil. However, the main and easier point to consider is perhaps to make sure that the range of soil properties is correctly covered with enough sites for both sampling strategies. Some oversampling issues can be solved a posteriori, whereas under-sampling is much trickier to deal with.

Oversampling might even be desired under some circumstances. An example is agricultural land in SE. The proportion of agricultural land is 6–7 % and with a strictly proportional sampling this will lead to very few samples. However, agricultural land is heavily affected by management and is crucial to monitor, calling for a denser sampling in this land cover to ensure good representation. In this case the sampling strategy is designed to better capture "hot spots" of potential soil degradation. On the other hand, Sleutel et al. (2021) calculated that cropland in Belgium (Flanders) have the smallest variability in OC stocks (0–30 cm) in comparison with grasslands, forests, natural areas or residential land covers. Therefore, they allocated a denser sampling in the N-SIMS to those land covers with larger variability (especially natural areas and forest). In LUCAS Soil, croplands are greatly oversampled compared to other land uses. If the cropland soils are considered as the ensemble to be monitored in priority, the sites density under agriculture is rather homogeneous across MS in LUCAS Soil. However, the focus of national and E.U.-wide soil health assessment is changing from agricultural soils to soils under all land use categories (Commission, 2023).

4.2.2. *Improving coverage of features and geographical spaces in N-SIMS and LUCAS Soil*

Monitoring soil health under all conditions requires to optimize the sampling design by allocating sampling units in order to cover both the feature and geographical spaces. However, the specific design of soil monitoring network is shaped by the underlying objectives (e.g. detecting changes of soil properties in specific domains, mapping soil properties at different scales for policies actions etc.). Since the spatial probability distribution function of soil health indicators values over EU is unknown, covering feature spaces would be needed to get a reliable overview of soil health indicators. The feature spaces, describing combinations of some possible auxiliary information linked to our target variable, might be covered when the main combinations of soil forming factor are covered, for instance soil types, land cover categories, relief and climate conditions are covered. Our study clearly shows that the feature coverage varies greatly among N-SIMS and is incomplete for LUCAS Soil under several soil types, land cover categories and relief and climate conditions. In addition, land cover categories may be too restrictive to assess the feature space coverage. Adding land use criteria would enable capturing more variability and reporting and taking actions in a more land use-oriented way. Nevertheless, considering the higher number of samples in N-SIMS compared to LUCAS Soil in many MS being more evenly spread through the territory would probably lead to a higher reliability of soil properties distribution.

Building the sampling strategy only on the feature space makes the implicit hypothesis that all the current and future drivers of soil health status and changes are already known which is obviously not the case. As some future changes that may impact soil health are not predictable (e.g. volcano eruption, accidental contamination, floods, earthquake, tsunami, etc.) or are simply too important, covering the geographical space will also enable to better capture unsuspected local gradients and identify unexpected combinations of local conditions that cannot be covered by an a priori feature space strategy.

Filling the feature and geographical gaps will require adding new monitoring sites in either or both N-SIMS or LUCAS Soil by selecting new locations using criteria aiming at targeting uncovered feature space occurrences (for instance, decide on a sampling to capture the land cover/climate/relief/main soil type combinations that are not currently covered). This can be done based on already well documented methodologies for spatial sampling using stratification (de Gruijter et al. 2006). For instance, a two-phase random sampling approach could be applied using the estimator from Särndal, Swensson, and Wretman (1992) for the combination of probability sampling designs. Considering jointly existing N-SIMS and LUCAS Soil monitoring sites would optimize soil information at the national but also at the EU level. New LUCAS Soil sites could be added to help N-SIMS to fill their feature space gaps (strategy promoted by the SML proposal), whereas LUCAS Soil gap-filling could benefit from a set of existing or new N-SIMS sites. Nevertheless, the feature coverage should be considered when combining the results from both N-SIMS and LUCAS Soil to conduct soil health assessment at the EU scale. Indeed, an oversampling of very similar sites at the EU scale by both LUCAS Soil and N-SIMS could occur that would then make it more complex to estimate the population of statistical parameters of soil properties and soil health assessment. Another main consequence of this limitation is the multiplication of costs.

The addition of new monitoring sites, as previously described, might also result in filling any gap in geographical space of LUCAS Soil and N-SIMS considering what minimum density of sites should be required and if this minimum density should be the same everywhere (or if good reasons exist to adapt it at sub-national level). Doing so will ensure that the resulting soil monitoring networks do not miss unsuspected existing large gradients in soil health, and even unexpected future large gradients that may occur due to e.g. climate change, atmospheric deposition, long distance transport, deposit of contaminants or regional trends on agricultural management. Then, if all the national feature and geographical spaces are conveniently covered, the EU feature space would automatically be covered too.

4.2.3. Optimizing and developing a common strategy

At national level, it is logical to use N-SIMS to guide national and/or sub-national actions. Considering the high spatial variability of soil properties, a very high sampling density is the simplest solution to ensure that the geographical and feature spaces are covered and that reporting, and recommendations can be delivered to local actors. In the case of N-SIMS, one clear objective should be to be able to map changes in soil health at scales enabling the implementation of practical actions. Therefore, priority efforts should focus on maintaining dense N-SIMS where they exist, and densifying them, when necessary, especially on undersampled soil type/land cover/climate/relief/ranges of soil properties combinations. Potential threats to soil health should be added to these combinations when they are known and/or expected, such as for instance in *peri*-urban areas, soil-scapes highly prone to erosion, or degradation of "rare" soils ensuring important services (e.g., peats, soils located in catchments that provide drinking water, high quality vineyards, *peri*-urban green belt soils, including market garden soils, etc.). All these densification actions can be best identified and implemented at national level by using up-to-date and scale-relevant information. Such densification is also very relevant to increase the connectivity between soil monitoring and local actors (landowners, farmers, foresters, etc.). Involving numerous actors having a monitoring site located in their land will enable results to reach many structures and relay people communicating major outcomes of soil monitoring results to their local communities. This could be done though collaborative tools, such as soil living-labs (Bouma, 2022; Commission, 2022) to develop concerted actions involving soil scientists, farmers, citizens, and stakeholders.

Conversely, the aims of an EU level network such as LUCAS Soil would be to deliver tools for implementing EU policies, and to provide a set of harmonized indicators to policymakers, ensuring that information is comparable over the whole EU and between MS. Therefore, targeting small areas of local importance would not be the priority but a minimum sampling density over the MS stays preferable. This was not the case in the three first LUCAS Soil campaigns (especially 2009 but also 2015 and 2018) with too low densities for some MS. In a previous study, Morvan et al. (2008) concluded that the minimum density required for both covering landcovers, main soil types and geographical space should be at least 1 site per 300 km^2. This is far from being the case for some MS, and for almost all MS considering specific landcovers such as woodland and grassland. The priorities would be to get a general overview of soil health in Europe and a harmonised basis for pan-European mapping of changes in soil health.

4.3. Perspectives of harmonizing sampling and analytical protocols

Harmonisation between N-SIMS is a crucial step if the objective is to use N-SIMS results with EU wide LUCAS Soil monitoring network. Here, the focus is on harmonising within-site sampling protocols and soil observations and analyses. It might be very difficult, and even counter-productive, to ask MS to change their N-SIMS protocols. However, it might be rather easy to ask MS to add some measurements to their analytical protocols, provided that financial resources are available. Changing all protocols is not realistic, neither useful. The MS will lose the comparability with their previous data, which would obviate a large part of their efforts and the possibility of an analysis of temporal evolutions.

Harmonizing the results of chemical analyses is likely one of the easiest tasks, although far from trivial. Some small differences e.g. those due to dilution effect linked to soil/solution ratio are rather simple to correct (e.g., for pH, Aitken and Moody, 1991; Miller and Kessel, 2010). Some other relations between methods can be established rather easily provided that some additional information are available and that their uncertainty and validity domain are well defined (e.g., for pH, Sumner, 1994; Miller and Kissel 2010; Libohova et al., 2014; and for OC, Jolivet et al., 1998; De Vos et al., 2007; Sleutel et al., 2007; Meersmans et al., 2009). However, many other changes in analytical protocols may require other data than the measurements only to build relevant transfer functions between results (e.g., Ahem et al., 1995; Hu et al., 2021). The two main limitations to establishing these transfer functions are: (i) the access to these complementary data that can be numerous, and (ii) the restricted validity domain of the functions that are established. Harmonising the results of physical characterisations is generally more difficult than aligning chemical procedures. Though it is very important, it is not easy to derive transfer functions between different methods of texture analysis (clay, silt and sand fractions). A main issue is that MS may use different size fractions to define clay, silt and sand. Most literature on harmonization of soil texture data deals with harmonizing differences in reported particle size fractions. Several well-known studies dealt with solving this issue (e.g., Rousseva, 1997; Nemes et al., 1999; Minasny and McBratney, 2001). The authors obtained results of varying success. Whatever parameters the transfer functions used, there was always a quite large uncertainty when converting particle size fractions from different systems. Moreover, in LUCAS Soil the method changed from a protocol resulting in mass percentages to a method resulting in volume percentages between the different LUCAS campaigns. In any cases, either when harmonising results or inferring missing values, one crucial point is to be able to estimate the uncertainty generated by these processes (e.g., De Vos et al., 2005; Nemes et al., 2010). The intrinsic error in the implementation of an analytical procedure should therefore be considered. In the view of combining results produced by different laboratories, only certified laboratories, participating in ring-testing procedures should be used both by N-SIMS and LUCAS Soil.

Overall, the development of such transfer functions may more easily be developed if the samples are preserved. Thus, it is highly recommended that all soil monitoring networks to implement a systematic archiving of samples in large quantities and under ad hoc and controlled temperature, moisture, lightness and containers quality conditions. This is a prerequisite for carrying out a posteriori analyses and inter-comparisons. Archiving samples will also enable to re-analyse part of- or all- the samples from previous sampling campaigns using new techniques when they become available.

Harmonising results from different sampling depth intervals is a common issue which is not always easy to solve, especially when data from topsoil only are available. In this case, one simple recommendation could be to add sampling of deeper layers and horizons to the current sampled ones, and down to a commonly accepted minimum depth. This practice would enable a better transformation of results to common depths and equivalent soil mass. Several methods are available, such as various weighted averages based on layer thickness (Laborczi et al., 2019*)* or equivalent mineral soil mass (Ellert and Bettany, 1995), or equal area quadratic splines (Bishop et al. 1999). These methods have more-or-less specific data requirements and various pros and cons. They also generate uncertainties that are not trivial to estimate.

Sampling and analysing a large number of common sites using different analytical methods might be a way to validate and/or generate transfer functions, estimating at the same time the uncertainties underling the conversion. Such an experiment is ongoing in the framework of the EJP Soil programme. One should remain aware that even a fixed protocol carries its own uncertainties. The level of uncertainty which remains acceptable, given the magnitude of changes that we aim to monitor, must be also considered. These uncertainties, and their acceptability, will of course differ among soil properties. Being too strict on the uncertainties generated by harmonisation procedures may lead to a prohibitive number of common sites to settle. For instance, when running this exercise for the 550 sites of two French forest soils monitoring networks using different sampling depths and analytical methods for a couple of trace elements, Louis et al. (2014) concluded that 300 common sites would be necessary to reach a rather strict level of uncertainty.

5. Conclusion and key messages

This study conducted in 12 EU MS demonstrated the differences between N-SIMS and LUCAS Soil at national levels considering the effect of both sampling strategies and soil properties statistical distributions on the results of soil health indicators. The comparison of sampling strategies revealed discrepancies in the spatial distribution of the sampling sites by LUCAS Soil in several MS resulting in an oversampling of some land covers and soil types at the expense of others. Discrepancies of the estimates of the population statistical parameters of organic carbon, pH_{H2O} and clay content between LUCAS Soil and N-SIMS underlined the impact of the monitoring network considered which may affect soil health evaluation. In addition, these discrepancies may increase with the elaboration of integrative soil health indicators involving the combination of several soil properties. Moreover, attention must be paid to the fact that some MS sampling densities in LUCAS Soil 2009–2018 were not sufficient to derive conclusions, evolutions or digital soil maps from them.

Elaborating on the future of soil monitoring in European MS is therefore a key issue for policies and the Soil Monitoring Law. N-SIMS and EU-wide LUCAS Soil are complementary, but they might target different types of end-users. They might be complementary from a scientific point of view, as they may address processes occurring at different time and spatial scales. For mapping purposes, the complementarity between LUCAS Soil and N-SIMS data may prove efficient, for instance by using LUCAS Soil derived maps as covariates for national digital soil mapping, or by using model ensemble mixing LUCAS Soil derived maps and N-SIMS derived maps.

Nevertheless, combining both sources of data from LUCAS Soil and N-SIMS to increase data coverage for the EU or single member states is not straightforward, in part due to large discrepancies in soil properties between them. In addition, due to obvious differences in soil condition between the N-SIMS and LUCAS Soil systems, it is likely that trends will also differ. Those should thus be double-checked with one or the other complementary dataset. Additionally, restricting sampling to shallow depths in some N-SIMS impedes the comparison with other N-SIMS results and LUCAS Soil. It is particularly problematic to change the sampling depth within a time series, which will pose a severe challenge for the interpretation of the LUCAS Soil 2022, for which the sampling depth was increased from 20 to 30 cm. Therefore, a perspective of combining existing LUCAS Soil and N-SIMS datasets would be the establishment of transfer functions between results obtained using various methods, which is an ongoing work from the EJP Soil. Further research is needed regards to advanced and robust methods to settle these functions, evaluate their uncertainties, and defining/enlarging their validity domain.

The objectives of soil health protection involve all land covers and land uses, and they should be adequately represented in soil monitoring sampling design which is not currently the case for many of N-SIMS assessed in this study. Moreover, changes in land cover and land use are one of the main drivers of changes in soil condition. Therefore, deliberately undersampling some land covers/uses may impair the assessment of future changes in soil health. A sampling design based on a sampling density strictly proportional to the area covered by all soil type/soil properties/land cover/land uses/climate/relief/threats combinations may be useful if the aim is to derive straightforward national or EU statistics on changes in mean values or total stocks over large areas. Nevertheless, the data processing should take these drivers and their geographical and statistical distributions into account to assess and report changes in soil health and their related causes. Given the flexibility of LUCAS Soil samples distribution, N-SIMS and LUCAS Soil should collaborate to suggest new sampling sites completing national programs and LUCAS Soil on specific soil types, land covers, land uses, climate conditions, etc. LUCAS Soil cannot substitute national networks, but a collaboration between N-SIMS and LUCAS Soil would be highly beneficial for both soil monitoring systems. In addition, soil is not only topsoil but a continuous volume which has to be considered in the policies. Consequently, sampling deeper soil layers by both N-SIMS and LUCAS Soil would help capturing a better view of soil health in the different dimensions. The future sampling efforts from N-SIMS and LUCAS Soil should therefore aim at (i) increasing the sampling density of N-SIMS so as they become fully relevant for more local assessment of trends of changes in soil health and their related causes and national soil health monitoring and reporting, (ii) filling the large gaps in the geographical and feature spaces of both N-SIMS and LUCAS Soil, (iii) integrating deeper soil layer in both monitoring systems, and (iv) improving N-SIMS connectivity to local actors and stakeholders.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2024.117027.

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