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SURVEY ARTICLE

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National soil data in EU countries, where do we stand?

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Abstract

At the European scale, soil characteristics are needed to evaluate soil quality, soil health and soil-based ecosystem services in the context of the European Green Deal. While some soil databases exist at the European scale, a much

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EJP SOIL

larger wealth of data is present in individual European countries, allowing a more detailed soil assessment. There is thus an urgent and crucial need to combine these data at the European scale. In the frame of a large European Joint Programme on agricultural soils launched by the European Commission, a survey was conducted in the spring of 2020, in the 24 European participating countries to assess the existing soil data sources, focusing on agricultural soils. The survey will become a contribution to the European Soil Observatory, launched in December 2020, which aims to collect metadata of soil databases related to all kind of land uses, including forest and urban soils. Based upon a comprehensive questionnaire, 170 soil databases were identified at local, regional and national scales. Soil parameters were divided into five groups: (1) main soil parameters according to the Global Soil Map specifications; (2) other soil chemical parameters; (3) other physical parameters; (4) other pedological parameters; and (5) soil biological features. A classification based on the environmental zones of Europe was used to distinguish the climatic zones. This survey shows that while most of the main pedological and chemical parameters are included in more than 70% of the country soil databases, water content, contamination with organic pollutants, and biological parameters are the least frequently reported parameters. Such differences will have consequences when developing an EU policy on soil health as proposed under the EU soil strategy for 2023 and using the data to derive soil health indicators. Many differences in the methods used in collecting, preparing, and analysing the soils were found, thus requiring harmonization procedures and more cooperation among countries and with the EU to use the data at the European scale. In addition, choosing harmonized and useful interpretation and threshold values for EU soil indicators may be challenging due to the different methods used and the wide variety of soil land-use and climate combinations influencing possible thresholds. The temporal scale of the soil databases reported is also extremely wide, starting from the '20s of the 20th century.

KEYWORDS
agricultural soil databases, EJP SOIL, Europe, harmonization, soil, soil data, soil parameters

1 | INTRODUCTION

Without soil, no life on land is possible, since soil is the source of many ecosystem services (Dominati et al., 2010). It provides the means for plant growth (and animal and human food production) and plays a crucial role in water, carbon and nitrogen cycling among others. Human-induced global changes (i.e., climate change, land-use and land-management) are however threatening soils as recognized by the European Commission (EU, 2006). In 2020, 60% to 70% of the European soils were considered unhealthy (Emmett, 2020), as acknowledged by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2019), the Intergovernmental Technical Panel on

Highlights

- A large diversity in amount and quality of soil data in databases among EJP SOIL countries.
- A set of soil data systematically included in databases, while others are missing.
- A minimal requirement for soil data exchange among the countries and with the EU to be defined.
- A systematic harmonization approach needed to use the data available at the European scale.

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Soils (ITPS, 2015), the European Court of Auditors (ECA, 2018), and the Intergovernmental Panel on Climate Change (IPCC, 2019), which also stated that soils contain a major part of the solution, such as the 4p1000 initiative for climate change mitigation (Rumpel et al., 2020).

Recently, the need to consider soils for sustainable development has been first translated into a clear role of soils in at least eight of the 17 UN Sustainable Development Goals (SDGs) adopted in 2015 (Keesstra et al., 2016) and at the EU level, in the European Green Deal launched in 2020. Given their contribution to multiple ecosystem services and their position in the critical zone, soils are key to a number of European policies such as the EU Biodiversity Strategy, the Farm to Fork Strategy, the 7th EAP "no net land take by 2050" initiative, the forthcoming Zero Pollution Act, the new Common Agricultural Policy (CAP) and the European Climate Law. The "A Soil Deal for Europe" Mission has been implemented that will be guided by the new EU Soil Strategy 2030, adopted in 2021, which sets out the vision that by 2050 all soils should be healthy and ensure that the protection, sustainable use and restoration of soils has become the norm by that time (EC, 2021). One of the objectives of the new EU Soil Strategy is to have at least 75% of all soils in Europe healthy by 2030. To monitor the progress towards the achievement of these goals, the EU Soil Observatory was launched in December 2020 and soil data from EU countries are expected to be included in this observatory (Maréchal et al., 2022).

To avoid soil degradation and promote sustainable soil management, stakeholders, including land managers and decision makers, need indicators of soil quality, health (Bonfante et al., 2020) and/or functions (Dominati et al., 2010; Millennium Ecosystem Assessment, 2005; Robinson et al., 2009; Robinson et al., 2012). These indicators are based on classical pedological physical–chemical characteristics such as soil organic carbon (SOC), pH, soil texture, bulk density, but also on hydrophysical soil characteristics (water storage capacity, water content at wilting point, soil aggregation, among others), chemical soil characteristics (nutrient content, trace elements, persistent organic pollutants (POPs), among others) and biological soil features (soil respiration, microbial biomass, edaphon groups abundance and diversity, among others). These characteristics are needed at the global scale, for example, for the UN SDGs, at the European scale for the Green Deal (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en), but also at scales ranging from field to national scale, for policy development, implementation and evaluation, and for evaluating the contribution of soils to climate change mitigation (e.g., Pellerin et al. 2020, 4p1000 initiative). Therefore, with the awareness of the importance of soils growing also at (inter)national level, soil data have become increasingly important for policy makers and land managers at all levels, as has traditionally been the case for farmers and foresters.

The need for soil data has resulted in the rescue and curation of existing legacy data (Arrouays et al., 2017, 2020), the development and maintenance of soil monitoring networks (Morvan et al., 2008) and soil databases and (open) soil information systems at different scales, regional (e.g., Belgium, Italy), national (e.g., France, the Netherlands, Sweden, Germany, Ireland, etc.), European (ESDAC, Panagos et al., 2012, 2022; LUCAS (Orgiazzi et al., 2018) and global (Arrouays et al., 2014, 2017, 2020; WoSIS, Ribeiro et al., 2018; SoilGrids, Poggio et al., 2021). For the same reason, one of the key objectives of the large European Joint Programme on agricultural soils, the EJP SOIL "Towards climate-smart sustainable management of agricultural soils" (EU, 2019), launched by the European Community and which brings together the efforts of the 24 European countries, is to foster the collaboration among the participating partners on: data standardization and harmonization, measurement standardization, their implementation, and data sharing conditions and licensing, to promote soil data interoperability and soil data FAIRness (FAIR: findable, accessible, interoperable, reusable) in general to make it easier for countries to exchange and join their soil data, mainly on agricultural soils. Joint use of European and national and regional soil data will allow more detailed soil assessments at national and at European level, potentially both in space and time, given the wealth of soil data in countries, often with longer time series and more detail, and the European harmonized data collection.

However, while a lot of soil data are present on many soil parameters at the national level, the origin of the data (e.g., resulting mainly from survey or monitoring programmes) induces differences among datasets. As a result, data are not always comparable across regions and countries and also not easy to integrate at the EU scale. In addition, while some soil parameters are reported in most of the EU country's databases, others—that are important for soil quality, soil health or soil-based ecosystem services indicators—are lacking because they are not systematically included in databases everywhere. Finally, data sharing among EU countries remains an issue. The extent of such issues associated with data for meeting EU objectives that rely on soil data has not previously been researched. Therefore, the aim of this work has been to establish a picture of available soil databases and the type of data they include across 24 partners participating in the EJP SOIL programme, focusing on agricultural soils. This would allow for an analysis of soil knowledge at EU scale with the objective to propose possible solution pathways. The evaluation is focused on existing efforts to standardize and harmonize European soil databases and soil information systems, overcome the soil data sharing issues, and further ambition for a standardized European soil information system to target efforts towards meeting ambitions in relation to soil health as outlined under the European Soil Strategy.

2 | METHODOLOGY OF THE SURVEY

To establish the availability of soil databases on agricultural soils across Europe, a standardized survey was developed and distributed to the EJP SOIL programme partners (Austria, Belgium, Czechia (Czech Republic), Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, the Netherlands, Türkiye (Turkey), and the United Kingdom (UK)). Two surveys were conducted (reported in the Supplementary material 1 and https://zenodo.org/record/7956364) to identify the national and regional soil databases including agricultural land use available in the different participating countries, their structure, the data they contain, the frequency of the sampling campaigns and the amount of sampling point locations they include, and their availability or openness (Pavlů et al., 2020; van Egmond et al., 2020). Questions were divided in three sections: (1) the data source; (2) information about the data (availability, spatial and temporal resolution, sampling strategy, format); and (3) the list of soil parameters included in the datasets and the methods used to measure them. Data were collected using structured Microsoft Excel forms.

All surveys underwent data cleaning to check for data errors and omissions. These included lack of information in some fields (number of points collected for example), the absence of data on the evaluated soil parameters (e.g., soil maps containing information only on soil types with no other parameters, dataset discarded), datasets focused on forest soils only, or were very narrowly focused (also discarded). EU databases were excluded as already described (Panagos et al., 2022) and the objective was to see how soil assessments would improve when existing data would be included that are owned by the countries, but are not currently included in the European databases or used in European soil information systems. As a result a total of $n = 170$ datasets were included in the analysis.

Because of the large amount of soil parameters included in the survey, they were grouped in the following five groups:

1. Main soil characteristics according to Global Soil Map specifications (Arrouays et al., 2014): profile depth; soil depth available for plants; soil organic carbon (SOC) concentration; particle size distribution; coarse fragments; soil pH measured in water; cation exchange capacity (CEC); total bulk density (with gravel); bulk density of the fine earth fraction; available water capacity;
2. Other chemical parameters: pH (KCl extract); electrical conductivity; $CaCO_3$; SOC stock; organic matter quality; base saturation; salinity; macronutrients; micronutrients; potentially toxic elements; organic pollutants (OCPs; PAHs; PCBs);
3. Other physical parameters: porosity; water field capacity; wilting point; infiltration; soil resistance to penetration; soil structure stability; saturated hydraulic conductivity;
4. Other soil characteristics: soil type (based on either national or international classifications); clay mineralogy; near and mid infrared analysis (NIR/MIR).
5. Biological parameters of soils especially biological activity (soil respiration), microbial biomass, abundance of specific groups of organisms (earthworms, nematodes), or enzymes.

Of course, the inclusion of a given soil parameter in soil databases of that country may also depend on the pedological context of the country, which is notably a function of climate. Country level responses were further grouped into four geographical zones (Figure 1): central Europe (Switzerland, Slovenia, Slovakia, Poland, Hungary, Germany, Czechia, Austria), northern Europe (Sweden, Norway, Lithuania, Latvia, Finland, Estonia, Denmark), southern Europe (Türkiye, Spain, Portugal, Italy) and western Europe (UK, the Netherlands, Ireland, France, Belgium). This classification is rather coarse compared to the main Environmental Zones defined for Europe by Metzger et al. (2005). However, because soil databases are typically at national scale this overcame the challenge that some countries comprise several of the Metzger et al. (2005) Environmental Zones.

3 | RESULTS

3.1 | How are soil data collected and analysed in the EJP SOIL programme countries?

3.1.1 | A large diversity in amount of soil data available, history of collection and their organization in databases among EJP SOIL countries

One hundred and seventy soil databases or soil information systems were identified in the 24 EJP SOIL

FIGURE 1 Map of the four geographical zones used to group the countries in this study (concept and map by Julia Fohrafellner and Sophie Zechmeister-Boltenstern).

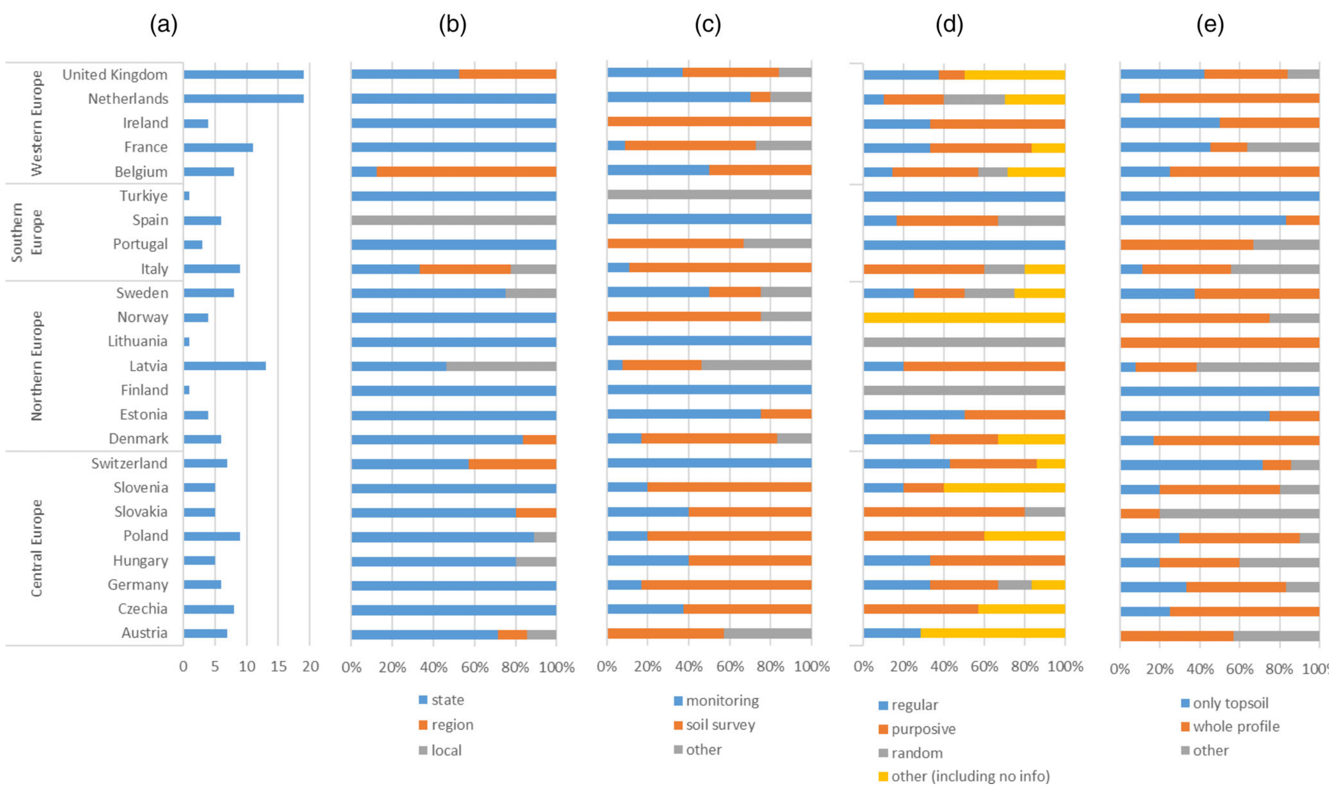

FIGURE 2 Characteristics of the soil databases identified in each participating European country. (a) Number of soil databases identified; (b) scale covered by the identified soil databases; (c) type of survey; (d) type of sampling scheme; (e) sampling depth. Note that not all existing databases were reported by the different countries. Germany for example only reported national databases on agricultural soils.

countries. The results reported here are limited to the information supplied by the participants of the survey and can therefore deviate from the full overview or presence of soil data in countries. The differences in interpretation of the questions in the questionnaire may also have influenced the results.

The reported databases were built for soil type, health and quality description, soil and land evaluation and soil protection purposes, in relation to the European, national and regional soil (data) legislations and needs. They result from surveys for soil inventory, soil mapping, soil monitoring programmes or other data collection efforts, resulting in datasets covering different spatial, from local to national, and temporal scales, different levels of detail and different purposes. There is a rather large disparity in the number of databases, datasets and soil information systems available per country, from one in Finland, Lithuania and Türkiye to 19 in the UK and the Netherlands, with a median of 6 (Figure 2a). The number of soil databases is not an indicator of soil data quantity nor quality because the soil databases can be organized differently in each country. Indeed, depending on the country, there are a few very centralized national databases (Czechia, France, Germany, Ireland, Poland, Slovenia, among others), or a number of regional (Belgium, Italy, UK) and even local (Spain) databases (Figure 2b). For example, in Latvia, because of the lack of a unified (nationwide) soil information system, the challenges in future are related to systematization and harmonization of the existing information (soil and agrochemical survey materials and analytical data, etc.), for creation of a national soil database, as well as adaptation of the information to the European Union Standards. Differences in interpretation of the survey, for example, the difference between a dataset, database or a soil information system, may have affected the results as well. For example, local databases were reported only by some countries, so may have been underestimated in this study. Germany decided to only report national databases for agricultural soils, excluding local databases (e.g., notably long-term experiments) that were included by some countries. They also excluded forest and urban soils that were included by others (e.g., France). The number of soil databases or datasets is also not representative of the number of sampled points. In addition, as already observed by Arrouays et al. (2017) at the global scale, there is no relation between a country's size and the number of soil points gathered in the databases (Figure 3). Some rather small countries (e.g., Belgium (Walloon region), the Netherlands, Latvia, Lithuania, Slovakia) have databases including a very large amount of data, whereas some very large countries have relatively few sampled points in their databases (e.g., Spain, Finland; Figure 3). Southern European countries in general have less sampled points in their

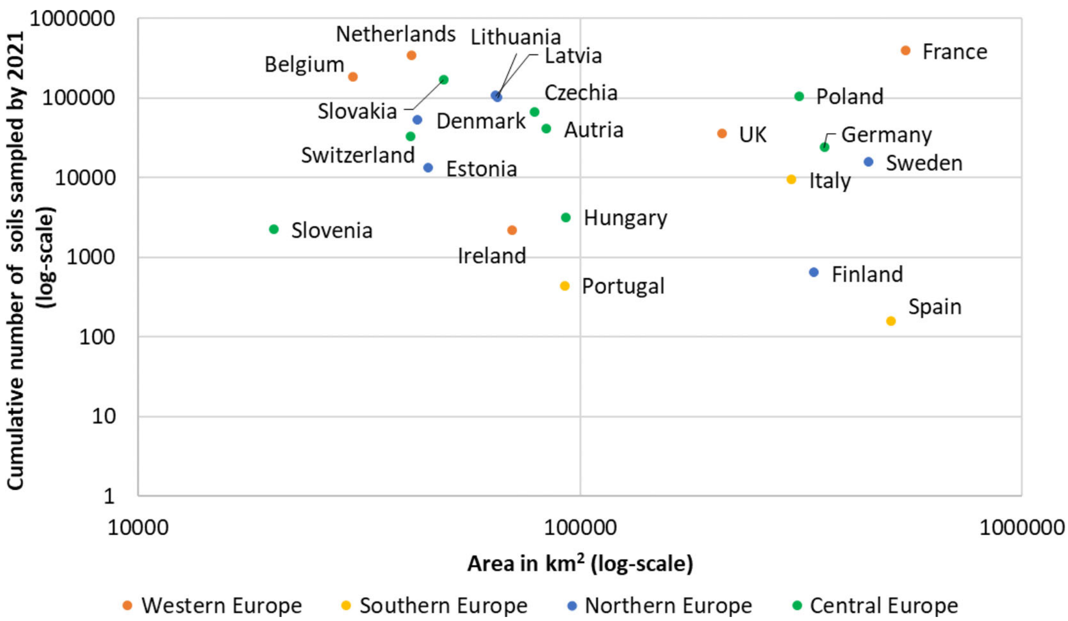

FIGURE 3 Cumulative number of soils sampled by 2021 for the different EJP SOIL partners. For some countries, the provided information is incomplete such as Belgium that has provided numbers of sampled points for Wallonia only, or even absent such as for Norway and Türkiye that have not provided information here. Germany, decided to only provide information on national soil databases. Their sampled points gather location belonging to monitoring network with legacy data for agricultural soils that are by nature more heterogeneous. This situation also applies for other counties (e.g., France). At last some countries restricted their soil database to agricultural soil (e.g., Germany) while other also considered other land uses (e.g., France).

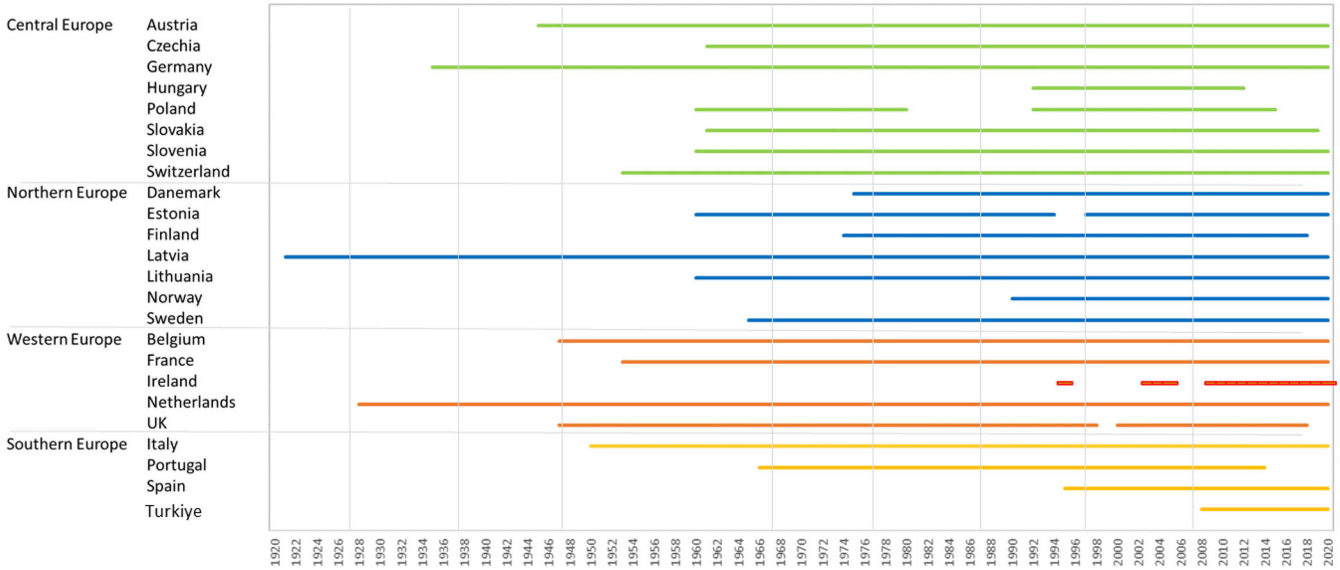

FIGURE 4 History of soil data acquisition in the different surveyed countries with central Europe in green, northern Europe in blue, Western Europe in orange and southern Europe in yellow. The databases reported here are heterogeneous in nature as some countries reported only national databases (e.g., Germany, France), while other included long-term experiments (e.g., Latvia, which explain the very early data acquisition in this country).

databases and a larger amount of local or regional databases. Nevertheless, we have to keep in mind that the number of sampled points reported in Figure 3 might be underestimated for some countries, as this question was not always answered in the questionnaire (e.g., Norway, Türkiye). However, the number of sampling points obtained in the present study was equal to or even higher than that provided by Arrouays et al. (2017) for the countries that had provided information for their study. The current stock take also identified more European countries having a soil information system than the one made by the Global Soil Partnership (https://www.fao.org/soils-portal/soil-survey/national-soil-information-systems/other-national-systems/fr/), with a total of 1,666,642 sampled points for the 24 countries considered.

The objectives of the listed databases also vary a lot. In some countries, the soil databases for soil properties entered in the questionnaires were built mainly for mapping purposes (Ireland, France, Hungary, Italy, Denmark, the Netherlands, Portugal, and the central European countries with the exception of Switzerland and Poland), while in others they are more dedicated to soil monitoring (Netherlands, Spain, Lithuania, Finland, Estonia, Poland Switzerland, Norway) or to other undefined purposes (Türkiye, Latvia, Figure 2c). As an example, the Dutch database contains a lot of soil profile descriptions for mapping purposes, but very few samples were analysed in the lab during the 40-year spanning campaign. Therefore, the reported datasets in the questionnaire are more monitoring and field level focussed since they were analysed in the lab.

Most of the European countries started building soil databases after the Second World War (most of the western European countries, Italy, Estonia, Austria, Switzerland), or from the 1960s (Czechia, France, Lithuania, Poland, Slovenia, Slovakia, Sweden). Three countries started earlier (Latvia from the 1920s; Germany and the Netherlands from the 1930s or even earlier for the latter according to Hartemink & Sonneveld, 2013), while most of the southern European countries, but also Norway and Hungary, started only from the 1990s or later (Figure 4). It is worth noting that the very long data gathering for Latvia consist in a long-term experiment field. Such databases were not reported by all the countries as already discussed above (e.g., Germany, France). Most countries have had a continuous activity of soil database implementation. In some countries, different studies resulting in dataset implementation occurred at different time points with some gaps between the different studies found (Estonia, Ireland, Poland, UK, Slovakia). For example, in Slovakia, there has been two main periods of soil data collection campaigns. The first one lasting from 1961 to 1970 (when the sampling was done for the national soil inventory), and the second one, from 1991 till today. In other countries, the process seems to have reached an end (Hungary, Finland, Poland, Portugal, UK).

This analysis highlights a large disparity in terms of policies, purposes and efforts on soil data in the different European countries surveyed. Some started very early, are highly organized with a few centralized databases at the country or regional level (e.g., Belgium) containing many sampled soil points, while other countries have started gathering soil data more recently and have more local databases with little coordination (e.g., Spain) and/or few sampling points (e.g., Spain, Finland).

3.1.2 | A large diversity in sampling strategy and sampling depth

Different sampling strategies are followed for the campaigns that supply the data to the different databases, with mainly regular sampling along a grid which cell size varies among databases, (stratified) random sampling, or purposive sampling (Figure 2d). The most common sampling strategy is purposive (36% of the databases) followed by the regular sampling scheme (25% of the databases). Random sampling is less common (Figure 2d). For 29% of the databases, the sampling strategy information was not provided (Figure 2d). No link could be established between the type of sampling scheme and the objective of the database (soil monitoring versus soil survey and mapping).

The depth of sampling also varies from a systematic sampling of the different horizons of the soil profiles (48% of the databases) to the topsoil only (33% of the databases), and sampling along the depth with fixed intervals; this last situation is less common in the considered databases (Figure 2e). The first (horizon level) sampling scheme provides a lot of pedological information but requires people that are highly qualified in pedology to perform the soil description and sampling, and is generally limited in terms of spatial variability integration (one pit per site only). Finally, the horizon division can strongly depend on the soil surveyor's evaluation of the soil features which can be described and estimated in field. In contrast, the topsoil sampling is easy, rapid and allows a certain spatial integration by the realization of composite samples on a given surface area. However, it prevents gathering of information on soil type and risks mixing very different soil layers into one, thus possibly misrepresenting the properties of the rooting zone of plants. In a context of global change, taking into account the subsoil horizons becomes essential, because of, for example, their contribution to the water availability for vegetation in a drought context (Cousin et al., 2022), or their significant contribution to carbon storage (Balesdent et al., 2018).

The last approach, sampling at fixed depth intervals, allows gathering of information on the whole soil depth without the need for pedological knowledge of the soil surveyor and also no soil surveyor effect. It is, for example, used by France for the second campaign of its soil monitoring network (Jolivet et al., 2018).

3.1.3 | Methods used to measure the soil parameters are diverse

The methods used to measure the soil properties or parameters of the samples in the laboratory often vary among countries and/or among regions, but also over time. We provide examples to illustrate these differences for four soil parameters: soil organic carbon (SOC), soil pH measured in saline solution and considered as potential acidity, trace element concentrations, and particle size distribution.

SOC is measured by two main groups of methods: dry combustion and wet oxidation that, in turn, comprise of a large variability of lab protocols. Dry combustion is the most common approach nowadays with a wide range of instruments or even with a simple loss on ignition approach (e.g., Netherlands and UK), when some other countries use mainly wet oxidation methods (Estonia, Hungary, Italy, Poland; Figure 5a). Several countries do not use only one method but a variety of the different methods with variations in space and/or over time (France, Belgium, Portugal, UK, Spain, Austria, Italy). Wet oxidation that was used more frequently in the past was found to be replaced by dry combustion or near infrared (NIR) spectroscopy (e.g., Czechia, Slovakia) because of the safety issues associated with this method. Latvia did not provide information on the method used for SOC measurements.

Potential acidity is measured in a KCl extract in some countries (Spain, Estonia, Hungary, Italia, Lithuania) while in other countries, a $CaCl_2$ extract is used (Denmark, Germany, Czechia, Austria, UK, Portugal), and other have used both methods either simultaneously in different regions (Belgium, Slovakia) or in time (France; Figure 5b). As for SOC, some countries did not provide information on the method used for soil pH (Finland, Norway, Sweden).

For trace element concentrations, a large number of lab methods is recorded, ranging from total element analysis—by hydrofluoric acid (HF) acid digestion, fusion or fluorescence-X analysis—or pseudo-total analysis by Aqua Regia (1st group), to smooth extraction with DTPA, EDTA, Mehlich or $CaCl_2$ reagent (2nd group). Therefore, depending on the method, the same soil pool of trace elements has not been analysed, as it ranges from total concentrations in the 1st group of methods to a fraction which is more or less mobile in the soil for the 2nd group of methods. The most commonly used method is Aqua Regia, a pseudo-total method (main extractant used in UK, Portugal, Lithuania, Denmark, Slovenia, Slovakia, Poland and Czechia). Some countries however use mainly total elements analysis (Austria, France) while others use only smooth extractions (Finland, Turkiye, Ireland; Figure 5c).

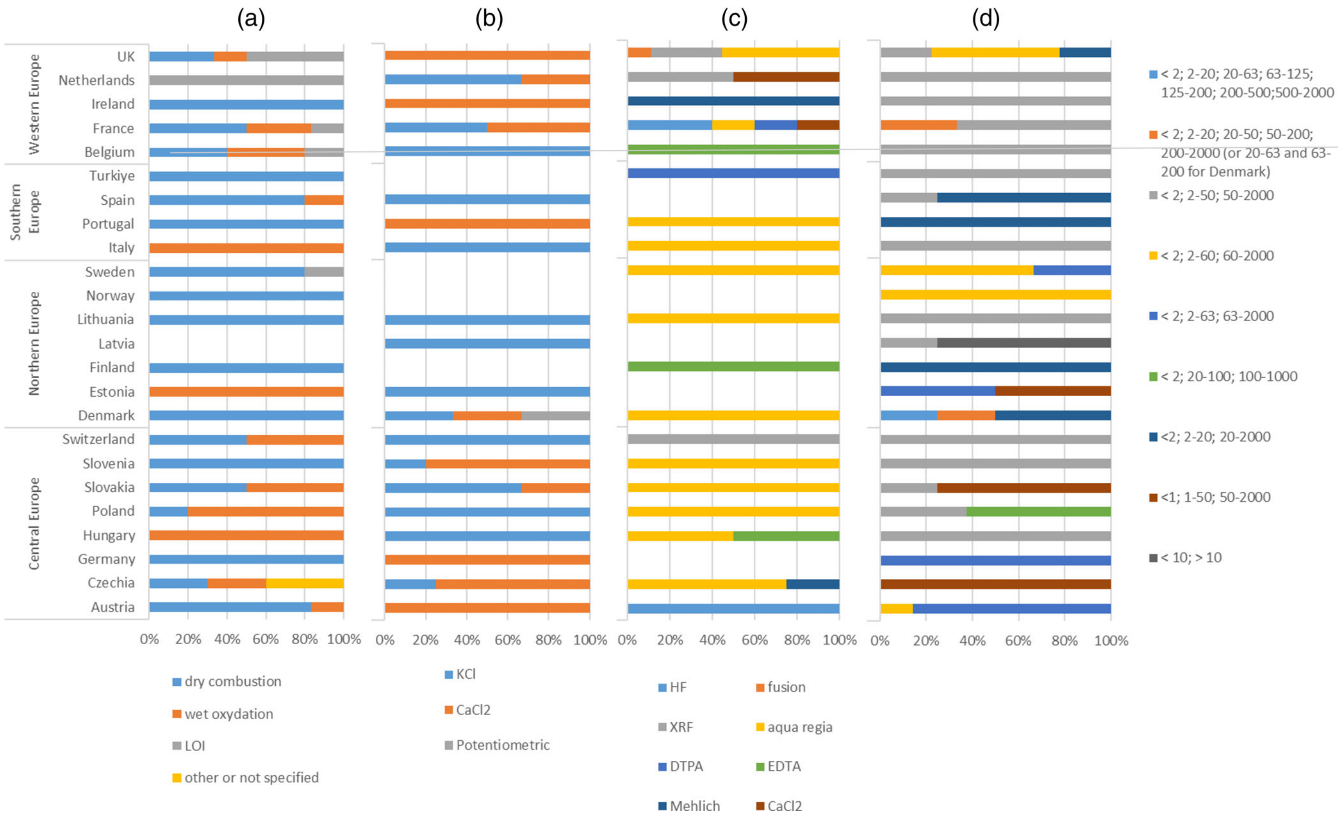

FIGURE 5 Variability of the methods used in the different databases of the different European countries for: (a) soil organic carbon; (b) soil pH measured in saline solution; (c) trace elements; and (d) particle size distribution. The methods used by some countries is variable because many databases were reported with different scale, while in other countries, as Germany, only national homogenized database were reported. LOI stands for loss on ignition.

Particle size fractionations are performed with various cut sizes in the different countries. The most frequently used method consists of three fractions (<2 μm, clay; 2 μm–50 μm, silt; 50 μm–2000 μm, sand). Some countries subdivide the two last fractions into 2–20 μm and 20–50 μm; 50 μm–200 μm and 200 μm–2000 μm (e.g., France), offering an easy conversion. But some countries use different cutting sizes (<1 μm instead of 2 μm, Czechia and Slovakia; 60, 63, or 100 μm instead of 50 μm, Germany, Austria, Estonia or Poland mainly; 10 μm instead of 20 μm (Estonia) and 1000 μm instead of 2000 μm (Poland and Estonia); or a single cut at 10 μm (Latvia) Figure 5d). This is because of the early start of few monitoring programmes in some countries (e.g., long-term experiment started in 1921 in Latvia) that used old fraction cut size and therefore does not correspond to that adopted more recently by the World Reference Base (WRB), for example. In those cases, the conversion is more complex. This results in nine different methods for the particle size fractionation considering only the differences in cutting size. The sample-pre-treatments (decarbonisation or not, strength of sample grinding, organic matter destruction) can play a key role in determining particle size fractionations. However, these information were rarely, if at all, provided in the questionnaires.

For the two first examples (SOC and pH), the methods differ but the parameter measured is the same. However, that is not the case for the two last parameters (trace elements, particle size distribution), for which comparison between countries becomes more challenging, if possible at all.

3.2 | Data included in soil databases to characterize soil status across European countries

3.2.1 | A set of soil data systematically included in databases, while others are missing

It is important to remember that the information provided by the countries relates to the inclusion of the various soil parameters in the databases. These parameters are however not always systematically measured on all the sampled points.

The parameters listed can be divided in five groups: the main soil characteristics according to Global Soil Map specifications (Arrouays et al., 2014), other chemical characteristics (including pollutants), other physical characteristics, other soil characteristics and biological characteristics.

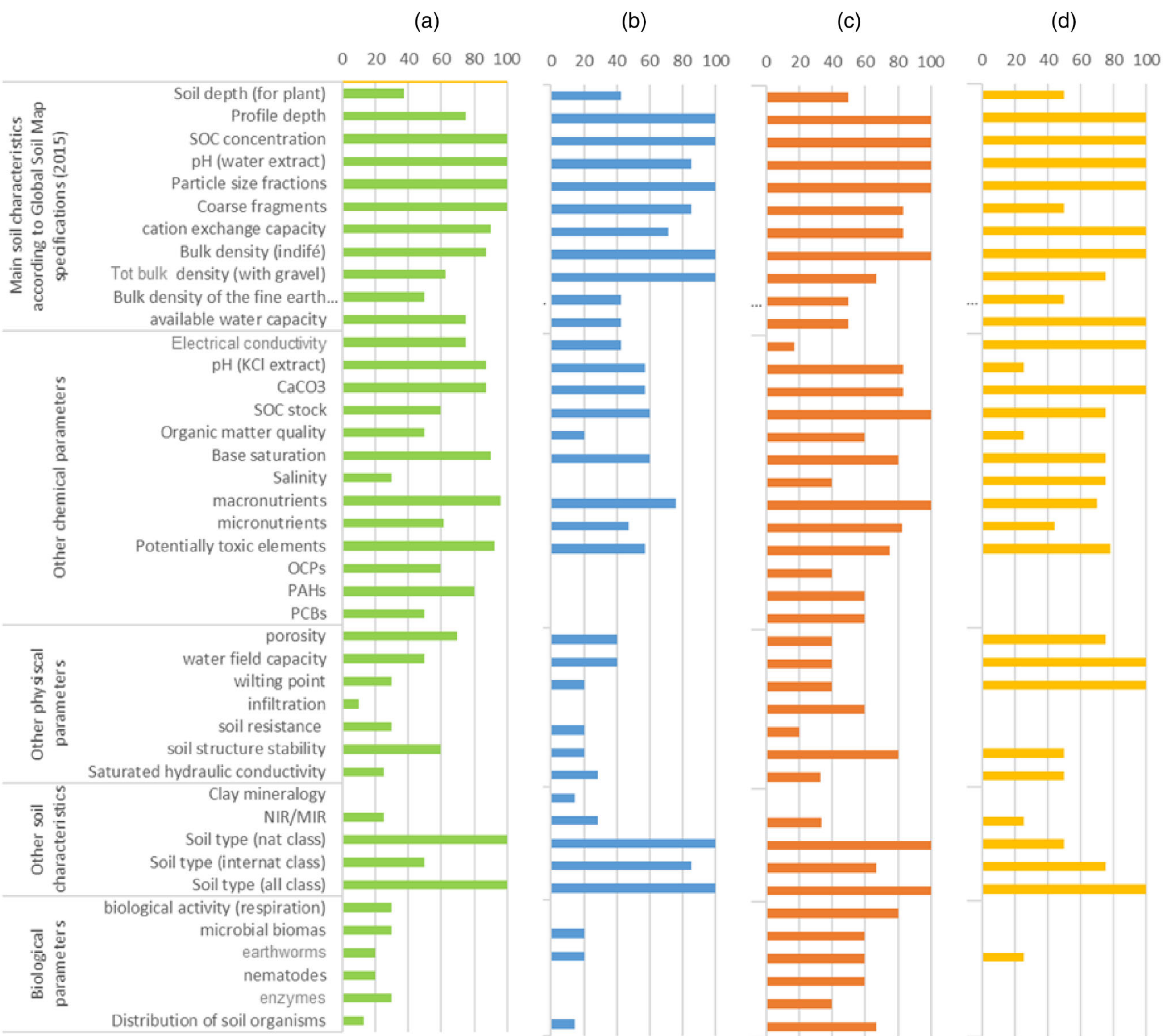

FIGURE 6 Percentage of countries participating to EJP SOIL in the different geographical zones ((a) Central Europe; (b) Northern Europe; (c) Western Europe; and (d) Southern Europe including Türkiye) that includes the different soil parameters in the soil databases they reported in this study. Note that some countries reported only national homogenized soil databases, while other reported local soil databases as long-term experiments.

Overall, biological characteristics are generally the least frequently determined parameters in Europe. When included in databases, they mainly consist of soil respiration measurements (Figure 6) and are mainly present in soil databases from Western Europe (Figure 6c). The other groups of soil parameters are detailed below.

Main soil characteristics according to Global Soil Map specifications (Arrouays et al., 2014), the most often included soil parameters

Globally, the main soil characteristics according to Global Soil Map specifications (Arrouays et al., 2014) are parameters that are most often included in the soil databases of the surveyed European countries. This is likely due to the explanatory potential of these variables in dedicated surveys. However, the situation differs among the parameters. Most countries include in their databases: soil profile depth, SOC concentration, pH in water extract, particle size fractions, and CEC. Bulk density, generally as total bulk density (including gravels), and water holding capacity are included in more than 70% of the country's databases in Western and Central Europe. In less than 50% of the countries, soil depth available for plants and bulk density of fine earth are included in databases (Figure 6). Coarse fragments are included in the databases of most of the Central, Northern and Western European countries, but only in the databases of half of the Southern countries, which is surprising as Mediterranean soils are often gravelly (Rodrigo-Comino et al., 2017).

Other soil characteristics are often missing or heterogeneous among countries

The soil type is usually described using national soil type classifications. For mapping on European scale, this is an impediment since national classifications are often not directly translatable to international soil classification systems. The Southern European countries are an exception as they mainly use international classifications in their databases (Figure 6). Despite this challenge. the Joint Research Centre (JRC) of the European Commission with partners has produced a harmonized soil type map of the Europe according to the World Reference Base (WRB) classification (https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data).

Finally, infrared spectroscopy data are included in one third of the countries' databases. Infrared spectroscopy is a rapid and cost-effective alternative to conventional chemical analysis. With this method, one spectrum can be used to derive many of the soil parameters of interest in the soil databases: SOC (Biney et al., 2020; Gholizadeh et al., 2013; Janik et al., 1998; McCarty et al., 2002; Minasny et al., 2009; Soriano-Disla et al., 2014; Viscarra Rossel et al., 2006), macro- and micronutrients (Bertrand et al., 2002; Vašát et al., 2014), pH extracted either in water or in $CaCl_2$, particle size fractions, CEC, moisture content at 10 and 30 kPa (Gholizadeh et al., 2018; Janik et al., 1998; Soriano-Disla et al., 2014; Viscarra Rossel et al., 2006), trace elements extracted by aqua regia (Gholizadeh et al., 2021; Gholizadeh, Borůvka, & Saberioon, 2015; Gholizadeh, Borůvka, Saberioon, Kozák, et al., 2015; Soriano-Disla et al., 2013, 2014), and even biological activity (Soriano-Disla et al., 2014). These methods could thus be operationalized to fill a gap in the databases of countries that are currently missing some of these parameters. National and international spectral libraries are being developed to make application of this technique practically possible and more accurate (Benedetti & van Egmond, 2021; Brodský et al., 2011; Viscarra Rossel et al., 2016).

Other chemical parameters: Mineral elements are more often included in soil databases than organic components

The chemical parameters included in soil databases are nutrients (macro and micro), pollutants, physico-chemical parameters (as pH measured in KCl extract, EC, base saturation), $CaCO_3$ content and the organic matter quality. While in most countries the macronutrient contents are included in soil databases, micronutrient contents are less often considered (with the notable exception of Western European countries, Figure 6c), most of the time limited to Cu, Mn and Zn. S, Se and Si are not determined in Southern European countries.

The pH in KCl extract is included mainly in the Western and Central European country soil databases. Electrical conductivity is considered in Central and Southern countries, the latter being the only ones to measure salinity. Base saturation and $CaCO_3$ content are measured in all countries but the Northern ones. It seems that these parameters are included in soil databases depending on the characteristics of the soil encountered in the different zones.

Soil contaminants included in soil databases are mainly Cd, Co, Cr, Cu, Ni, Pb and Zn. Hg and As are included less frequently. Soil contaminants are less often included in Northern European countries' soil databases. Contaminations by organic pollutants are only considered by some countries of Western and central Europe (e.g., Maliszewska-Kordybach et al., 2009, Orton et al., 2013; Maliszewska-Kordybach et al., 2014; Ukalska-Jaruga et al., 2020; Froger et al., 2021, for France or Poland).

The soil organic matter quality is generally poorly considered. Despite the importance of this characteristic both in relation to the vegetation and to the stabilization of carbon in the soil, the wide range of methods and ways to evaluate the quality of organic matter as well as the lack of standardized methods (Bispo et al., 2017) might be an obstacle to its systematic inclusion in soil databases.

Other physical parameters are generally poorly documented in soil databases

As already mentioned, soil physical parameters listed in the Global Soil Map specification (Global Soil Map 2015) were not always well considered in soil databases. The situation is worse for other physical parameters describing either the soil structure (porosity, soil penetration resistance, aggregate stability) or the water retention characteristics (soil water field capacity, wilting point, infiltration capacity, saturated hydraulic conductivity).

Among the soil parameters describing the physical state of the soil (porosity, soil penetration resistance, aggregate stability), aggregate stability is reported in 80% of the Western European countries and 60% of the Central European countries, while porosity is mainly reported in the Southern and Central European countries. Only five countries report soil penetration resistance measurements.

Soil hydro-physical or soil water parameters (wilting point, available water capacity and water field capacity, saturated hydraulic conductivity) are included in less than 40% of the soil databases of the surveyed countries with the notable exception of the Southern European countries that all include some of these parameters in their soil databases. This is probably due to concerns about soil water management in these countries due to their long and dry summers. Assessments of water infiltration capacity by the soil are mentioned by only 4 of the 24 countries.

A wealth of much dispersed soil data

The previous analysis shows that while most classical pedological parameters are included in most soil databases, some parameters are still insufficiently considered. For example, coarse element content or fraction, a crucial parameter for any stock evaluation, is present in half of Southern European countries despite the frequency of stoniness in soils in the Mediterranean region. Another crucial parameter for stock calculations is bulk density. While this parameter is included in most databases, the bulk density of the fine earth is much less considered. The latter is the one used in the estimation of the SOC stocks that is generally calculated for fine earth only (<2 mm). This can be one of the reasons why about one third of countries lack information on SOC stocks. This information is vital to assess carbon storage as highlighted at the Climate Summit (COP21) in Paris in December 2015 (Lal, 2021). In addition, the inclusion of a parameter such as bulk density in databases does not mean that the parameter is systematically measured. Often bulk density is missing (Sequeira et al., 2014; Xu et al., 2016; Tifafi et al., 2017), in particular for deep horizons. However, Balesdent et al. (2018) showed that half of the SOC stock was located in the 30–100 cm soil layer, highlighting the importance of having soil information on deeper soil layers. A limitation with many databases therefore is that they only address topsoil. As a result, both for top- and subsoil, bulk densities are often derived using pedo-transfer functions.

For soil contamination, mainly trace elements are included in soil databases, while organic pollutants including pesticides are much rarer or even absent from soil databases of Northern and Southern European countries, and plastics or antibiotics are totally absent. It thus appears that the list of the soil parameters gathered by the different countries is variable and incomplete for indicator development.

3.2.2 | Sharing data, a legal issue

Depending on the database considered, the soil data can be available freely at a website or on request. Indeed, the availability of soil datasets depends on the type of soil data considered. For several countries, the point georeferenced soil data are considered as personal data, therefore falling under the exception for environmental data sharing because of General Data Protection Regulation, which is foreseen in the Directive 2007/2/EC (INSPIRE Directive) and Directive 2003/04/EC on public access to environmental information. This is the case under the legislation of Germany, Spain, Finland, France, Ireland, and Norway. Italy and Sweden state that "public access cannot be given because it adversely affects the interest or protection of any person who supplied the information requested on a voluntary basis without being under, or capable of being put under, a legal obligation to do so, unless that person has consented to the release of the information concerned." To get the consent from landowners for the open disclosure of point georeferenced soil data is, therefore, a prerequisite to overcome these sharing constrains. In the Czechia, Finland, Türkiye, and the UK, instead, the point georeferenced soil data cannot be used to produce maps, nor any other land evaluations, without the approval of the person and/or without their participation to the mapping elaborations. In Belgium and the Netherlands, the point georeferenced soil data is not considered personal data and (public) access is only refused when specifically excluded in land access permissions by land owners. Options to overcome this impediment are easy restricted or dedicated soil data sharing systems, or federated learning (the algorithm visits the data instead of collecting the data to run the algorithm), or re-evaluation of the sensitivity of soil data coordinates and the conflicts between national and EU legislation at the EU level. When soil data are provided in a soil map format, either as polygon or as grid formats, the main data sharing restriction is the recognition of intellectual property rights, that is, the recognition of authorship to the people involved in the maps' elaboration.

4 | DISCUSSION: CONSEQUENCES OF THE SOIL DATA SITUATION IN EUROPEAN COUNTRIES FOR PRESENT AND FUTURE EU POLICIES ON SOILS

Recently the Soil Mission proposed a set of eight objectives to improve soil health in Europe by 2050 (European Commission Directorate for Agriculture, 2021). At least the following five objectives will directly need to consider the soil status and require data to quantify baselines and progress in maintaining or improving soil health: (1) conserve soil organic carbon stocks; (2) reduce soil pollution and enhance restoration; (3) prevent erosion; (4) reduce desertification; and (5) improve soil structure to enhance soil biodiversity.

Even if those objectives are currently not yet precisely defined (i.e., what needs to be measured) it is nevertheless possible to link them with a required minimum soil dataset and check if those data are available.

Note that these objectives are not specific to agricultural soils but also include forest, natural vegetation and urban areas that also provide important services (such as carbon sequestration and habitat for biodiversity). Even if the EJP SOIL project is focused on agricultural soils, some of the reported databases also include other land uses as they were not considered in different databases in the various countries (e.g., France) and other European research project are currently dealing with forest soil, for example, Holisoils (https://holisoils.eu/).

In addition, the soil databases available in each country may also be heterogeneous in the data they integrate: soil parameters, sampling and measurement methods, and date of collection can be different as the result of different campaigns across time. Mixing old data with more recent data to establish target or threshold values or develop maps is problematic as the methods used have changed in time and many of the measured parameters have evolved over the 40 past years, for example, soil organic carbon and nitrogen concentrations evolve with land use changes and management practices, pH with liming and or acid deposition, and bulk density with heavy machine use and loss of soil organic matter. Nevertheless, old data could be remobilised in comparison to more recent data to assess soil characteristics' evolution providing that data have been harmonized over time and may thus have value from a historical perspective. Soil monitoring activities offer this possibility even if the frequency of data collection can be uneven over time. Depending on the size of the country, an annual soil sampling at the same point is generally impossible because of its especially financial and human resource intensiveness. The data collection density of soil sample-based monitoring networks with less frequent return time (5 to 10 or 10 to 15 years) slowly matches with the recurring survey campaigns-like repeating soil inventories (e.g., Germany, France). The spatial pattern of sampling is also changing to better meet the objectives of digital soil mapping, moving from "characteristic" points according to land uses/managements to grids targeting a uniform spatial coverage (e.g., France and the EU-wide LUCAS).

Based on the stock take presented here, data on soil organic carbon content is available in most of the countries, at least at national scale (data may be scarcer at local or regional level), but the lack of data on bulk density or of data for deeper soil layers up to 100 cm in the databases of some countries may be an issue to determine soil carbon stocks. Data availability from different sampling depths depends on specific goals/tasks of the project, despite of a large number of investigations. Differences in presence and availability of data from the past that can be used for baseline or trend calculations can also be a limiting factor. In addition, the lack of data on soil textures may prevent the understanding of carbon sequestration, carbon stock, greenhouse gas (GHG) emissions and total soil quality evaluation for which this soil parameter is a driving factor (Feiziene et al., 2011; Feiziene et al., 2018).

Considering soil pollution, data on trace elements are generally available and may be used to qualify the status of soils. However, because of the fact that natural background concentrations of elements in soils may be high (Birke et al., 2017; Saby et al., 2009) depending on geology, the diagnosis of pollution may be difficult and will require a proper procedure (Baize & Sterckeman, 2001; ISO 19258, 2018). Note that if the definition of soil pollution would include organic contaminants as PAHs, PCBs, or pesticides, the picture is quite different as only few countries have data capacity to report on these.

Erosion is generally not directly measured but modelled (Borrelli et al., 2021; Borrelli et al., 2022; Panagos et al., 2021; Stroosnijder, 2005) using soil data together with climate, land use, land management and landscape information. The different models generally consider the soil organic carbon content, the cation exchange capacity and the texture of soils to calculate a risk of erosion. As all are being quite systematically measured, it will be possible to report on this objective for all countries, although model calibration data is possibly not available everywhere. The same occurs for desertification if its definition only refers mainly to the organic carbon content of soils (Perez-Marin et al., 2022). If other forms of desertification are considered, such as due to salinity for example (Rubio & Bochet, 1998), this will vary per country as soil salinity data is not available everywhere. The Mission objective dealing with soil structure and biodiversity may be the most difficult to assess, let alone quantify across EU countries as data are rare in national databases. This may be because of the difficulty and time needed to measure them in the field. Another reason is that several soil biological properties' change are quite sensitive to measurement circumstances (temperature, moisture, land use) and time of the year. They would therefore benefit from seasonal or yearly estimates (Brammer & Nachtergaele, 2015) compared to a monitoring interval of 5–10 years for soil organic carbon proposed by Black et al. (2008). Soil biological properties are at present among the more expensive to measure (Imbert et al., 2023; O'Sullivan et al., 2017), possibly because it is still a relatively young and developing field of science. Several approaches based on soil DNA extraction and sequencing to address this challenge at larger spatial scales can yet be applied for bacteria and fungi (Dequiedt et al., 2011; Karimi et al., 2018; Orgiazzi et al., 2022) but are still under research for other groups as invertebrates (Kirse et al., 2021). These factors among others result in a still ongoing discussion on relevant parameters and methods to be used, that may also explain the poor number of soil biodiversity data.

This analysis clearly shows that progress reporting at EU member state level will be dependent upon the Soil Mission objective considered. An alternative option could be to define the indicators based on already existing data, allowing most EU countries to report on the Soil Mission objectives. However, this option suffers two main drawbacks: (1) it will lock the system in its current situation (no need to monitor new parameters such as soil biodiversity or soil structure measurements); and (2) it will provide a poor representation of the status of the soils with respect to some of the Soil Mission objectives for which the defined indicators will not be adequate, such as for the sixth objective (Improve soil structure to enhance soil biodiversity) for example.

Reaching the Mission objectives will in addition require the establishment of interpretation values (e.g., normal operating ranges, limit values, thresholds…) to decide upon the status of soils (healthy, not healthy). Setting such values will be a challenge as methods used to measure soil parameters are different across EU countries (e.g. for pH, trace elements, carbon). Such values may be defined (e.g., per region and soil-land use type) using one harmonized dataset and lab and sampling methods. Ideally it could be reached using a unique European dataset such as LUCAS soil, however LUCAS soil data are not representative for all countries because density of LUCAS points differs a lot among countries. Another option would be the application of pedotransfer functions to convert the results obtained with one method to another one. Some pedotransfer functions have been developed to transform pH measured in KCl to pH measured in $CaCl_2$ for example (Kabała et al., 2016; Libohova et al., 2014) or to compare the different SOC lab methods (De Vos et al., 2005 for TOC and LOI; Jankauskas et al., 2006; Chartin et al., 2017: conversion from wet oxidation to dry combustion; Shamrikova et al., 2022,). Another way may be to use a scoring function to develop separate rankings region by region, with the prerequisite that a single standard analytical method is applied in each region: applying the same ranking (or relative scoring) method can result in similar and comparable values making it possible to compare across countries and regions, even if different methods are applied in each region (Fine et al., 2017, Nunes et al., 2021). Other kinds of geostatistical and statistical methods for posterior combination of soil datasets obtained with different soil sampling protocols and analytical standards have been tested by researchers in recent studies (Baume et al., 2011; Ciampalini et al., 2013).

Both (pedo)transfer and scoring functions are currently being tested within EJP SOIL in work package 6. Thanks to the collaboration between JRC and the EJP SOIL countries, a double sampling campaign is currently ongoing, which will permit to have a portion of the LUCAS 2022 soil samples both analysed by the JRC selected central laboratory and the national laboratories. This will permit to elaborate transfer functions between the national and the European standards for soil sampling and lab analyses. It is important to note that until data are interoperable and harmonized across EU partners, comparing data between Member States is not meaningful. At the same time there is added value in the establishment and maintenance of national soil databases and soil monitoring systems because (1) the soil protection laws are applied locally; (2) the choice of meaningful soil indicators, parameters and lab methods and the resulting target and threshold systems depend to some extent on local soil, climate and land use systems; (3) the systems should serve national needs (of stakeholders, land users, policy) as well; and (4) countries do not want to discontinue existing soil monitoring data sequences. This is the reason why work package 6 of EJP SOIL programme is proposing the establishment of a system of national soil databases and monitoring networks, that can be harmonized to a European standard (on sampling protocol, lab methods) which is given by the LUCAS soil monitoring of JRC. Furthermore, the country-driven approach is proposed by EJP SOIL also as a method to overcome the soil data sharing issue and ensure regular update and maintenance of the data.

If soil threats (soil erosion, soil organic carbon loss, nutrient imbalance, soil acidification, soil contamination, waterlogging, soil compaction, soil sealing, salinization and loss of soil biodiversity) need to be assessed, recent initiatives (https://www.eea.europa.eu/publications/soil-monitoring-in-europe) are also pushing for the assessment and valuation of soil-based ecosystem services (i.e., according to Dominati et al., 2010: cultural services—spirituality, knowledge, sense of place, aesthetics among others; regulating services—food mitigation, filtering of nutrients, biological control of pest and diseases, recycling of waste and detoxification, carbon storage and regulation of N_2O and CH_4; provisioning services—of physical support, of food, wood and fibre, of raw materials). Moving from a threat to service vision may foster soil protection. As for the soil threat assessment, to be usable by stakeholders, notably decision makers, these soil data have to be transformed into measurable indicators. However, this will require much more data. As an example, assessing a service such as "regulation of water fluxes and quality" will require basic soil parameters such as those currently gathered in databases (e.g., texture, stone content, pH), but also others that are often not measured at all such as the water infiltration capacity, the diversity and density of earthworm communities able to influence soil macroporosity, the diversity and activity of soil microorganisms that can degrade soil organic contaminants, etc. The relative absence of the soil water parameters from the databases is a true knowledge gap, as this information is crucial for determining and predicting water retention in the soil, influencing hydrological cycles. Such assessments are also needed to better exemplify the role of soils for society and promote its protection. This can be elaborated with similar results for other soil ecosystem services.

5 | CONCLUSIONS AND RECOMMENDATIONS

The launch of the EJP SOIL programme that associates many European countries, allowed to gather and elaborate an unprecedented detailed vision of the current state of the available soil information in Europe at the country scale, which is much needed in the current context of the Mission "A soil deal for Europe" and for the elaboration of a Soil Health Law by the European Commission. This analysis indicates that there is a large disparity in policies on soil monitoring, soil data and soil data access in the different European countries surveyed. This ranges from long standing to recent monitoring and mapping, and from highly organized with a few centralized databases at the country or regional level, to local and more ad hoc databases, and from containing many sampled and described soil points and samples analysed on many properties, to fewer sampling points (per km^2) with less data available per point.

If the aim is to better use the wealth of soil information at the local, regional, national and EU level, for instance for policy development and evaluation or for better informed decision making for land managers and use in, for example, Measuring, Reporting and Verification (MRV) systems for SOC and soil health, several activities need to be undertaken, several of which are planned in the EJP SOIL programme. It should be noted that global surveys on soil databases have not been carried out in the last few years, and it may be expected that similar challenges exist at the global level, to which largely the same possible solutions apply as proposed here for Europe. Pedotransfer and scoring functions need to be tested and developed to support harmonization of data among countries, to produce statistics and maps at the European scale, and identify soil changes over time. In addition, methods need to be developed to combine soil monitoring datasets that are based on different sampling designs for statistically sound statistics on the status or change of a soil property in a given region or country. Soil data access differences should be addressed either by decreasing the variety of different sharing policies or by developing mechanisms that allow authorized use of data for the abovementioned purposes, without sharing the soil point data openly themselves. Options for this are, for example, restricted access for specific purposes or federated learning. More cooperation on (the structuring of) data storage and sharing and acceptance and implementation of developed soil data standards between countries and institutions, or data owners/producers, will result in more harmonized and easily exchangeable soil data at national and EU level. Joint discussion and possibly agreement on soil indicators and their thresholds for soil ecosystem services, soil functions, properties and threats or at least the soil indicator framework to identify thresholds for healthy soils at different soil scales or soil-land use-climate combinations is highly advisable. Attention and additional research on the cost benefit and possibilities of new measurement techniques such as soil spectroscopy and other proximal and remote sensing techniques and of existing measurement methods for soil properties and indicators is needed to make effective choices and keep soil monitoring affordable and of sufficient quality. Standardization of measuring methods is also required through the development and use of ISO TC 190 standards (https://www.iso.org/committee/54328.html) or by joining the Global Soil Partnership initiative GLOSOLAN (Benedetti & Caon, 2021). These recommendations will result in a more systematic harmonization approach to be able to use the wealth of data already available at the European scale while overcoming border and time effects. For countries with no or little information on soil parameters, European soil monitoring in LUCAS is a very valuable starting point to contribute to the harmonized soil monitoring approach. Many of the listed recommendations are addressed in the EJP SOIL programme from a technical perspective. Lastly, a minimal requirement for soil data exchange among the countries and with the EU needs to be defined to allow collaboration on soil protection at the EU level and collaboration with the European Soil Observatory.

AUTHOR CONTRIBUTIONS

Sophie Cornu: Writing – original draft; conceptualization; formal analysis. **Saskia Keesstra:** Writing – review and editing; supervision. **Antonio Bispo:** Writing – review and editing; investigation; formal analysis. **Maria Fantappie:** Writing – review and editing; investigation; formal analysis.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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