The diagnostic continua of the soils of Europe

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Abstract

Diagnostic horizons, properties and materials are commonly applied building units of national and international soil classification systems. The presence, depth or absence of diagnostic information supports the process of objective soil classification, such as the World Reference Base (WRB). While the diagnostic units and associated descriptive qualifiers convey information that reflect pedogenesis, they also indicate important, and often complex properties that are related to soil fertility and other soil functions. The spatial extent or the continuum of diagnostic information is often different from the spatial extent of the mapping units in general soil maps (mostly reflecting soil types). This paper presents the spatial distribution of selected diagnostic units and qualifiers for the European Union and describes their significance for key soil functions. The derivation of selected diagnostics was performed based on the information provided in the European Soil Database and by taking into consideration the definitions, rules and allocation procedure of soils to the appropriate Reference Soil Group (RSG) defined by the WRB key. The definition of the presence/absence of the diagnostic units were performed by extracting information related to the first level of the WRB classification and to the qualifiers provided by the ESDB on the Soil Taxonomic Units (STU) level. The areal percentage of the STUs (thus, the derived diagnostics) within Soil Mapping Units (SMUs) was calculated and was visualized on separate maps. The study demonstrated the importance of the spatial information that the diagnostic elements convey, especially related to soil functions.

Keywords: diagnostic units, World Reference Base, European Soil Database, soil functions

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Introduction

Sustainable land management is based on appropriate soil information (European Commission 2006, p. 231) and on the understanding of the functional capacity of different soils (Bouma, J. *et al.* 2012). The concept of soil functions builds on the soil-based ecosystems services (Haygarth, P.M. and Ritz, K. 2009; Bouma, J. *et al.* 2012). Schulte, R.P. *et al.* (2014) and van Leeuwen, J.P. *et al.* (2017) related five major soil functions to agricultural land use. These include (1) primary productivity, (2) water purification and regulation, (3) climate regulation and carbon sequestration, (4) soil biodiversity and habitat provisioning, and (5) recycling of nutrients. The assessment or estimation of the capacity of a soil to perform these functions depends on complex interaction of soil properties with environment (climate) and management.

In the World Reference Base (WRB) (FAO 1998; IUSS Working Group WRB 2006, 2015) diagnostic horizons, properties and materials are used to define the highest taxonomic level – the Reference Soil Group (RSG) – while qualifiers provide supplementary information and serve to further define the soil type. To be

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considered "diagnostic", these elements must reach a certain degree of expression, which is determined by appearance, measurability, importance, relevance and quantitative criteria. For example, a surface, organic matter rich horizon requires a minimum thickness (20 cm), a minimum level of base saturation (50%) and organic carbon content (0.6%), together with structure and colour criteria to be considered as a mollic horizon.

The diagnostic units and the qualifiers convey information by themselves on complex soil properties, that are the result of soil forming processes, which in turn are related to a range of functions, such as the capacity of a soil to cycle nutrients (Michéli, E. *et al.* 2019). Most soils, belonging to a particular soil type, carry properties that might be characteristic for different other soil types, and the principles and rules of the applied soil classification system support the decision on the eventual soil type (RSGs in the WRB) (Dobos, E. *et al.* 2019).

However, the spatial extent or the continua of the diagnostic units may be, and often is, different from the soil mapping units in general soil maps. Therefore, in studies where the functional capacities of soils are a consideration, it is important to define the spatial extent of the constituent diagnostic units. For example, several RSGs might have hydromorphic properties related to groundwater caused by excess water (gleyic properties), but not all of those soils are classified as Gleysols because of the principles, priorities and construction of the classification key. However, as gleyic properties influence several soil functions, it could be important to define their overall spatial extent in all soils which are affected by hydromorphic properties, regardless of the taxonomic class (soil type).

The most complete and uniform soil map and database for the European Union is the 1:1 Million Soil Geographical Database of Eurasia (EC ESBN 2004; Panagos, P. 2006), hosted by the European Soil Data Center (ESDAC) at the JRC (https://esdac.jrc.ec.europa.eu/). The database provides the percentage of the dominant and all associated soil types per map unit while the visualized units reflect only the dominant soil types (RSGs with one qualifier) of the soil mapping units. The objective of this paper was to derive the spatial extent (in area percentage of the map units and in area percentage of the territory of the EU) of selected diagnostic units which may influence the capacity of the five soil functions in conjunction with environment and management.

Materials

The European Soil Database (ESDB)

The derivation of the selected diagnostics was performed based on the Soil Geographical Database of Eurasia (SGDBE), which is a part of the European Soil Database (ESDB) v2.0 (EC ESBN 2004; Panagos, P. 2006), and covers the interest area of the study, the territory of the European Union and Switzerland. This product is the result of a collaborative project involving all European Union member states and neighbouring countries. The ESDB is a simplified representation of diversity and spatial variability of soil coverage. The database consists of Soil Typological Units (STU), which represent soil names and are described by attributes specifying the nature and properties of the soils. As the original geographical representation (1:1 Million scale) did not allow the spatial delineation of STUs, they were grouped into Soil Mapping Units (SMU) to form soil associations. The associations refer to areal percentage of STUs and represented by one or more polygons in the geometrical dataset. The visualized maps generally present the polygons of the SMUs by representing the dominant STU *(Figure 1).*

The digital database includes further analytical and environmental information for the semantic units. Each dominant STU is also supplemented with a representative soil profile with basic horizon data. The SGDBE consists of a geometrical and a semantic dataset linking attribute values to the polygons. Besides the wide range of attributes defined for the STUs,

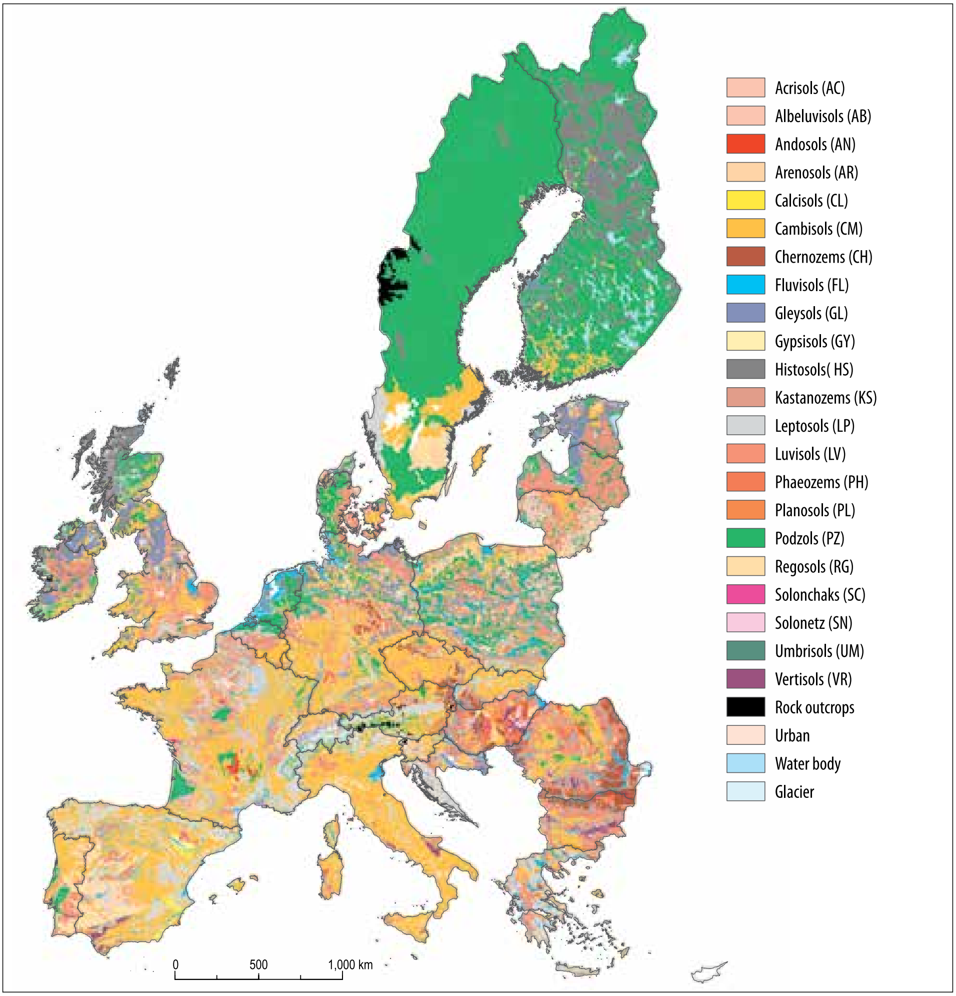


Fig. 1. The soils of the European Union. The distribution of the dominant Reference Soil Groups (WRB 1998) in the European Union and Switzerland according to the European Soil Database.

the database defines the WRB (1998) classification as well. The "WRB-FULL" attribute refers to the group code of the STU from the WRB. The attribute consists of the Soil reference group code (WRB-LEV1) and the first qualifier adjective code (WRB-ADJ1) of the STU.

Figure 1. shows the distribution of the major soil types for the European Union. The colours on the map refer to the RSG which is dominant in the particular SMU according to the ESDB.

The World Reference Base for Soil Resources

The World Reference Base for Soil Resources (WRB) is an international soil classification and correlation system endorsed by the International Union Soil Sciences (IUSS) (Deckers, J. *et al.* 2005). While most countries in the EU developed their own soil classification and mapping systems, the WRB enables the harmonization of soil databases and soil maps from different sources (Jones, A. *et al.* 2005). The 1st and 2nd editions of the WRB (FAO 1998; IUSS Working Group WRB 2006) served as a tool for the correlation of national soil classification units to the ESDB. The WRB consists of two categorical levels. The first level, the Reference Soil Groups (RSG) is defined by the classification key. The RSGs share an assemblage of defined diagnostic features and serve as reference for correlation of national classification units. The second level, the qualifiers, provides additional specific information. The diagnostic information of the RSGs and qualifiers were designed to provide practical considerations and expressions on ecological functions and management strategies. *Table 1.* summarizes the selected WRB units that were used in this study.

All diagnostic features are important for some aspects of soil functions. The selection was based on the expert judgement of the authors to select the ones that are mostly influencing agricultural land management. The information available at the time of the database construction was also considered and was often a limiting factor (eg., mollic horizon was not diagnostic for Umbrisols, or Stagnosols was not among the defined RSGs). Although the cambic horizon is the most common diagnostic horizon (with 26.14% area in the EU) it was not selected. The cambic horizon and the Cambisols are distinguished by moderate subsurface development without distinct features. For the Cambisols, the most informative indications are the associated qualifiers providing more specifics on function related properties, however, the structure of the database allowed only one qualifier.

The *spodic horizons* are also common, occupying 11.61 percent of the studied territory and carry important information on the soil forming environment. They generally develop in sandy material and represent subsurface accumulation of organic matter and iron oxides under leached, acidic conditions, determining limited choices of land use. Since the area percentage of the RSG Podzols for which the spodic horizon is diagnostic are identical no calculations were needed and *Figure 1.* provides the information on the spatial distribution.

The argic horizon is a clay enriched subsurface horizon with higher clay content than the overlying layer. The texture differentiation may be caused by illuvial accumulation of the clay, by destruction or selective erosion of the clay in the surface horizon, by biological activities or combination of causes. The argic horizon is diagnostic for the Acrisols, Albeluvisols, Alisols, Luvisols and Lixisols but may occur in several other RSGs.

The *calcic horizon* is an accumulation of secondary carbonates, mostly in the subsurface. In humid areas it is related to the leaching of the carbonates to deeper depth, while in dry areas the calcic horizon occurs closer to the surface and is often associated with carbonate rich parent material. The calcic horizon is diagnostic for the Calcisols, Chernozems and Kastanozems RSGs.

Gleyic properties are related to reducing conditions caused by saturation with groundwater at a shallow depth for long periods (FAO 2001a, b.) The gleyic properties are diagnostic for the Gleysols.

The *histic horizon* is related to the accumulation of organic material, consisting of partially decomposed plant biomass under wet conditions (Jobbágy, E.G. and Jackson, R.B. 2000; FAO 2001a, b). The slow decomposition is often associated with low temperature as well. The histic horizon is diagnostic for Histosols.

Table 1. Selected WRB units ("Diagnostics") and the RSGs (WRB-LEV1 and qualifiers (WRB-ADJ1) in the ESDB from which they were derived

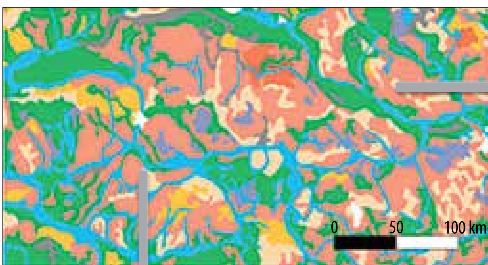
Diagnostics	WRB-LEV1 (RSG)	WRB-ADJ1 (Qualifier)
Argic horizon	Luvisols, Acrisols, Albeluvisols	Luvic (presence of argic horizon)
Calcic horizon	Calcisols, Kastenozems, Chernozems	Calcic (indicating calcic horizon)
Gleyic properties	Gleysols	Gleyic
Histic horizon	Histosols	Histic
Mollic horizon	Chernozems, Kastanozems, Phaeozems	Mollic

The *mollic horizon* is the result of the accumulation of well humified, stable organic carbon in the topsoil, mostly under ancient grassland vegetation (Lal, R. 2000). The mollic horizon is diagnostic for the Chernozems, Kastanozems and Phaeozems RSGs but occurs in other RSGs.

Methods

The derivation of the diagnostics and the qualifiers was performed by taking into consideration the definitions, rules and allocation procedure of soils to the appropriate RSG defined by the WRB key. By having a WRB RSG code (WRB-LVL1), and the first adjacent codes (WRB-ADJ1 (qualifier) for each STU in the ESDB, the definition of the diagnostic horizons, materials and properties is possible. While the areal percentage of the STUs within the SMUs is provided, the same attributes (in percent) were calculated for each of the diagnostics. An example of this approach is presented in *Figure 2*. In this example, SMU1 consist of three STUs. STU1 (Stagnic Luvisol) represents 50 percent, STU2 (Cutanic Luvisol) represents 30 percent and STU3 (Luvic Phaeozem) represents 20 percent of the SMUs' area (making a total of 100%).

Luvisols, by definition, have an argic horizon, while the Stagnic qualifier refers to the presence of Stagnic properties, hence STU1 has an argic horizon and stagnic properties. In STU2, the argic horizon is again present while the Cutanic qualifier indicates the presence of clay skins in the argic horizon (no additional information). Similarly, for STU3, Phaeozems by definition have a mollic horizon, while the Luvic qualifier indicates the presence of the argic horizon, hence STU3 has both mollic and argic horizons. On the visualized map, the entire SMU would be represented by the dominant Stagnic Luvisol STU. The database provides the information on the areal share of the Luvisols (80%) of the SMU. Based on the derived diagnostic information, the argic horizon occurs in the entire SMU and is combined with the mollic horizon in 20 percent of the SMU area and with Stagnic properties in 20 percent of the SMU area.



SMU1	Areal repres.	WRB name	Derived diagnostics
STU1	50%	Gleyic LUVISOL	Argic horizon Gleyic properties
STU2	30%	Cutanic LUVISOL	Argic horizon
STU3	20%	Luvic PHAEOZEM	Argic horizon Mollic horizon

Argic horizon	100%
Gleyic properties	50%
Mollic horizon	20%

SMU2	Areal repres.	WRB name	Derived diagnostics
STU1	50%	Luvic KASTANOZEM	Argic horizon Mollic horizon
STU2	30%	Arenic LUVISOL	Argic horizon
STU3	20%	Gleyic LUVISOL	Argic horizon Gleyic properties

Argic horizon	100%
Mollic horizon	50%
Gleyic properties	20%

Fig. 2. Exemplified derivation procedure of the selected diagnostics based on the Reference Soil Group and qualifier provided information in the ESDB.

Results and discussions

The map series of this study (*Figures 3* to *7*) provide (left) maps of the spatial distribution of the selected diagnostics together with the indication of their percentage area within the SMUs, and (right) the spatial distribution of the RSGs for which they are diagnostic, also with the indication of their percentage area within the SMUs. The areal percentages are given for the territory of the EU plus Switzerland.

The *argic horizon* occupies 17.81 percent of the examined territory *(Figure 3).* This is mostly affiliated to the Luvisols (14.74%), followed by the Acrisols (1.85%) and Albeluvisols (0.26%). The higher clay content in the subsoil influences infiltration and storage of water, nutrient movements and adsorption processes (Avery, B.W. 1983; Bockheim, J.G. and Hartemink, A.E. 2013). It should be emphasized that sampling of only the topsoil for nutrient management, monitoring or other purposes often misses this important information. The presence of a clay accumulation horizon also influences the depth distribution of the stable fraction of soil organic carbon (Torres-Sallan, G. *et al.* 2017), and so can be attributed to climate regulation. Only 0.96 percent of the argic horizons occur in other RGS (Chernozems, Phaeozems, Kastanozems, Planosols, Andosols and Anthrosols), therefore the maps in *Figure 3*, seem very similar. However, in the limited represented area the argic horizon has the same importance on the discussed processes.

The *calcic horizon* occupies 13.36 percent of the examined territory of Europe *(Figure 4)*, however, 11.16 percent of that does not occur in the RSGs for which the calcic horizon is diagnostic (Calcisols, Chernozems, Kastanozems) but in other RSGs (Gleysols, Luvisols, Gypsisols, Planosols, Solonchaks, Solonetz, Vertisols). The accumulated carbonates represent a significant, stable carbon reservoir that has implications on climate regulation (Monger, H.C. and Gallegos, R.A. 2000; Nordt, L.C. *et al.* 2000; Lal, R. 2004). At the same time, the presence of the calcic horizon, especially at shallow depth, is influencing (often limiting) the reaction of soil processes, the availability and cycling of nutrients and also biodiversity (Richter, A. *et al.* 2018).

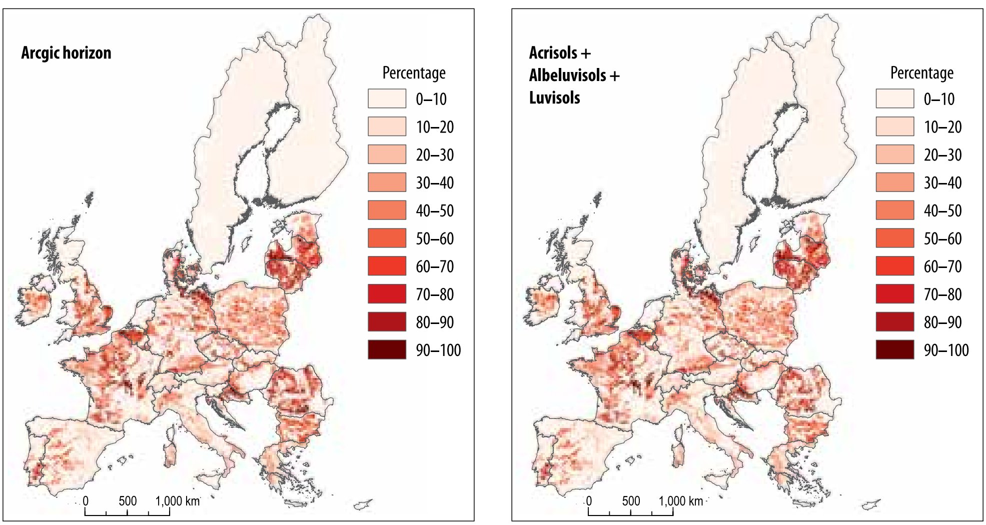


Fig. 3. The spatial distribution of the argic horizon with the indication of their area percentage within the SMUs (left), and the spatial distribution of the RSGs for which the argic horizon is diagnostic (AB, AC, LV), with the indication of their combined area percentage within the SMUs (right).

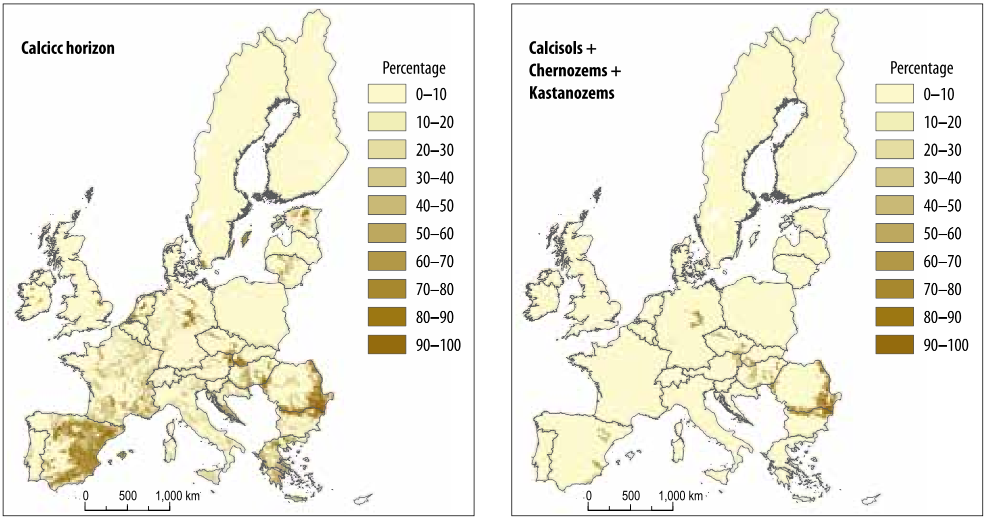


Fig. 4. The spatial distribution of the calcic horizons with the indication of their area percentage within the SMUs (left), and the spatial distribution of the RSGs for which calcic horizon is diagnostic (CL, CH, KS), with the indication of their combined area percentage within the SMUs (right).

Gleyic properties occur in 14.25 percent of the presented territory *(Figure 5)*, however, only 5.30 percent occur in the Gleysols for which the gleyic properties are diagnostic. The rest (8.95%) occur in many other RSGs (Acrisols, Albeluvisols, Cambisols, Chernozems, Fluvisols, Luvisols, Phaeozems, Planosols, Podzols, Regosols, Solonchaks and Umbrisols). Soils with Gleyic properties and the related reducing conditions, often suffer nutrient availability problems, which causes significant changes in soil biodiversity as well (Richter, A. *et al.* 2018). The presence of the gleyic properties may limit the rooting depth of several plants as well. While excess water has favourable influence on carbon sequestration and hence on part of the climate regulation function (Lal, R. 2004), we must also consider the other aspects of climate regulation, such as nitrous oxide and methane emissions which are strongly positively influenced by excess soil water for prolonged periods of time, as defined by the Gleyic properties (Anthony, T.L. and Silver, W.L. 2021).

Histic horizons occur in 6.66 percent of the territory of the EU and Switzerland *(Figure 6)*. Most of them (6.48%) occur in the Histosols, for which the histic horizon is diagnostic, while only 0.18 percent occur in other RSGs (Albeluvisols, Andosols, Fluviosls, Gleysols, Podzols, Planosols). The spatial distribution of Histosols well represents the distribution of the important diagnostic horizon. The histic horizon stores a significant portion of the organic matter of the world soils (Batjes, N.H. 1996; Lal, R. 2004; Jones, A. *et al.* 2005) and plays an important role in climate regulation. Their moisture and nutrient holding capacity are also important in the water and nutrient cycles. Therefore, management decisions should consider the preservation of histic horizons.

The *mollic horizon* occurs in 5.63 percent of the examined territory *(Figure 7)*, of which 3.62 percent occurs in the Chernozems, Kastanozems and Phaeozems, for which it is diagnostic according to the applied version of the WRB 1998. These soils are regarded as highly fertile soils, however, the mollic horizon serves the same important role in the many other RSGs (Andosols, Cambisols, Fluvisols, Gleysols, Leptosols, Planosols,

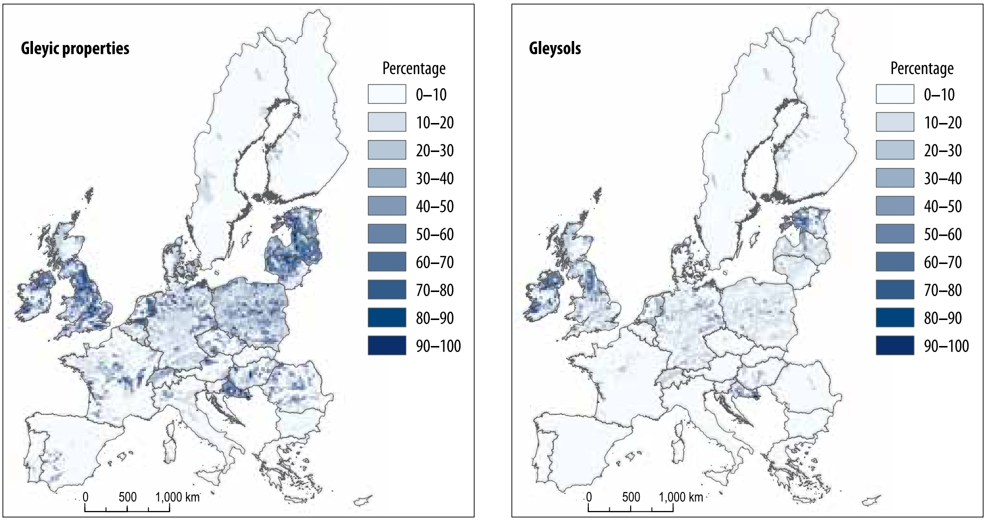


Fig. 5. The spatial distribution of the gleyic properties with the indication of their area percentage within the SMUs (left), and the spatial distribution of the RSG, the Gleysols for which is gleyic properties are diagnostic, with the indication of the area percentage within the SMUs (right).

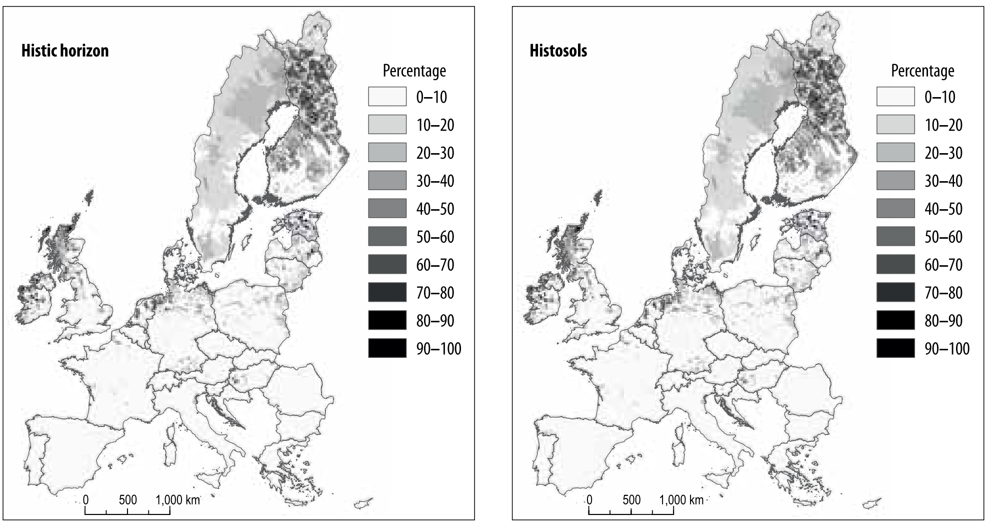


Fig. 6. The spatial distribution of the histic horizon with the indication of their area percentage within the SMUs (left), and the spatial distribution of the RSG, the Histosols for which the histic horizon is diagnostic, with the indication the area percentage within the SMUs (right).

Solonetz, Solonchaks) which occurs in 2.01 percent of the area. The mollic horizon has favourable physical and chemical properties. It is an important factor in relation to the water and nutrient holding capacity of soils (Sauerbeck, D.R. 2001) and is also a favourable habitat for biodiversity. The organic carbon that is stored and preserved in mollic horizons are important for climate regulation as the oxidation of the accumulated organic

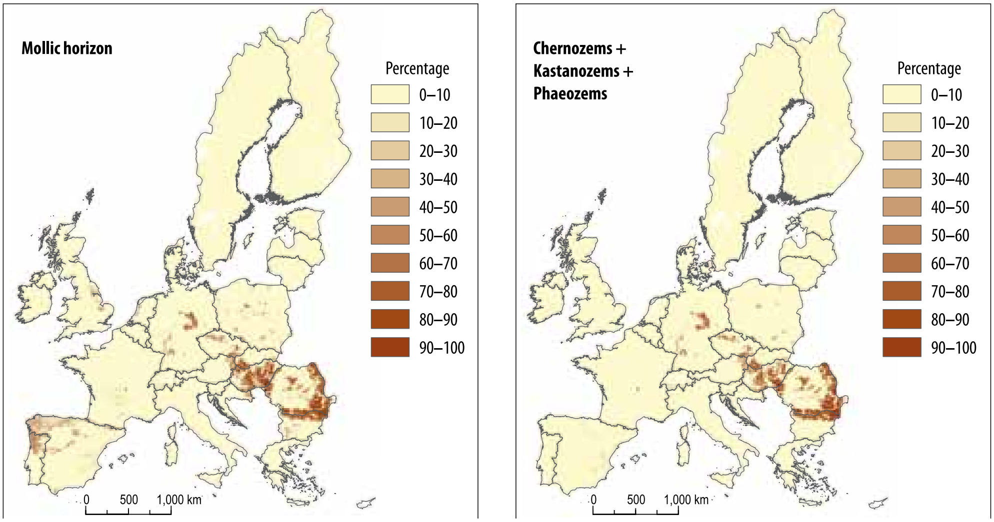


Fig. 7. The spatial distribution of the mollic horizon with the indication of their area percentage within the SMUs (left), and the spatial distribution of the RSGs (CH, KS, PH) for which the mollic horizon is diagnostic, with the indication the area percentage within the SMUs (right).

matter in cultivated soils may contribute to greenhouse gas emissions (Schlesinger, W.H. 2000; Lal, R. 2004).

Conclusions and limitations

In this paper we demonstrated the importance of the spatial definition of the diagnostic units and qualifiers, regardless of the RSGs, as they carry important information by themselves. With the described methodology, it was possible to extract all diagnostic information and define their areal percentage within the SMUs, thus, providing important information on the functional capacities of the areas covered. In addition to the units selected for this exercise, other diagnostic units and qualifiers could be presented. It must be stated that only one qualifier is provided to the RSGs in ESDB, while several more might be relevant to certain STUs, which might influence the percentage of the extent. The other limitation is that the exact spatial definition with the currently available map and database is not possible. Beside the identified presence of the diagnostics and qualifiers, their depth distribution is often an important issue. The ESDB was released in 2001 and updated in 2006, Since that time national databases and maps were improved or developed, while the 2nd and 3rd editions (2006, 2014) of the WRB were published.

However, the small scale of ESDB does not support field-scale management planning the result of this research can be the starting point to understand the diagnostic continuum of soils across Europe. Considering the importance of proper land use planning and the wealth of the European Union, it is suggested to encourage national soil data providers to make high spatial resolution soil data and associated semantic information more available. It is also important to emphasize that in upcoming surveys and data collection all the diagnostics should be established from observation and data and not be extracted from the classification.

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