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Assessing soil biodiversity potentials in Europe

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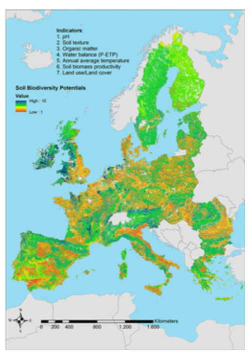
HIGHLIGHTS

- The overall potentials for soil biodiversity throughout Europe is assessed and mapped
- Some indicators that might affect the conditions of soils are used with thresholds
- Close to half of European soils (47%) has an average soil biodiversity potential
- The highest potentials in soil biodiversity levels found in pastures and grasslands
- Ireland, Slovenia and Sweden has the highest soil biodiversity potentials

GRAPHICAL ABSTRACT



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ABSTRACT

Soil is important as a critical component for the functioning of terrestrial ecosystems. The largest part of the terrestrial biodiversity relies, directly or indirectly, on soil. Furthermore, soil itself is habitat to a great diversity of organisms. The suitability of soil to host such a diversity is strongly related to its physico-chemical features and environmental properties. However, due to the complexity of both soil and biodiversity, it is difficult to identify a clear and unambiguous relationship between environmental parameters and soil biota. Nevertheless, the increasing diffusion of a more integrated view of ecosystems, and in particular the development of the concept of ecosystem services, highlights the need for a better comprehension of the role played by soils in offering these services, including the habitat provision. An assessment of the capability of soils to host biodiversity would contribute to evaluate the quality of soils in order to help policy makers with the development of appropriate and sustainable management actions. However, so far, the heterogeneity of soils has been a barrier to the production of a large-scale framework that directly links soil features to organisms living within it. The current knowledge on the effects of soil physico-chemical properties on biota and the available data at continental scale open the way towards such an evaluation. In this study, the soil habitat potential for biodiversity was assessed and mapped for the first time throughout Europe by combining several soil features (pH, soil texture and soil organic matter) with environmental parameters (potential evapotranspiration, average temperature, soil biomass productivity and land use type). Considering the increasingly recognized importance of soils and their biodiversity in providing ecosystem services, the proposed approach appears to be a promising tool that may contribute to open a forum on the need to include soils in future environmental policy making decisions.

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1. Introduction

Soil is one of the most diverse habitats on earth and contains the most diverse assemblages of living organisms. Soils are home to over one fourth of all living species on earth, and one teaspoon of garden soil (about one gram) may typically contain one billion bacterial cells (corresponding to about ten thousand different bacterial genomes), up to one million individual fungi, about one million cells of protists, and several hundreds of nematodes (EU, 2010). Therefore, soils are a key reservoir of global biodiversity, which ranges from micro-organisms to flora and fauna (FAO, 2015).

Soil biodiversity refers to all organisms living in the soil. Turbé et al. (2010) defines it as "the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes". The biodiversity of a soil is vital as it is the engine driving soil-based ecosystem services such as food production, nutrient cycling, carbon sequestration, soil formation, decontamination and bioremediation of pollutants, control of pest outbreaks and water purification (Turbé et al., 2010). Soil biodiversity should also be considered as a guardian of food security and ecosystem services in the face of climate change because of its "considerably more complex and thus more resistant structure to change than aboveground organisms (Veresoglu et al., 2015)".

Even though no legislation or regulation exists that specifically targets soil biodiversity, the European Commission acknowledged the importance of soil biodiversity in the role of ecosystem functioning, stating that "these functions are worthy of protection because of their socio-economic as well as environmental importance" (Stone et al., 2016). Further, "biodiversity pool, such as habitats, species and genes" soil function is mentioned in the UN "Sustainable Development Goals (SDGs)" for the period 2015–2030 by relating the topics "ensure healthy lives and promote well-being for all at all ages" and "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (Keesstra et al., 2016). FAO also recognises the fundamental role of soil biodiversity in supporting and safeguarding soil functions and soil ecosystem goods and services in principle 8 of the revised World Soil Charter (FAO, 2015). Moreover, the decline in soil biodiversity is identified as one of the 8 main soil threats in the Thematic Strategy for Soil Protection (COM (2006) 231). The threat is considered as the reduction of forms of life living in soils, both in terms of quantity and variety (Jones et al., 2005) and of related soil functions (Huber et al., 2008). Whenever soil biodiversity decline occurs, it can significantly affect the soils' ability to normally function, respond to perturbation and recover. Decline in soil biodiversity is usually related to other deteriorations in soil quality and can be linked with other threats like erosion, organic matter depletion, salinization, contamination and compaction (Stolte et al., 2016). Soil biodiversity assessment and biological monitoring is required to correctly assess soil degradation and correlated risks and also soil quality (Menta, 2012).

Despite its importance in global ecosystem functioning, the sustainability of agriculture, and the high value of the numerous ecosystem services that it provides, soil biodiversity has often been overlooked in global assessment and mapping studies (Constanza et al., 1997; Pimentel et al., 1997; Gardi et al., 2013). This has occurred for various reasons, including the fact that the soil biota is usually hidden from view and so suffers from being 'out of sight and so out of mind' (Jeffery and Gardi, 2010). Furthermore, there is a lack of soil biodiversity data at different scales (from field scale up to regional scales and beyond) and the lack of awareness of the value of soil biodiversity. Therefore, the spatial assessment of the potential of soils to serve as a biodiversity pool across Europe, which is the main goal of this study, is very important.

1.1. Threats to soil biodiversity

This connection of soil biodiversity with other soil degradation processes was already recognized by Turbé et al. (2010) who describe the main threats to soil biodiversity as soil degradation, land use management and human practices, climate change, chemical pollution as well as genetically modified organisms (GMOs), and invasive species. Gardi et al. (2013) and Orgiazzi et al. (2016) added or further specified habitat fragmentation, intensive human exploitation, soil organic matter decline, soil compaction, soil erosion, soil sealing, and soil salinization as important threats.

To mitigate the threats to soil biodiversity; the development of indicators and establishment of monitoring schemes to track soil biodiversity (Stone et al., 2016), as well as reaching adequate levels of knowledge by assessing spatial and temporal (Menta, 2012) distribution of soil biodiversity potential along with threats to soil biodiversity are considered important solutions. At the same time, assessing soil biodiversity potentials is also a helpful tool for building monitoring schemes for soil biodiversity, as such assessments highlight regions with high and low potentials, giving an indication where monitoring stations may be most appropriate.

1.2. Soil biodiversity data for mapping purposes

Although there are several studies on assessing soil properties (e.g. LUCAS topsoil survey (Toth et al., 2013), Global gridded soil information; SoilGrids (Hengl et al., 2014), SOC distribution with combined dataset (LUCAS, BioSoil and CZOs) (Aksoy et al., 2016)) and soil threats (erosion (Panagos et al., 2015), compaction, pollution, desertification, etc.) at European level, indicators related to (the decline of) soil biodiversity are measured very rarely at an appropriate scale or resolution (Morvan et al., 2008).

The general state of soil biodiversity is well described in the European Atlas of Soil Biodiversity (Jeffery et al., 2010) with the contribution of the distribution maps of soil faunal groups (e.g. Tardigrades, Rotifers, Nematodes, etc.) of Europe, which show the estimated number of species per biogeographic areas or countries in NUTS-0 level.

Rutgers et al. (2016) have recently published the map of earthworm communities in Europe where earthworm data were collected and harmonized for the Netherlands, Germany, Ireland, Northern Ireland, Scotland, France, Slovenia, Denmark and small part of Spain. Griffiths et al. (2016) recently published a study on predicting and mapping soil bacterial biodiversity using European and national scale data sets using geostatistical methods.

Further, there are a number of national surveys which include soil biodiversity, such as in the Netherlands (BISQ; Rutgers et al., 2009), France (RMQS; Cluzeau et al., 2009), the UK (Countryside survey; Black et al., 2003), and Germany (BDF; Römbke et al., 2013) (Breure, 2004; Stone et al., 2016). Some EU projects have equally looked into monitoring schemes for soil biodiversity over the last 20 years (ENVASSO - Kibblewhite et al., 2008; Bispo et al., 2009; EcoFINDERS -Stone et al., 2016; BioSoil - Hiederer et al., 2011).

Despite the availability of these studies, Tsiafouli et al. (2015) highlight the lack of an integrative approach, with many of the above studies focussing on only one aspect of soil biodiversity (e.g. species richness, abundance, food webs, community structure), promoting the need for more multi-factorial approaches. Similarly, a map reflecting the spatial distribution of the potential of soils to serve as a biodiversity pool across Europe, synthesising information across soil biota, has not been generated until now. Therefore, the main objective of this study is assessing and mapping the overall potentials for soil biodiversity in Europe based on available variables.

1.3. Driving factors

Soil is a challenging habitat and finding clear and unambiguous relationships between soil characteristics and the overall soil biodiversity is very difficult. However, as a rule of thumb it can be considered that soil biodiversity will increase with increasing variability of the micro-

Table 1
Data sets and their source.

Indicator	Name of the source	Version/Year of the data set	Website
Soil pH	EFSA Spatial Data set	Version 1.1	http://esdac.jrc.ec.europa.eu/content/european-food-safety-authority-efsa-data-persam-software-tool
Soil texture (ESDB textural classes)	JRC ESDB database	Version 2	http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB/Index.htm
Soil organic matter	EFSA Spatial Data set	Version 1.1	http://esdac.jrc.ec.europa.eu/content/european-food-safety-authority-efsa-data-persam-software-tool
Water balance (P-ETP)	ETC-ULS calculation (based on P and ETP)	2015	
Precipitation (P)	EFSA Spatial Data set	Version 1.1	http://esdac.jrc.ec.europa.eu/content/european-food-safety-authority-efsa-data-persam-software-tool
Evapotranspiration (ETP)	JRC MARS Unit	2015	https://ec.europa.eu/jrc/en/mars
Annual average temperature	EFSA Spatial Data set	Version 1.1	http://esdac.jrc.ec.europa.eu/content/european-food-safety-authority-efsa-data-persam-software-tool
Soil biomass productivity	ETC-ULS + JRC	2015	Toth et al., 2013
Land Use/Land cover	CORINE Land Cover (CLC)	V16	http://www.eea.europa.eu/data-and-maps/data/corilis-2000-2

environment in the soil, whereas extreme conditions (very wet/dry or hot/cold climates, etc.) are associated with a lower soil biodiversity.

The most suitable habitats where the underground species can live change for each of the species, for example soil organisms are mostly concentrated around roots and in the litter-rich top layer. These habitats are shaped by processes acting at nested spatial scales. At the scale of entire landscapes, climate and soil texture set an envelope of possible habitat conditions. At an intermediate ecosystem level, variable factors influenced by land use and management, such as soil pH and organic matter content, determine the prevailing conditions of the habitat (Turbé et al., 2010).

Further, soil biodiversity varies in terms of its taxonomic richness, relative abundance, function and distribution per soil type, vegetation, land use, land management and climatic conditions (Lemanceau et al., 2016; Thomson et al., 2015; Lemanceau et al., 2014). This means that some soil-forming factors are seen as direct determinants of soil biodiversity.

Generally, climate change, land use change, pollution, invasive species, and any factor contributing to soil degradation can impact biodiversity (Brevik et al., 2015). Many studies (Trasar-Cepeda et al., 2008; Mills and Ad, 2011; Lohaus et al., 2013; Bartz et al., 2014) have quantified the impact of land management and land use on the diversity and functioning of soil biota (Creamer et al., 2016). Increasing agricultural intensity, for example, has been shown to generally reduce soil biodiversity (e.g. Tsiafouli et al., 2015). More specifically, the main driving forces that influence biodiversity in agricultural soils are intensification of land use, crop rotation and crop species, fertilizers and pH, type and frequency of periodic tillage, pesticides application and pollution (ecotoxicological studies) (Breure, 2004).

The activity, abundance and diversity of soil organisms are also regulated by a hierarchy of abiotic and biotic factors. The main abiotic factors are climate (including temperature and moisture), soil organic matter, soil texture and soil structure, salinity, and pH (Turbé et al., 2010). Due to the reliance of soil biological community structure and activity on the stability of abiotic and biotic soil properties, any change in these conditions may precipitate a shift in biodiversity.

In line with the above driving factors, measures that may promote soil biodiversity include reduced soil tillage, increasing soil organic matter, erosion control, prevention of soil sealing and surface mining activities, and prevention of extreme soil perturbation (Keesstra et al., 2016). Wall et al. (2015) analysed the benefits of soil biodiversity on human health, suggesting some agro-ecological management options, such as reduced tillage with residue retention and rotation, cover crop inclusion, integrated pest and soil fertility management, drainage water management, etc.

All in all, many factors have been identified as determinants of soil biodiversity patterns but the relative contributions of each of these factors is still largely unknown (Keesstra et al., 2016). To maintain soil biodiversity, it is essential to take into account the spatial distribution of belowground organisms with the help of the in recent years' accelerated available biogeographical information technologies (Wall et al., 2015). Mapping the spatial distribution of the potential of the soil to host the biodiversity pool, the subject of this study, responds to this call.

2. Material and method

2.1. Material

Despite the absence of clear and unambiguous relationships between soil and other relevant parameters and the overall soil biodiversity, the most likely spatial locations of soil biodiversity can be identified by formulating general assumptions based on the information available. The variables that are used in this study for the assessment of soil biodiversity potentials in Europe are chosen based on a literature review and additional expert knowledge on the conditions that affect soil biodiversity. The selected variables are pH, soil texture, soil organic matter, potential evapotranspiration, average temperature, soil biomass productivity and land use. Their relations and interactions with soil biodiversity are described more in detail below. The sources of the data sets used in this study are given in Table 1.

Relationships with soil pH are controversial; there are taxa for which a direct relationship with pH has been observed, while for other taxa the relationship is negative. Changes in soil pH can affect the metabolism of

Table 2
Threshold and score of the indicators which might have strong effect on soil biodiversity (Legend: P-ETP, potential evapotranspiration; ESDB, European soil database; Textural class codes: 1. Coarse; 2. Medium; 3. Medium-fine; 4. Fine; 5. Very fine).

Variable		Value thresholds and related scores				
1. pH (−)		<4	4–5.2	5.2–8.2	>8.2	
	Score	1	2	3	2	
2. Textural classes (ESDB classes)		1	2	3	4	5
	Score	1	2	2	2	2
3. Organic matter (%)		<1	1–2	2–4	>4	
	Score	1	2	3	4	
4. P-ETP (mm)		<−500	−500–500	>500		
	Score	1	2	3		
5. Annual average temperature (°)		<5	5–20	>20		
	Score	1	2	1		
6. Soil biomass productivity		Poor	Average	Good		
	Score	1	2	3		
7. Land Use/Land cover		Artificial	Arable	Permanent crops	Others	
	Score	0	1	1,5	2	

species (by affecting the activity of certain enzymes) and nutrient availability, and are thereby often lethal to soil organisms. The availability of phosphorus (P), for example, is maximized when soil pH is neutral or slightly acidic, between 5.5 and 7.5. Soil pH (in water) values lower than 5.2 exclude the possibility to host anecic earthworms, for instance. Griffiths et al. (2016) showed a very strong relationship/correlation

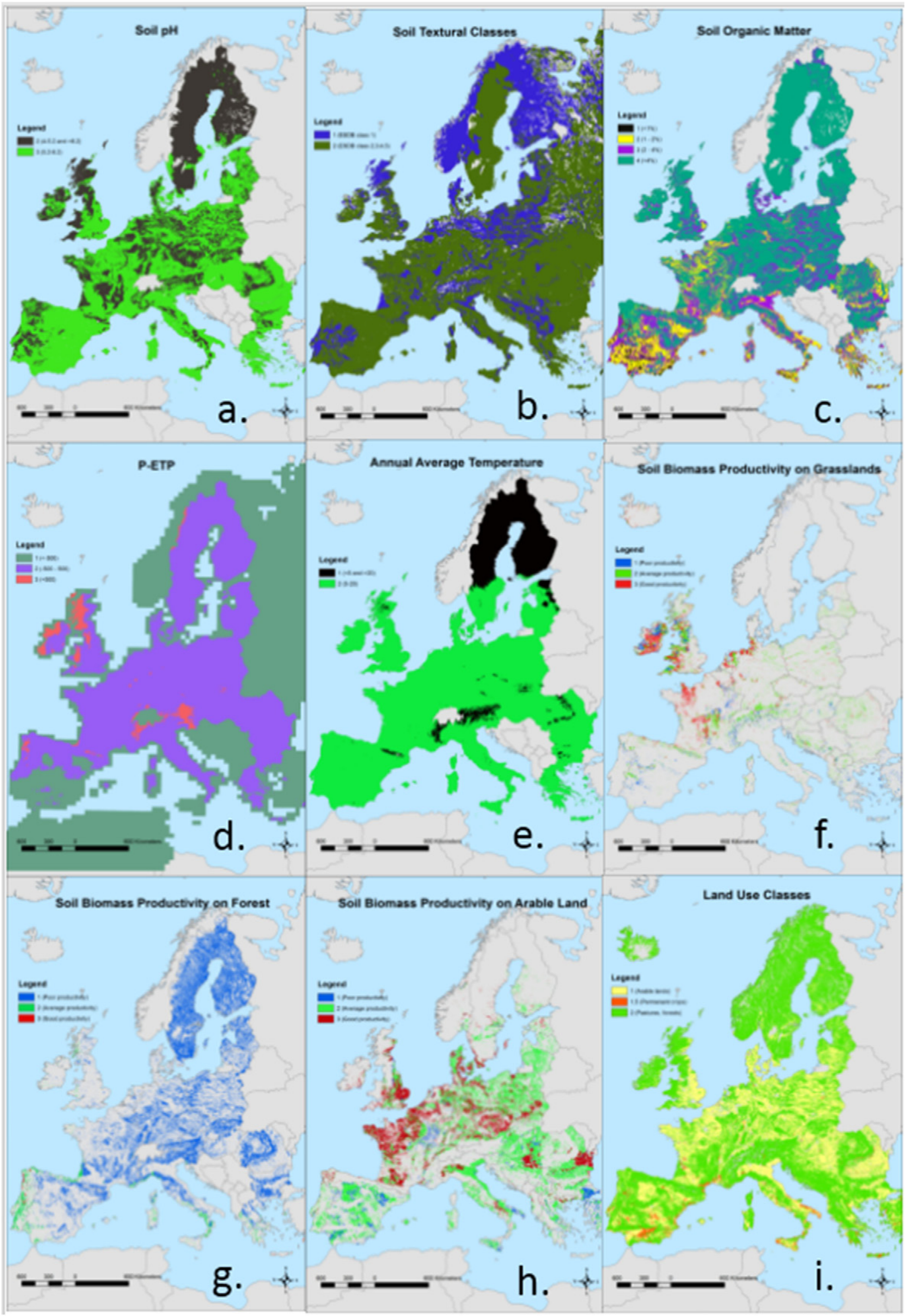

Fig. 1. Maps of the indicators defining soil biodiversity, classified according to the given thresholds. a.Soil pH, b. Soil textural classes, c. Soil organic matter, d. P-ETP, e. Annual average temperature, f. Soil biomass productivity on grasslands, g. Soil biomass productivity on forest, h. Soil biomass productivity on arable land, i.Land use classes.

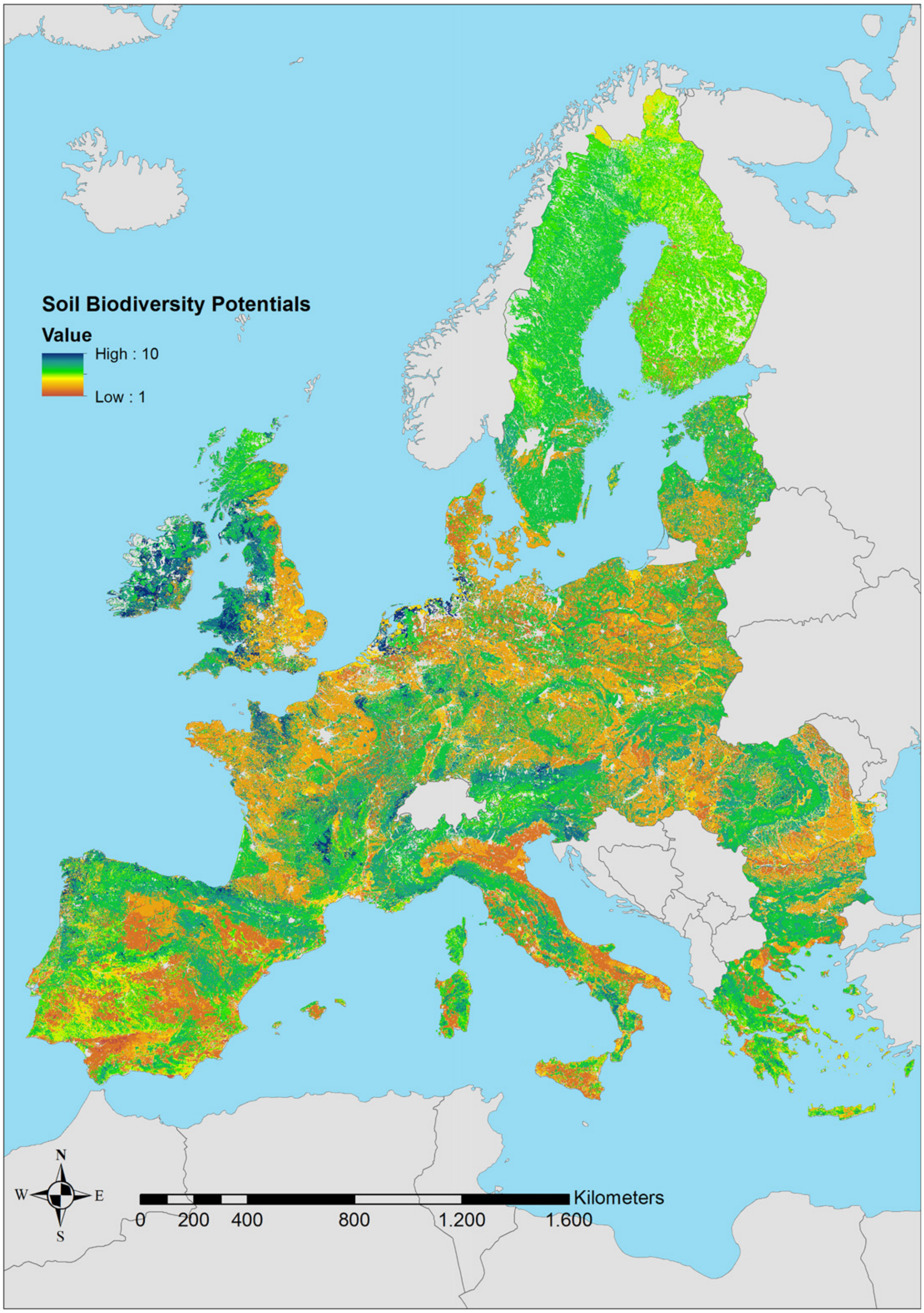

Fig. 2. Map of the potential of soils to serve as a soil biodiversity pool (Index).

($R^2 = 0.91$, $p < 0.001$) between soil bacterial biodiversity, and pH. Based on the modelled relationship between soil pH and bacterial biodiversity found for the surveyed soils, they could predict biodiversity in soils for which soil pH data had been collected as part of national scale monitoring.

As to soil texture, coarser soil generally hosts a more limited contingent of biodiversity. The presence of a wide range of pore sizes determines the coexistence of several micro-habitats, facilitating the presence of several species, even with contrasting ecological profiles. For example, medium-textured loam and clay soils favor microbial and earthworm activity, whereas fine-textured sandy soils, with lower water retention potentials, are less favorable. Soil microorganisms live within the pores left between soil particles, free or attached to surfaces, such as in water films surrounding soil particles (Stotzky, 1997). The pore space can be of various shapes and sizes, depending on the texture and structure of the soil. Texture characterizes the relative importance of clay (<5 μm), silt (5–50 μm) and sand particles (>50 μm). The smaller the particles, the more space they leave between them that can be filled

Table 3
Level of soil biodiversity and the area covered in Europe (Index values goes from 1 to 10, poor potential has the lowest value which is 1, good potential has the highest score which is 10).

Soil biodiversity level	Total area (%)
1	0,3
2	10,8
3	21,6
4	4,8
5	4,4
6	12,1
7	29,9
8	11,0
9	3,7
10	1,4

by water and/or soil organisms. Indeed, a high density of small pores can result in less water availability for plants and small animals due to the intrinsic physical properties of water. For instance, clay soils have many small particles which make them more porous, whereas sandy soils have coarser particles. Accordingly, the surface area of pore space can exceed 24,000 m^2 in 1 g of clay soil, and this area decreases as the silt and sand contents increase (Gardi et al., 2009). According to Alvarez et al. (2002), fine-textured soil (<50 μm) has a protective effect on total microbial biomass, due to the higher proportion of micropores compared to sandy soil which limits *meso* fauna development. Soil texture also largely determines other soil characteristics, such as pH and organic matter content. Fine-textured soils typically contain greater quantities of organic matter and microbial biomass than coarse-textured soils (Meliani, 2012). Bonneau and Souchier (1994), demonstrated that this fine texture promoted the bacterial growth (i.e., clay humic complex). Clay-sized particles are thought to protect organic matter through adsorption and aggregation and shelter soil microorganisms from predation (Elliott et al., 1980). Given the poor water retention capacity of sandy soils, nutrients and lime will be easily washed out, making these soils more acidic. Moreover, clay minerals can form aggregates with the humic compounds in the soil, thereby protecting organic material and affecting its availability in the soil. Soil organisms also directly modify soil architecture, creating further habitats within the pores, by building networks of solid structures. (Turbé et al., 2010).

Organic matter represents the engine of the soil food web, and consequently a positive relationship between organic matter content and the level of soil biodiversity can be assumed. Contrary to aboveground biodiversity, soil biodiversity is not strongly regulated by competition, and competitive exclusion does not occur when resource availability in the soil is increased (Wardle, 2002). Hüttl et al. (2007) discuss optimal carbon values and refer to the fact that "the optimal soil biological activity correlates with organic matter values between 1.5 and 3.5%", in their study. For example, at 10% organic matter, decomposition would take 2 to 10 times longer than at the 'optimal' value range; below this range, decomposition is reduced up to one third. However, the main reason for the reduced decomposition under very low organic matter conditions is due to the low productivity (reduced amount of substrate for microbial growth) (Bartz et al., 2014). Although the mineralization of organic matter is currently considered as redundant, a positive relationship has recently been established between this function and the number of microbial species (Tardy et al., 2014), with mineralization falling significantly when microbial diversity is reduced; similarly, a loss of biodiversity was shown to affect the nitrogen cycle (Philippot et al., 2013b). Such effects of soil biodiversity on the mineralization of organic matter directly impacts the release of mineral elements but also the emission of CO_2, and therefore soil fertility and environmental quality, respectively (Lemanceau et al., 2014). De Graaff et al. (2015) revealed significant negative effects of loss of soil biodiversity on rates of soil respiration and litter decomposition in his quantitative analysis. According to this study, declines in soil biodiversity could significantly affect the rates and dynamics of C cycling. Recently, Kergunteuil et al. (2016) found that nematode abundance and diversity increased with providing available organic carbon sources based on progressive increase of the amount of organic carbon entering to the soil food webs from nematode food sources at high elevation (below 3000 m), besides other biotic factors.

Climate influences the physiology of soil organisms, such that their activity and growth increases at higher temperatures and soil moistures. As climate conditions differ across the globe, and, in the same places, between seasons, the climatic conditions which soil organisms are exposed to vary strongly. Soil organisms vary in their optimal temperature and moisture ranges, and this variation is life-stage specific, e.g. larvae may prefer other optima than adults. For instance, the optimum average temperature for springtail survival is just above 20 °C, with the higher limit around 50 °C, while some bacteria can survive up to 100 °C in resistant forms. Banerjee et al. (2009) found a very strong positive correlation of the abundance and group diversity of soil mite with soil moisture in their study. Similarly, Kergunteuil et al. (2016) also found that higher nematode abundance at mid- to high-elevation is most probably linked with the observed increase in soil moisture at high elevation which is related to higher rainfall frequency and amount. The increasing CO_2 concentrations in the air due to climate change modifies temperature and precipitation rates, and all of them together modify the availability of soil organic matter (Turbé et al., 2010) which is the main source of food and might significantly affect the growth and the activity of the organisms in the soil. However, some studies also discuss that soils may be insulated against many drivers of climate change, including drought, warming and extreme events; for example, natural CO_2 levels in the soil atmosphere are much higher than in the air above, because of soil biological activity (including root and microbial respiration) coupled with gas diffusion limitation; and also, soil offers temperature insulation, and at the microscale it may be partially insulated against drought events through capillary water reserves (Veresoglu et al., 2015). To cover different effects of climate including those that soil biodiversity are less protected from, both annual average temperature and water balance (P-ETP) have been used in this study.

Soil biomass productivity: The positive relationship between microbial biodiversity and productivity (fertility) was clearly demonstrated during analyses of plant-microorganisms interactions in the study of van der Heijden et al. (1998). The activity and diversity of soil organisms are directly affected by the reduction of soil organic matter content, and indirectly by the reduction in plant diversity and productivity (Turbé et al., 2010). In agricultural systems, soil-borne pathogens can disrupt the metabolic flow of nutrients within plants, reduce plant above and belowground biomass, or even kill the plant entirely (Wall et al., 2015). Van Groenigen et al. (2014) reveals that average earthworm presence in agroecosystems leads to a 25% increase in crop productivity

Table 4
Summary statistic of the soil biodiversity index levels by major land use classes.

Value	Count	Min	Max	Mean	Standard deviation	Sum	Variety	Majority	Minority	Median
Arable Lands	1,530,082	1	10	3,50	1,68	5,362,525	10	3	10	3
Forests	1,309,477	1	10	6,80	1,18	8,909,947	10	7	1	7
Pastures, Grasslands, Shrubs	811,963	1	10	6,92	1,67	5,615,736	10	7	1	7
Open Spaces with little green	38,782	1	10	6,19	1,07	240,135	10	7	10	6

Table 5
Statistical information of soils according to their biodiversity potential per country.

Country	Count	Min	Max	Mean	Standard deviation	Sum	Variety	Majority	Minority	Median
Austria	75,678	2	10	6,27	2,09	474,359	9	7	5	7
Belgium	22,657	2	10	5,01	2,36	113,561	9	7	5	4
Bulgaria	100,361	2	10	5,53	2,28	554,998	9	7	10	7
Czech Republic	70,691	2	10	5,17	2,11	365,171	9	3	5	6
Germany	301,511	1	10	5,15	2,37	1,551,940	10	3	1	4
Denmark	37,202	2	10	3,50	1,74	130,138	9	3	9	3
Estonia	38,881	1	10	6,34	1,70	246,407	10	7	1	7
Spain	473,091	1	10	4,93	2,31	2,331,174	10	7	10	5
Finland	279,089	2	8	5,53	0,91	1,543,328	7	6	8	6
France	496,456	1	10	5,47	2,39	2,715,560	10	3	1	6
Greece	117,893	1	10	5,46	2,03	643,306	10	7	10	6
Hungary	82,331	2	10	4,53	2,28	372,914	9	3	10	3
Ireland	48,955	2	10	8,04	1,85	393,507	9	9	5	9
Italy	269,393	1	10	4,95	2,44	1,333,859	10	2	10	6
Lithuania	59,675	2	10	4,97	2,22	296,435	9	3	4	3
Luxembourg	2312	2	10	5,78	2,18	13,373	9	7	5	7
Latvia	59,756	2	10	6,32	1,91	377,711	9	7	4	7
Netherlands	26,966	2	10	5,81	2,77	156,685	9	7	5	6
Poland	290,272	2	10	4,76	2,25	1,381,279	9	3	5	4
Portugal	80,725	1	10	5,16	2,15	416,509	10	7	10	6
Romania	207,333	1	10	5,39	2,32	1,118,254	10	7	1	7
Sweden	371,317	2	10	6,47	1,08	2,403,334	9	7	10	7
Slovenia	18,851	1	10	6,93	2,08	130,604	10	7	1	7
Slovakia	45,527	2	10	5,59	2,28	254,291	9	7	10	7
United Kingdom	207,036	1	10	6,27	2,42	1,298,219	10	3	1	7

and 23% increase in aboveground biomass. Moreover, Evans et al. (2011) show in a field experiment that ants and termites increase crop yield by 36% in warmer and drier habitats like similarly earthworms serve this functional role in cooler and wetter latitudes.

Land use/land cover and land management: Grassland soils are the soils that present the richest biodiversity, before forests and cropped or urban lands (Turbé et al., 2010). Natural diverse vegetation contributes to an increase in soil biodiversity, while intense mono-cropping supports the growth of only a subset of soil microbes, causing a decrease in biodiversity (Figuerola et al., 2014). Within rural lands, soil biodiversity tends to decrease with the increasing intensification of farming practices (e.g. use of pesticides, fertilizers, heavy machinery). Wall et al. (2015), emphasize that land use such as agricultural intensification can reduce the diversity and densities of beneficial organisms that control pests and pathogens, thereby negatively affecting the health of plants, animals and humans. Similarly, Tsiafouli et al. (2015) analysed the effect of agricultural intensification across Europe on the structure, diversity, food web assembly and community dynamics of soil biota, and summarized that agriculture intensification reduces soil biodiversity, resulting in fewer functional groups and reduced diversity. Europe has experienced drastic land use changes throughout its history, which have shaped the communities of soil organisms found today and these changes are still occurring today, towards increased urbanisation and intensification of agriculture, and also towards forest growth. Soil biodiversity can only respond slowly to land use changes, so that ecosystem services under the new land uses may remain sub-optimal for a long time (e.g. reduced decomposition of soil organic matter). Land conversion, from grassland or forest to cropped land, results in rapid loss of soil carbon, which indirectly enhances global warming. It may also reduce the water regulation capacity of soils and their ability to withstand pests and contamination (Turbé et al., 2010). Griffiths et al. (2016) also found predictable relationships between community biodiversity and land use factors in their currently published article. However, not all soil management practices have a negative impact on soil biodiversity and related services. While in general chemical treatments and tillage aimed at improving soil fertility trade off with soil carbon storage and decontamination services, in contrast mulching, composting and crop rotations all contribute to improve soil structure, water transfer and carbon storage. Tiemann et al. (2015) reveal that crop and/or land rotations enhance belowground communities and functions in agroecosystems; Wall et al. (2015) say that agro-ecological practices (effective management options for cropping systems by including reduced tillage with residue retention and rotation, cover crop inclusion, several forestry practices, etc.) enhances soil organic matter content and soil biodiversity. These studies are all good references to find the link between the soil biodiversity and land use/land cover.

The data sets that are used in this study and include 7 variables are given in Table 1. These variables are re-classified according to the thresholds given in Table 2, and can be seen from Fig. 1. Some further descriptions of the variable are as follows:

- pH values were reclassified into four classes (<4, 4–5.2, 5.2–8.2, >8.2) and three different scores (1–3) were given.
- The five domain surface textural classes (1. Coarse; 2. Medium; 3. Medium-fine; 4. Fine; 5. Very fine) of ESDB were used and two different scores (1 or 2) assigned to those classes. Only the coarse texture has a low score which is 1.
- The organic matter values were reclassified into four classes (<1, 1–2, 2–4, >4) and four different scores (1–4) were given. This variable which is found in the regions that have over 4% organic matter in their soils has the highest influence on the soil biodiversity with the given scoring 4.
- The water balance, P-ETP, is calculated by subtracting the total potential evapotranspiration (ETP) from the total precipitation (P). The values were reclassified into three classes (<−500, −500–500 > 500 mm) and three different scores (1–3) were given.
- The annual average temperature values were reclassified into three classes (<5, 5–20, >20) and two different scores (1 or 2) given to those classes. Both having <50 or over 20^0 average temperatures has assigned with the low score which is 1.
- Three soil biomass productivity layers on arable land, grassland and forests are used in this study. They are masked by specific CORINE Land Cover classes, such as, classes 311–313 for forest; classes 231–321 for grassland and classes 211–213, 241, 242 for arable lands. The values of the original layers are indexed between 1 and 10, thus, they are reclassified into three classes as poor-average-good productivity potentials. Poor productivity has the lowest which is 1, whereas good productivity has the highest score which is 3.
- CORINE 2000 land use/land cover classes are used. Artificial areas

Table 6
Statistical distribution of soils according to their biodiversity potential per country (green colour shows the highest share among the three classes).

	Poor %	Average %	Good %
Austria	24	49	27
Belgium	52	33	15
Bulgaria	41	36	23
Czech Republic	48	42	9
Denmark	80	18	2
Estonia	18	65	18
Finland	7	93	0
France	44	32	24
Germany	51	31	18
Greece	30	60	10
Hungary	66	13	20
Ireland	8	27	65
Italy	47	37	16
Lithuania	51	36	13
Luxembourg	33	49	17
Latvia	21	57	21
Netherlands	44	30	25
Poland	56	34	10
Portugal	37	54	9
Romania	44	34	21
Spain	44	44	12
Sweden	7	89	4
Slovenia	18	34	49
Slovakia	38	41	21
United Kingdom	33	32	35
Total	37	47	16

(classes 111–142), wetlands (classes 411–423) and water bodies (classes 511–523) are excluded/masked out from the assessment by assigned as zero value. Other land use classes are classified into three classes as given below and three different scores (1, 1.5 and 2) were assigned to them.

Arable land:
211: Non-irrigated arable land
212: Permanently irrigated land
213: Rice fields
241: Annual crops associated with permanent crops
242: Complex cultivation patterns
Permanent crops:
221: Vineyards
222: Fruit trees and berry plantations
223: Olive groves
Others;
231: Pastures
243: Land principally occupied by agriculture, with significant areas of natural vegetation
244: Agro-forestry areas
311: Broad-leaved forest
312: Coniferous forest
313: Mixed forest
321: Natural grasslands
322: Moors and heathland
323: Sclerophyllous vegetation
324: Transitional woodland-shrub
333: Sparsely vegetated areas

2.2. Method

In this study, potentials of soil biodiversity throughout Europe have been assessed and mapped by using critical thresholds (Table 2) of the selected variables that potentially affect the conditions of soils for biodiversity and thus soil biodiversity levels (Table 1). The thresholds are defined in line with levels that are expected to regulate soil biodiversity levels and range from 0 to 4, depending on the main parameters as described in the material section. Using these threshold levels and their corresponding scores, the general status of soil biodiversity potentials could be assessed and mapped on a European scale. The assessment of the soil biodiversity potential is calculated as the spatial sum of the reclassified layers of each indicator (Fig. 1) by the given scores described in Table 2. The score of the land cover/land use indicator is used as a multiplying factor.

3. Results

Fig. 2 shows the map illustrating the potential of soils to serve as a soil biodiversity pool and the related database that gives the degrees of soil biodiversity potential, as well as the area covered in Europe. Generally, this map and the underpinning model express the potential in terms of quantity (or abundance), rather than the diversity of soil organisms.

The levels of biodiversity are mainly driven by the “soil biomass productivity” and the land use variables as can be seen from the map of the potential of soils to serve as a soil biodiversity pool (Fig. 1). In line with the attributed scores (Table 2), all arable land is modelled as having a low potential for soil biological activity, while all pastures and forest land (particularly in Northern Europe) appear as having a very high biological activity. This is also illustrated by some of the hot-spots (i.e. with very high levels of biodiversity) located in grassland areas (e.g. in the UK, Ireland, the Netherlands and France) (Fig. 2).

The highest areal coverage (29.9%) is found in the soil biodiversity level 7, and followed by level 3 (21.6%) and level 6 (12.1%) (Table 3).

The averages of the soil biodiversity levels per land use reveal that the highest soil biodiversity potentials are found on “Pastures, Grasslands, Shrubs” and secondly in “forests” (Table 4). As expected, lowest level of soil biodiversity potentials is found on arable lands.

When the soil biodiversity potentials of soils were calculated per countries, the highest levels were found in Ireland, Slovenia and Sweden; contrarily, the lowest levels are found in Denmark, Hungary and Poland (Table 5).

To allow for an easier interpretation, the data on soil biodiversity potential were subsequently classified based on their value distribution and their quantiles. This resulted in classes of soils with a “good”, “average” and “poor” potential to serve as biodiversity pool (Table 6, Fig. 2).

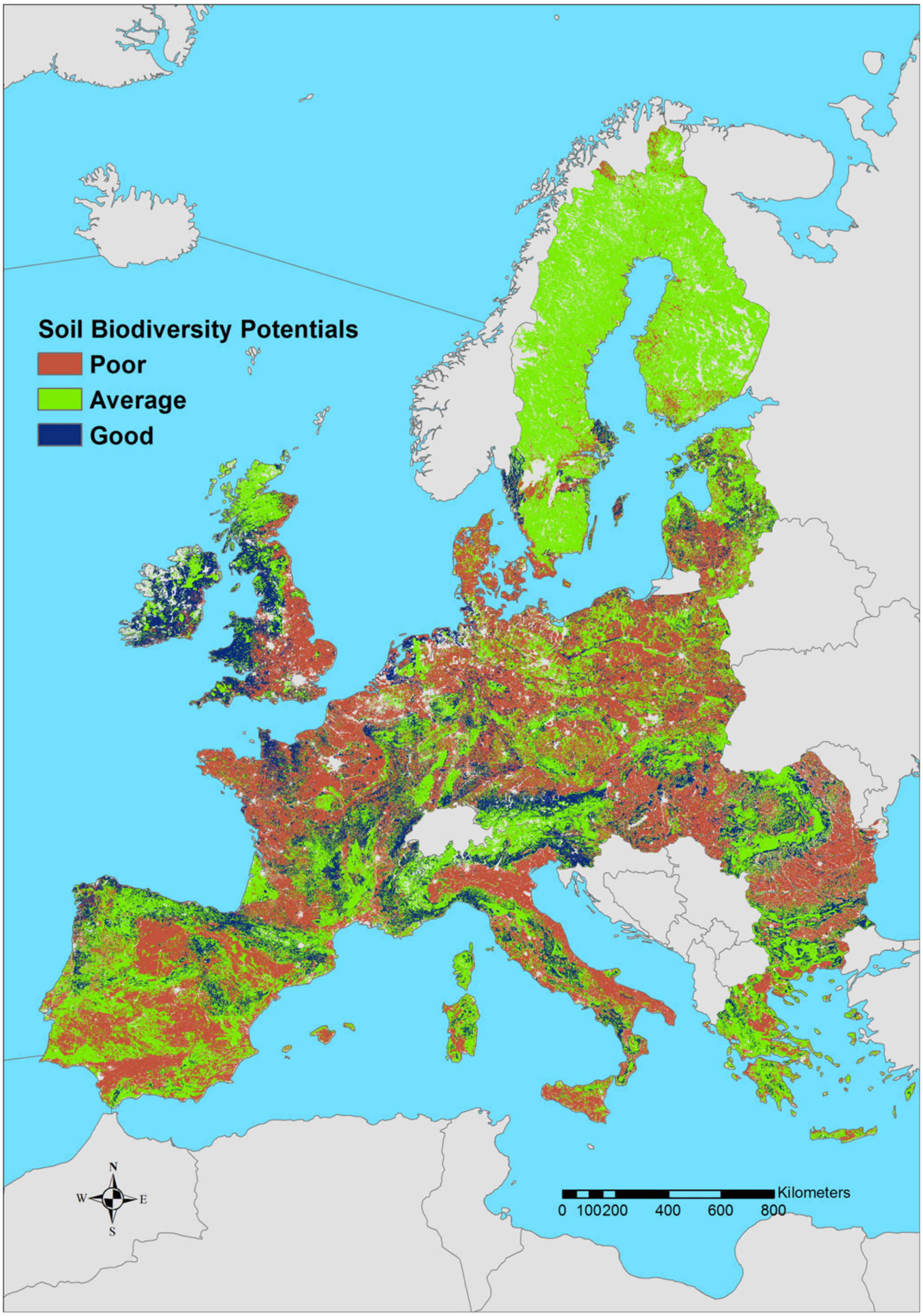

Fig. 3. Re-classification of soil biodiversity potentials into poor, average and good potentials (Brown is poor; green is average; blue is good).

Table 7
Correlation matrix of the indicators (Significance level p < 0.01).

	Earthworm abundance	Earthworm diversity	Earthworm richness	Potential soil biodiversity
Earthworm abundance	1000	0,082	0,147	0,001
Earthworm diversity	0,082	1000	0,597	0,353
Earthworm richness	0,147	0,597	1000	0,160
Potential soil biodiversity	0,001	0,353	0,160	1000

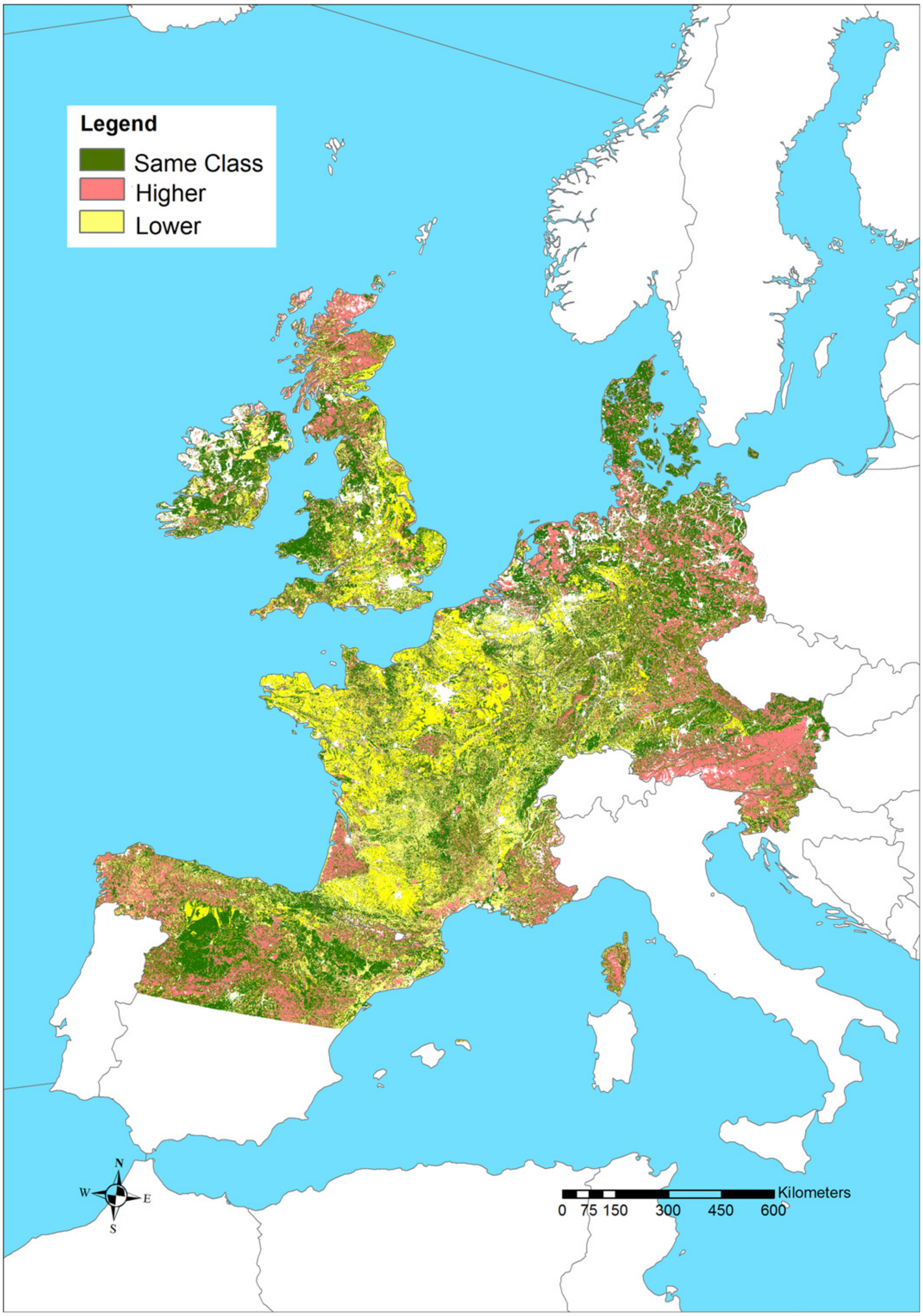

Fig. 4. Correspondences of potential of soil biodiversity levels with earthworm diversity (Shannon-Wiener index) (Green reflects the same classes for both of the layers; red reflects higher prediction of soil biodiversity level; yellow reflects lower prediction of soil biodiversity level).

This means that the lower quantile is classified as "poor" (class 1), the upper quantile as "good" (class 3), and the values in between as "average" (class 2).

Close to half of the European soils (47%) has an average soil biodiversity potential, whereas over a third (37%) have poor and about a sixth (16%) have good potential (Table 6). Further, most of the countries (13 countries out of 26) have the majority of their soils classified as having poor soil biodiversity potential. Only the UK, Ireland and Slovenia are modelled as having over a third of soils with good soil biodiversity potential (Table 6).

Because of the high effects of soil biomass productivity on grassland and land use indicators, grassland and forest dominated regions are among the regions where good soils for biological activity dominate. Particularly, high shares of good soils for biological activities can be found in UK and Ireland, particularly the west coast of England, as well as in southern Sweden. Other hotspot areas correspond to the

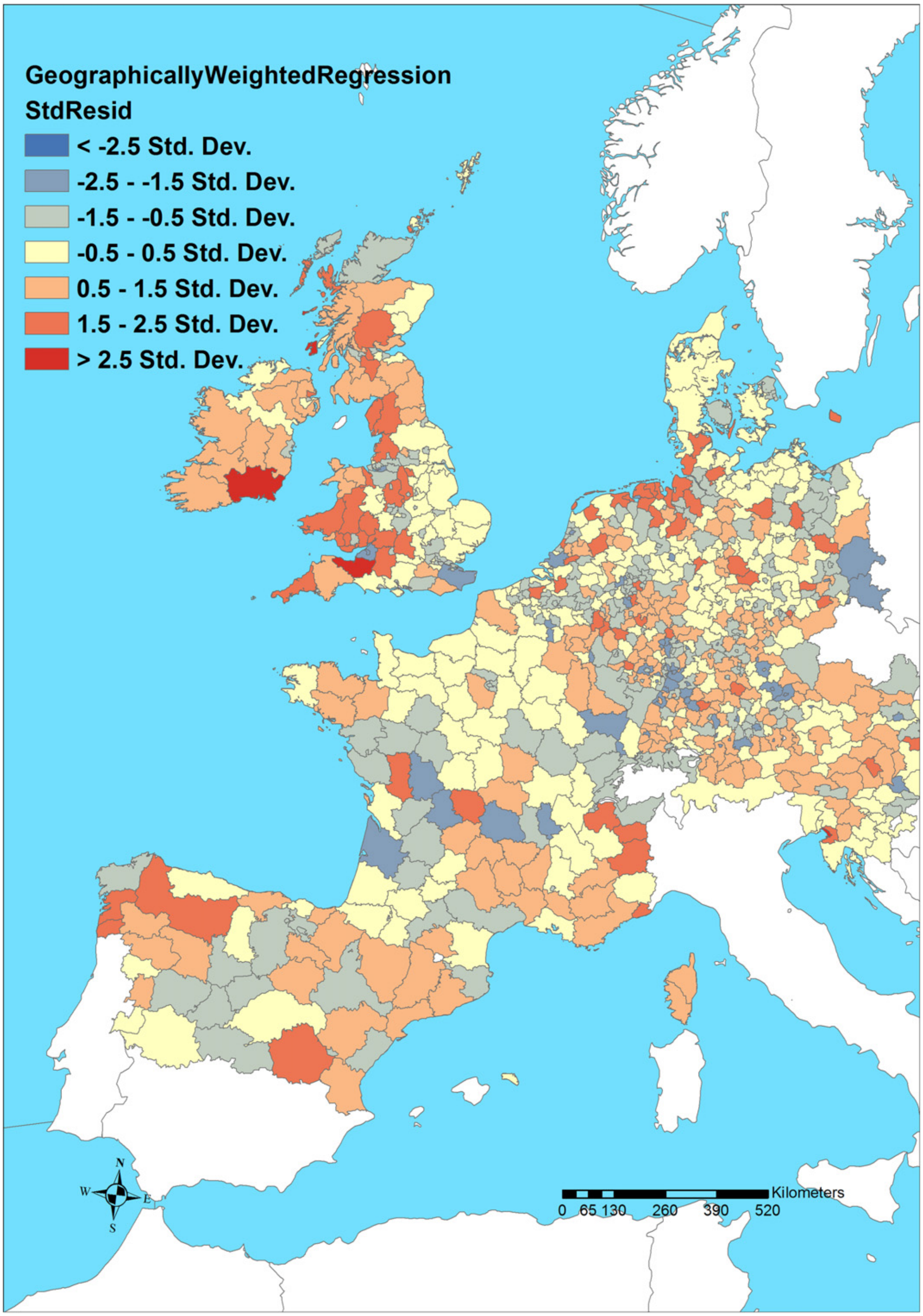

Fig. 5. The result of GWR model which was built by using all variables (soil biodiversity& earthworm abundance, earthworm diversity, earthworm richness).

regions around the Alps, in Southern Germany, Austria, western France and Slovenia as well as in some regions along the border between Belgium and Germany. Finally, there are some smaller clusters of very high shares in the Basque Country (ES), coastal regions on the French-Italian Riviera and in Southern Bulgaria.

Northern Sweden and practically the entire territory of Finland are the regions with the highest shares of average soils; additionally, regions in Northern Scotland, Southern Greece and some regions in the South-Western part of the Iberian Peninsula pop up.

Finally, the highest shares of soils with poor soil biodiversity can be found in specific regions characterized by arable land. This is particularly true for the regions dominated by loess soils like eastern Germany, areas in Belgium, France, Slovakia and Hungary and a broad strip along the lower Danube River and its delta in Romania. Other river valleys such as the Po Valley and Delta as well as the upper Danube in Germany can be identified as well. Additionally, there are hotspot areas in Eastern England, North Western Germany and Central Poland and some single regions in France and Spain.

4. Validation

Since spatial predictions of the soil biota components have not been studied so widely as stated in the introduction part and none of the measured samples coming from the other studies were available for our use, we did not have raster layers that cover the entire study area to carry out a validation. Therefore, the below listed layers of predicted earthworm communities from the study by Rutgers et al. (2016), which only cover nearly 40% of our study area, were used to validate our soil biodiversity potential map.

- Predicted abundance of earthworms in Europe (Ind/m^2)
- Predicted richness of earthworms in Europe (Number of taxa)
- Predicted diversity values of earthworm communities in Europe (Shannon-Wiener index)

These layers were predicted by using digital soil mapping and harmonized database which were built by collected earthworm data from the Netherlands, Germany, Ireland, Northern Ireland, Scotland, France, Spain, Slovenia and Denmark, with the combination of other auxiliary data such as land use, vegetation, climate and soil characteristics (soil pH, soil organic matter, and soil texture (clay-silt-sand)) (Rutgers et al., 2016).The problems of the harmonized earthworm database which are mainly based on the strong divergence due to the differences of the applied sampling methods and the sampling dates (weather/season) should not be forgotten when considering the validation results.

First of all, the spatial correlation between the soil biodiversity potential map (Fig. 3) and the predicted earthworm layers was investigated by using "Band Collection Statistics".

Then, the raster layers were also analysed separately to identify the spatial locations of the over-under-well-fit estimations ("well-fit" means the same classes are founded for both of the layers; "over" means soil biodiversity potential is found higher than the other layer; "under" means soil biodiversity potential is found lower than the other layer) and correlated regions by using the "Combine Tool" and "Geographically Weighted Regression Tool" in ArcGIS 10.3.

Before starting the validation, all earthworm layers were reclassified into 3 classes according to their quantiles to make them compatible with the soil biodiversity potential map. Thus, the data was simplified and reclassified into three classes as 1 (lower quantile), 2 (between lower and upper quantile) and 3 (upper quantile). Correspondences of potential of soil biodiversity levels with all predicted earthworm layers were investigated separately.

According to the correlation matrix (Table 7) of the layers, a positive significant correlation ($p < 0.01$) between potential soil diversity and the earthworm diversity (Shannon-Wiener index) on the one hand and between potential soil biodiversity and richness of earthworms on the other hand was found. These findings were also supported by the analyses of the correspondences of the layers separately. The results of the combined layers of soil biodiversity levels with earthworm diversity (Shannon-Wiener index) are presented in Fig. 4, which reveal 45% of the spatial assessment fit well meaning that both of the layers correspond in the same classes (class 1,2 or 3, green colour); for 24% of the pixels of the potential soil biodiversity is estimated higher than the predicted earthworm diversity (red); whereas the opposite (lower) is the case for 31% of the pixels (yellow). The reason of the lower or higher correspondences of soil biodiversity potentials in this analysis might be the high scoring of the land use indicator based on the visual interpretation, since the areas with lower predictions mainly overlaps with the arable lands and similarly higher predictions mostly coincide with the grasslands or forests.

The areal coverages of the matching results (i.e. results in the same class) decrease to 34% and30% for richness and abundance respectively.

The geographically weighted regression (GWR) method which is the possibility of assessing relationships in spatially explicit information (Toth et al., 2013) was also applied to validate the prediction results. GWR builds a local regression equation for each feature in the dataset.

Per pixel biodiversity values of predicted earthworms and soil biodiversity were averaged within the regions of the NUTS3 dataset (Eurostat 2011) for selected countries of the European Union which are coming from the earthworm study.

The GWR models were built separately for each of the layers (potential soil biodiversity& earthworm abundance; potential soil biodiversity& earthworm diversity; potential soil biodiversity& earthworm richness) and all variables (potential soil biodiversity& earthworm abundance, earthworm diversity, earthworm richness). In the models, soil biodiversity potential layer was used as dependent variable, and the others were independent variables. Each regression run was weighted by the number of pixels within the NUTS3 polygons. The results of the GWR models for each of the layers were found as very low with the averages of local R^2 as 0.073 for soil biodiversity& earthworm abundance; 0.135 for soil biodiversity& earthworm diversity; and 0.102 for soil biodiversity& earthworm richness. However, the overall average of local R^2 was found as 0.28 (the highest local R^2 is 0.697 (yellow colour) and lowest 0.007 (blue or red colours)) (Fig. 5), for the GWR result by using all of the variables together (earthworm abundance& earthworm diversity earthworm richness) with soil biodiversity potential layer. This means that since the predictive power of the overall regression result is found high, they are (3 of the layers together) spatially correlated and can be used in potential soil biodiversity assessments as predictive variables. For example, even though the lower correspondences were found for the potential soil biodiversity and earthworm diversity layers in France (Fig. 4, yellow colour), GWR results of local R^2 were found as very high (Fig. 5, yellow colour); meaning that usage of 3 layers together could improve the prediction results.

5. Discussion

Soils, which consist of a living reservoir of biodiversity, are complex and there are still knowledge gaps to understanding the driving factors on soil biodiversity and the relationships between different aspects of soils and the biodiversity potentials. Even though the importance of soil biodiversity is increasingly recognized as providing benefits to human health (Wall et al., 2015) and for the ecosystem management (Smith et al., 2015), soil biodiversity has not been usually included in the agricultural management and land conservation studies due to the lack of information about the potentials of soil biodiversity distribution data. Therefore, assessing the potentials of soil biodiversity and highlighting the biodiversity hot-spots and cold-spots were essential for delivering ecosystem services most efficiently and also for the several other reasons that are explained in this study.

This study focused on the potentials of the soil biodiversity pool function and these overall potentials of the soil throughout Europe was assessed and mapped successfully by this study on the basis of modelling by using a range of climate (potential evapotranspiration and average temperature) and land parameters (pH, texture, organic matter, soil biomass productivity and land use).

According to the results, close to half of the European soils (47%) has an average soil biodiversity potential, whereas over a third (37%) have poor and about a sixth (16%) have good potential. The highest potentials in soil biodiversity levels are found in pastures and grasslands whereas the lowest levels are found in arable lands. Moreover, Ireland, Slovenia and Sweden have the highest soil biodiversity potentials whereas Denmark, Hungary and Poland have the lowest potentials. Generally, precipitation, biomass productivity and land use are main variables affecting the soil biodiversity potentials, and thus, combinations of some suitable conditions such as "high precipitation, high biomass productivity on grasslands" or "suitable conditions of soil pH and texture, high precipitation on grassland" lead to the highest possible soil biodiversity hotspots. Even though the climatic and other soil conditions (e.g. soil organic carbon, pH, texture) were ideal for some of the regions, the soil biodiversity potential was found as poor because of the intensive land use in the arable land. This highlights the high impact of land use on soil biodiversity potential given the same soil conditions. Therefore, based on the results, we could suggest that the analysis of current conditions of soil biodiversity components in arable lands should be of priority.

Including more detailed data, such as meteorological data interpolated from the data coming from local stations, soil moisture data derived from high-resolution remote sensing images, detail map of soil management practices or real measurements of soil biota components, can improve our soil biodiversity potential assessment. Moreover, assessing and modelling the spatial distributions and current conditions of soil biodiversity on European scale by harmonizing the local datasets including real measurements of soil biota components together with the auxiliary variables such as soil properties and other environmental data is also urgently needed. Finally, monitoring soil biodiversity components regularly and including some basic soil biodiversity indicators into the large-scale soil surveys such as LUCAS etc. are critically important.

The validation results based on both correspondences and GWR between earthworm biodiversity and potential soil biodiversity were found as well fit for 45% of the study area and higher local regression predictive power respectively. Moreover, positive significant correlation ($p < 0.01$) between soil biodiversity and the earthworm diversity (Shannon-Wiener index); and also, soil biodiversity and richness of earthworms was also found. These results seem to indicate that, at least as far as earthworms are concerned, the estimated soil biodiversity levels are more an indication of diversity than of abundance. Besides, based on the high GWR results, three earthworm layers together as predictive variables might be good proxy in the assessment of the soil biodiversity potentials. Since earthworms are only one group of soil organisms with a specific habitat requirement, analysing the correspondences between other soil organisms could help to improve the results.

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