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A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity

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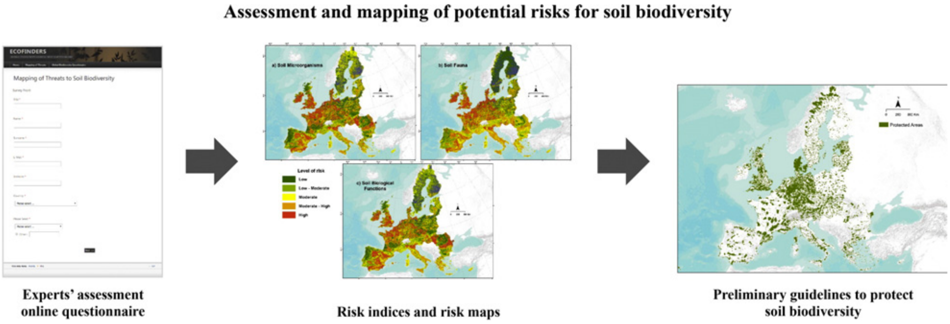
HIGHLIGHTS

- Soil microorganisms, fauna and biological functions are subjected to different potential threats
- It is possible to map potential threats to soil biodiversity
- The majority of EU countries have soils with high level of risk to soil biodiversity
- Soil under pressure is not well protected, actions are needed to preserve soil biodiversity

GRAPHICAL ABSTRACT



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ABSTRACT

Because of the increasing pressures exerted on soil, below-ground life is under threat. Knowledge-based rankings of potential threats to different components of soil biodiversity were developed in order to assess the spatial distribution of threats on a European scale. A list of 13 potential threats to soil biodiversity was proposed to experts with different backgrounds in order to assess the potential for three major components of soil biodiversity: soil microorganisms, fauna, and biological functions. This approach allowed us to obtain knowledge-based rankings of threats. These classifications formed the basis for the development of indices through an additive aggregation model that, along with *ad-hoc* proxies for each pressure, allowed us to preliminarily assess the spatial patterns of potential threats. Intensive exploitation was identified as the highest pressure. In contrast, the use of genetically modified organisms in agriculture was considered as the threat with least potential. The potential impact of climate change showed the highest uncertainty. Fourteen out of the 27 considered countries have more than 40% of their soils with moderate-high to high potential risk for all three components of soil biodiversity. Arable soils are the most exposed to pressures. Soils within the boreal biogeographic region showed the lowest risk potential. The majority of soils at risk are outside the boundaries of protected areas. First maps of risks to three components of soil biodiversity based on the current scientific knowledge were developed. Despite the intrinsic limits of knowledge-based assessments, a remarkable potential risk to soil biodiversity was observed. Guidelines to preliminarily identify and circumscribe soils potentially at risk are provided. This approach may be used in future research to assess threat at both local and global scale and identify areas of possible risk and, subsequently, design appropriate strategies for monitoring and protection of soil biota.

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1. Introduction

Soil biodiversity is recognized as a crucial player in guaranteeing the functioning of soil and as a provider of several ecosystem services (Lavelle et al., 2006). At the same time it is known that soils are becoming more and more vulnerable due to several pressures: from pollution and salinization to erosion and compaction. As a direct consequence, also the soil-dwelling organisms are under threat. The decline in soil biodiversity has been identified as one of the major threats and issues to deal with in the coming years (McBratney et al., 2014). However, the overall relationship between pressures on soils and below-ground organisms has been poorly investigated to date. A common framework and, consequently, suitable actions to protect soil biodiversity are still missing. This is mainly due to the difficulty inherent to the disentangling of the real threats that can affect soil biodiversity and to the lack of data on the distribution of soil organisms at large scale. Many studies have investigated the impact of individual potential threats (e.g. intensive human exploitation or soil pollution) on specific groups of soil organisms (e.g. bacteria or earthworms) (Verbruggen et al., 2012). Therefore, we can assume that the scientific community has an appropriate level of knowledge on this topic and, therefore, a knowledge-based assessment of potential risk is possible. However, the variables to consider in this type of analysis are numerous and should be carefully examined. In particular, three different dimensions should be taken into account in order to obtain a satisfactory evaluation.

The first dimension is related to the large number of stresses that, in principle, can represent a threat to soil biodiversity. The factors that can impact soils are of varying nature, i.e. biotic or abiotic. Starting from the available literature we proposed and assessed the potential risk related to thirteen possible stresses: (1) climate change (global warming) (Van der Putten, 2012), (2) land use change (Spurgeon et al., 2013), (3) habitat fragmentation (Halme et al., 2013), (4) intensive human exploitation (Tsiafouli et al., 2015), (5) soil organic matter decline (Heenan et al., 1995), (6) industrial pollution (Hafez and Elbestawy, 2009), (7) nuclear pollution (radioactivity) (Brodie et al., 2006), (8) soil compaction (Whalley et al., 1995), (9) soil erosion (Pimentel et al., 1995), (10) soil sealing (Setälä et al., 2014), (11) soil salinization (Sardinha et al., 2003), (12) use of genetically modified organisms (GMOs) in agriculture (Verbruggen et al., 2012), and (13) introduction and diffusion of invasive species (Kourtev et al., 2002).

The second assessment dimension is linked to the complexity of soil biodiversity itself, which is composed of extremely varied organisms, from microorganisms to macro- and mega-fauna (Briones, 2014). Each threat may potentially impact each single entity of soil-dwelling organisms at a different level of intensity (Spurgeon et al., 2013). Furthermore, the pressures may also affect the functions carried out by soil biota. For the evaluation, we proposed three main potentially threatened components: soil microorganisms, soil fauna, and soil biological functions. In the text the term ‘component’ will be used to indicate these three categories of soil biodiversity.

The third dimension of evaluation to be considered is the absence of a common framework to equally assess the strength, and therefore the actual risk, of each threat to each of the different components of soil biodiversity. Lacking this evidence, scientists may arbitrarily consider certain events more dangerous than others. When detailed data are missing at large scale, a good way to obtain a consistent assessment is by referring to the current knowledge of experts. Therefore, three different categories of scientists, namely soil biologists, ecologists, and other soil scientists, were taken into account as they represent an approximation of the major field of research in soil biodiversity. Their knowledge was used in order to identify the commonly recognized threats.

At present, this stratified complexity is responsible for the difficulty in assessing the potential of each pressure on soil biodiversity and is preventing us from obtaining a common framework for both the monitoring and the protection of soil-dwelling organisms. However, a lot of data on chemical-physical properties and uses of soils are available (Lugato et al., 2014). These data could be combined in order to identify the areas of potential risk, considering that the spatial representations of threat processes is often used as a first step to identifying priority locations for conservation (Tulloch et al., 2015). Nevertheless, before doing this, the potential of each possible threat on soil biodiversity must be estimated in order to identify which ones should be considered. Therefore, the three dimensions described above were combined by means of an expert assessment and the results were used to generate normalized indices of threat. The indices allow us to design maps at pan-European level, including 27 countries of the European Union (EU), and identify areas of potential risk in this region. Subsequently, the maps were compared with spatial distribution of land cover types, biogeographic regions and protected areas in order to identify common patterns and propose preliminary guidelines to start developing measures to preserve soil life.

2. Material and methods

2.1. Expert assessment

A list of potential pressures was subjected to evaluation by experts (i.e. researchers in this field). In order to assess the relevance of threats, an opinion poll was carried out whereby soil science experts expressed an opinion on a 0–10 scale (0 = minimum potential, 10 = maximum potential). The relevance of the threats was assessed on three different components of soil biodiversity: microorganisms, fauna, and biological functions. A dedicated questionnaire was developed and temporarily made available online (see Appendix A for full questionnaire). The questionnaire was firstly addressed to a pre-established list of experts (i.e. EcoFINDERS project partners). Subsequently, in order to increase the response rate from experts, a specific news item was sent out through the official the questionnaire was advertised through the European Soil Data Centre (ESDAC; Panagos et al., 2012) newsletter. A brief explanation of the purpose and use of the questionnaire was described on a page before proposing the three main steps of the questionnaire. Furthermore, a helpdesk service was made available to all experts so that they could contact us in case of need.

Firstly, the experts were asked to declare some of their personal details, including their field of expertise (soil biology, soil ecology, soil science, or other). Secondly, participants were asked to state whether the assessment of potential threats needs to be measured separately for the three main pre-established components of soil biodiversity or not. If the respondents replied affirmatively, they were asked to rank, on a scale from 0 to 10, a list of the 13 potential threats to each of the three components. If not, they were asked to rank the potential in relation to soil biodiversity as a whole. In the latter case the same values were copied in all three categories of soil biodiversity for further analyses. Lastly, experts were asked to declare whether they had already published peer-reviewed papers on one or more of the classes of threat and, if so, to indicate which among the 13. The replies to the last question were compared to data from a desk-based meta-search of the papers published to date in peer-reviewed journals for each of the potential threats as recorded in March 2015 in the largest database of peer-reviewed literature, SCOPUS Database (www.scopus.com; Appendix B). Each list of publications was checked in order to consider the appropriate ones.

In order to avoid any over- and under-evaluation of the values, all the obtained questionnaire scores of each expert were normalized and mean-centred, in order to obtain scores in the range between 0 and 1 for each expert. Data were tested for normal distribution (Appendix C). The significance of differences among the threats was performed through the non-parametric Kruskal-Wallis test. *Post-hoc* pairwise comparisons were calculated through the Mann–Whitney pairwise test (adopting Bonferroni correction) in order to assess the significance of inequality at pairwise level. On the basis of the obtained results, the threats were classified as (1) with low potential (score significantly lower than at least six other threats); (2) with moderate potential (score significantly lower/higher than three to six other threats); (3) with high potential (score significantly higher than at least six other threats). The threats that did not fit into these limits were defined as "unclassified potential". The differences among the three categories of experts were also tested through the Kruskal-Wallis test for each threat and category of soil biodiversity in order to assess the presence or absence of a common point of view in the group of experts. Lastly, the significance of variance was assessed among the threats applied to the three different components of soil biodiversity. This allowed us to verify whether the idea to create three different categories of possible targets was appropriate.

2.2. Development of indices of potential risk

The analysis of the questionnaire completed by the group of experts allowed us to select the relevant variables for the creation of three combined indices of potential risk to soil biodiversity: PR_{MIC} as index of Potential Risk to soil MICroorganisms; PR_{FAU} as index of Potential Risk to soil FAUna; PR_{FUN} as index of Potential Risk to FUNctions provided by soil organisms. In order to develop these indices, an additive aggregation model was used as it assumes linear relationships among the variables and it allowed us to consider different variables simultaneously and to assume that different pressures active at the same time have a cumulative effect. The presence of a cumulative effect due to simultaneous pressures is likely to happen, considering the extent of the three proposed categories of soil biodiversity, where the contemporary actions of factors may affect different groups of soil organisms within each category. Unclassified threats were excluded, while weighted coefficients were calculated for each potential threat according to the median scores given by the experts to each threat. The obtained formulae of indices are as follows:

$$\begin{aligned} PR_{MIC} = {} & 0.06HF + 0.07GMO + 0.08IS + 0.09SC + 0.1SS + 0.1SE \\ & + 0.1SSA + 0.1LUC + 0.1IP + 0.11OMD + 0.11HE. \end{aligned}$$

$$\begin{aligned} PR_{FAU} = {} & 0.09GMO + 0.13IS + 0.13NP + 0.14CC + 0.16LUC + 0.16OMD \\ & + 0.17HE. \end{aligned}$$

$$\begin{aligned} PR_{FUN} = {} & 0.04GMO + 0.07IS + 0.07HF + 0.08NP + 0.09SC + 0.09IP \\ & + 0.09SS + 0.09SSA + 0.09LUC + 0.09SE + 0.1OMD + 0.1HE. \end{aligned}$$

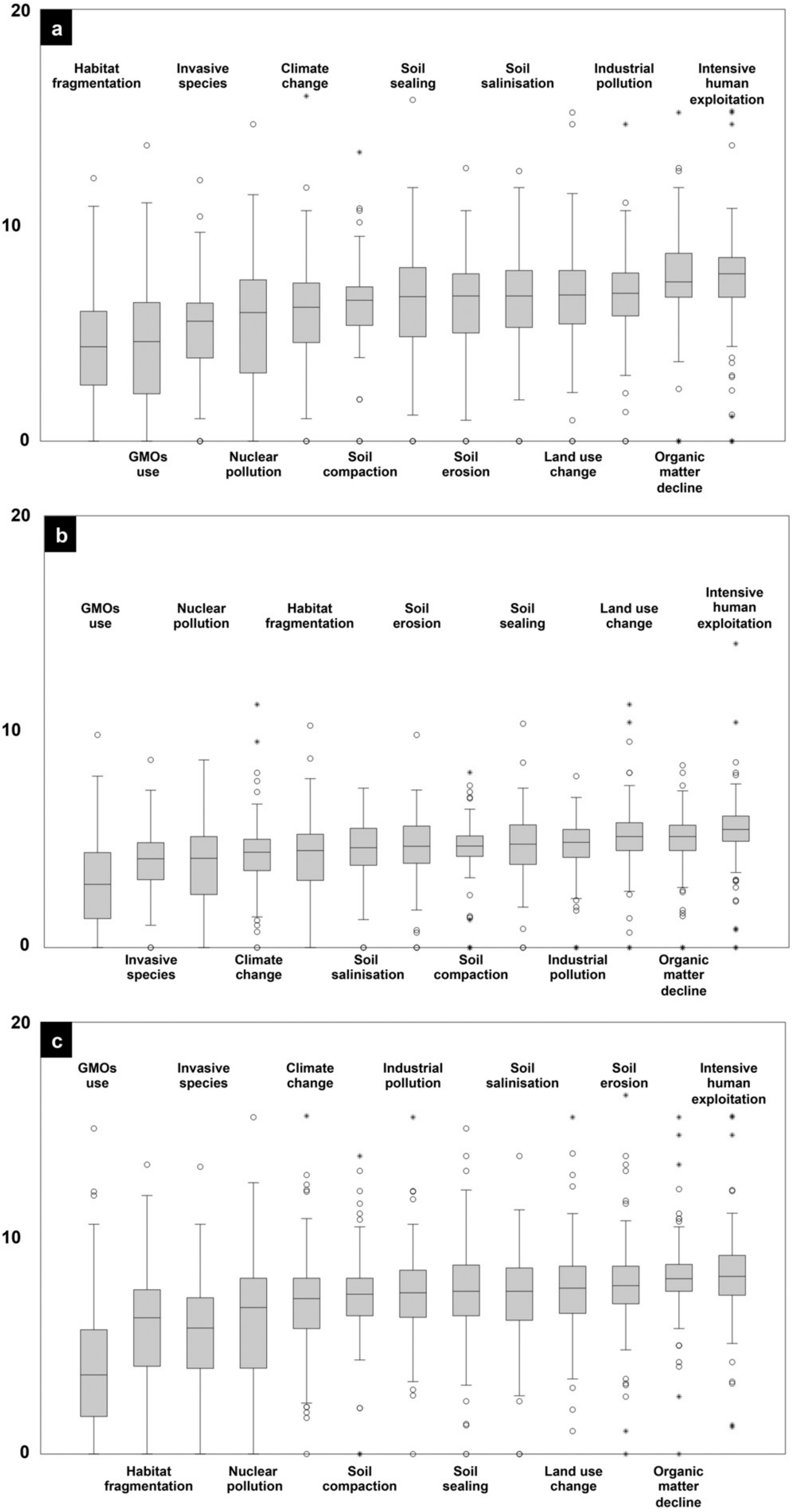
where *HF* refers to habitat fragmentation, *GMO* to use of GMOs in agriculture, *IS* to introduction of invasive species, *CC* to climate change, *SC* to soil compaction, *SS* to soil sealing, *SE* to soil erosion, *SSA* to soil salinization, *LUC* to land use change, *NP* to nuclear pollution, *IP* to soil pollution from industry, *OMD* to organic matter decline, and *HE* to intensive human exploitation. We applied these indices to map the potential threats to soil biodiversity across Europe. However, they can also be used on both local and global scales in order to identify the areas of potential risks to different components of soil biota.

2.3. Assessment of spatial distribution of threats

Three maps of threats to soil biodiversity were obtained as a weighted sum of different soil threats as resulted from the proposed indices. This was performed by multiplying the weighted values of the indices obtained through the expert opinion survey with a series of proxy thematic layers. These layers are a series of raster maps either specifically developed or derived from different sources. The layers used are assumed to be proxies of the process described in the survey provided to the experts. Where possible, the selected proxies were aimed at spatially representing the potentiality of each threat (i.e. susceptibility to pollution instead of current contamination, erodibility risk instead of rates of erosion) in order to not simply represent a static situation. Furthermore, the proxies were selected to spatially represent different factors in order to avoid double counting of the same effect. Some of the proxies were treated as discrete/dichotomic variables, while others were treated as continuous values. Nevertheless, all the variables were normalized in order to have a minimum value of zero and a maximum value of one, thus giving different properties an equal range of values. The normalization procedure allows us to directly compare the three different outputs in terms of relative change.

The details of the proxy layers developed are:

1. GMO use: map of potential cultivation of GMOs in Europe. The map was obtained by combining the European countries (Spain, Portugal, Romania, Czech Republic, and Slovakia) in which GMO maize cultivation (the only GMO plant cultivable in the European Union) is allowed (James, 2013) and CORINE Land Cover map of Europe (EEA, 2012) to circumscribe agricultural areas. This is a discrete map with two classes: 0, where no GMO cultivation is allowed and 1, where it is.
2. Habitat fragmentation: map of potential risk of fragmentation derived from the CORINE Land Cover map of Europe. The map expresses fragmentation of natural and rural areas in terms of density as defined by Riitters et al. (2000). The output is a continuous numerical map with range [0–1].
3. Industrial pollution: map of potential susceptibility to cadmium. Map derived combining partition coefficient (Kd) of cadmium and soil properties, namely soil pH and Organic Carbon percentage (%OC), derived from the European Soil LUCAS (Land Use/Cover Area frame Survey) survey. The LUCAS soil survey consists of ca. 20,000 points across 25 EU Member States (Tóth et al., 2013). The applied regression equation was: $\log(Kd) = -1.04 + 0.55 \cdot (pH) + 0.70 \cdot \log(\%OC)$ (Degryse et al., 2009). The output is a continuous numerical map with range [0–1].
4. Nuclear pollution: map of potential susceptibility to caesium. Map derived combining partition coefficient (Kd) of caesium and soil parameters, namely pH and clay content. The applied regression equation was: $\log(Kd) = 3.19 + 0.0798 \cdot (pH) + 0.00154 \cdot (clay) \cdot (pH)$ (Sheppard et al., 2009). The output is a continuous numerical map with range [0–1].
5. Sealing: map of land use change to urban or built and *vice versa* derived from Land Use Modelling Platform (Lavalle et al., 2013). The output is a discrete map with three classes: −1 where change goes from built to non-built, 0 where no change occurs, and 1 where the change is from non-built to built.
6. Human exploitation: map of agricultural land use intensity (Temme and Verburg, 2011) that uses nitrogen application, associated to a set of environmental and socio-economic location factors, as appropriate indicator for the intensity of arable lands. For grasslands the intensity of use was estimated based on the local stocking densities with cattle. The output is a continuous numerical map with range [0–1].
7. Climate change: European map of the Aridity Index ($AI < 0.5$). The AI is calculated as the ratio of the average annual *precipitation* and *potential evapotranspiration*. Annual precipitation and annual potential evapotranspiration were generated by combining two datasets. The annual accumulated precipitation was calculated by summing the monthly total precipitation available from the WorldClim dataset for the HadGEM2-ES forecast for 2050 (Hijmans et al., 2005). The output is a continuous numerical map with range [0–1].
8. Land use change: map of absolute land use change between 2010 and 2020 derived from LUMP (Lavalle et al., 2013). This is a discrete map with two classes: 0, where no change occurs and 1, where it does.
9. Organic matter decline: map of topsoil organic carbon content of Europe, from the European Soil LUCAS (de Brogniez et al., 2015). The output is a continuous numerical map with range [0–1]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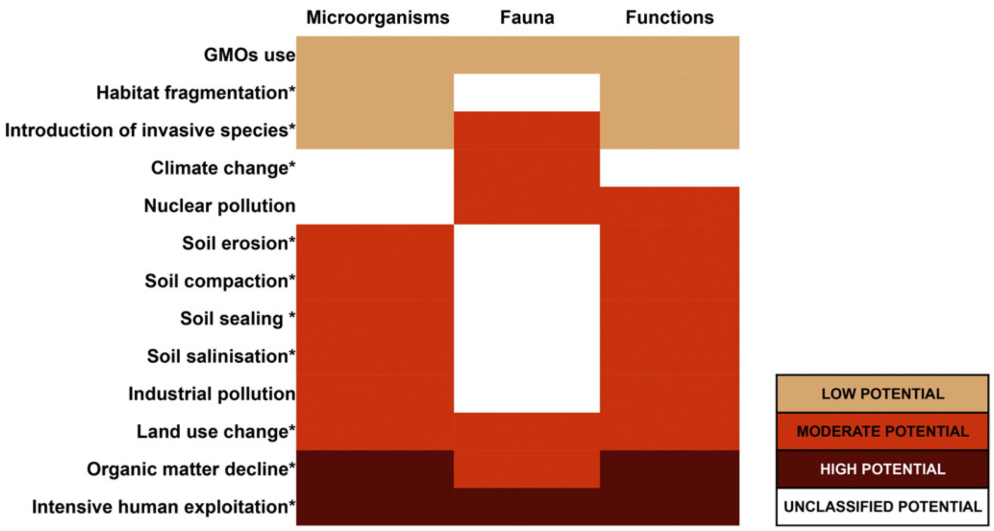

	Microorganisms	Fauna	Functions
GMOs use	LOW POTENTIAL	LOW POTENTIAL	LOW POTENTIAL
Habitat fragmentation*	LOW POTENTIAL	UNCLASSIFIED POTENTIAL	LOW POTENTIAL
Introduction of invasive species*	LOW POTENTIAL	MODERATE POTENTIAL	LOW POTENTIAL
Climate change*	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL
Nuclear pollution	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL	MODERATE POTENTIAL
Soil erosion*	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL
Soil compaction*	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL
Soil sealing *	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL
Soil salinisation*	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL
Industrial pollution	MODERATE POTENTIAL	UNCLASSIFIED POTENTIAL	MODERATE POTENTIAL
Land use change*	MODERATE POTENTIAL	MODERATE POTENTIAL	MODERATE POTENTIAL
Organic matter decline*	HIGH POTENTIAL	MODERATE POTENTIAL	HIGH POTENTIAL
Intensive human exploitation*	HIGH POTENTIAL	HIGH POTENTIAL	HIGH POTENTIAL

Fig. 2. Classification of potential threats to soil biodiversity. The table shows the potential (from low to high) assigned to each of the 13 possible threats for the three components of soil biodiversity. The threats with significant difference in scores given to each category of soil biodiversity are indicated with * (Kruskal–Wallis test, $p < 0.05$).

10. Salinisation: map of risk of soil salinisation (i.e. saline soils) in Europe derived from the European Soil Database (ESDB) (Panagos et al., 2012). This is a discrete map with three classes: 0, where no risk of salinization is present, 0.5 when the risk is moderate and 1, when the risk is high.
11. Compaction: map of soil compaction risk in Europe derived from the European Soil Database (ESDB) (Panagos et al., 2012). This is a discrete map with five classes in the interval [0–1] corresponding to an increasing risk of soil compaction.
12. Erosion: soil erodibility map of Europe. Erodibility is calculated as K-factor representing the soil reaction to the process of soil detachment and transport by raindrops and surface flow (Panagos et al., 2014). The output is a continuous numerical map with range [0–1].
13. Invasive species: map of spatial distribution of the terrestrial invasive species (plants and arthropods) recognized as high impact on ecosystems (Appendix D for full list of the 103 considered species) derived from the European Alien Species Information Network (EASIN) (Katsanevakis et al., 2012). Complete distribution data were available only for the United Kingdom, Ireland, Germany, the Netherlands, and Belgium. As for the invasive species layer data were available exclusively for these six countries, zoomed maps of those areas were developed (Appendix E). The output is a continuous numerical map with range [0–1].

The modelled potential risk was ranked into five classes using the quantile classification method: low, moderate-low, moderate, moderate-high, and high levels, respectively. A five-partite scale was used in order to avoid any possible misleading overlapping between the previous ranking of threats and the risk maps. The obtained data were aggregated and analysed in terms of European countries, land cover, and biogeographical regions. The distribution of the five classes of threat was also compared to the spatial distribution of the protected areas in Europe as derived from the World Database on Protected Areas (WDPA) in order to assess whether the soils under threat are currently under protection. The proxy layer maps of each threat, as all the final maps presented in this study, are available on the European Soil Data Centre (ESDAC — Panagos et al., 2012) web platform (http://esdac.jrc.ec.europa.eu/).

3. Results

A total of 107 experts from 21 different countries answered the questionnaire. Among them, 91 correctly worked through the questionnaire: 32% were soil ecologists, 26% soil biologists, and 27% other soil scientists. Seventy-two experts considered appropriate to split the assessment of potential threats into three components of soil biodiversity. The number of publications on each of the 13 potential threats of the examined poll of experts were significantly correlated (Pearson, $p < 0.01$) to the number of peer-reviewed papers indexed in the SCOPUS database, supporting the good representativeness of our sample (Appendix F).

The scores, and therefore the ranking, obtained from all the opinions on the level of potential pressure of the threats differed significantly ($p < 0.05$) from each other. For all three components of soil life, the lowest value was given to GMOs, and the highest to human exploitation (Fig. 1). For microorganisms, significant low scores were given to habitat fragmentation, use of GMOs, and introduction of invasive species ($p < 0.05$). In contrast, the scores given to soil organic matter decline and intensive human use/exploitation led them to be significantly unequal from at least six other threats. Habitat fragmentation, use of GMOs, and introduction of invasive species were classified as pressures with low potential; whereas soil organic matter decline and intensive human use/exploitation were the only ones to be classified as threats with high potential. All other nine proposed threats were categorized as stresses with moderate potential, except for climate change and nuclear pollution that were labelled as "unclassified potential" (Fig. 2). For fauna, the score given to the use of GMOs was the only one that differed significantly from those given to more than six other potential threats ($p < 0.05$). Therefore, the use of GMOs was classified as a pressure with low potential. Intensive human use/exploitation showed an opposite trend and was the only one with high potential (Fig. 1). For biological functions, three potential pressures had low threat potential: use of GMOs, habitat fragmentation, and introduction of invasive species ($p < 0.05$). In contrast, soil organic matter decline and intensive human exploitation were found to have a significantly higher score and were grouped as threat with high potential (Fig. 2).

Fig. 1. Expert assessment of potential threat to soil biodiversity. Boxplot of the weighted scores given by all experts to each of the 13 classes of threat to (a) soil microorganisms, (b) soil fauna, and (c) functions carried out by soil biodiversity. Boxes represent the 25–75% quartiles. The median is shown with a horizontal line inside the boxes. The bars represent the inner fences. White dots represent outliers, and extreme values are represented as asterisks.

The differences among the groups of experts were also tested for each threat and category of soil biodiversity. Considering the scores given to soil microorganisms, the data were not significantly different. In other words, the scientists were in agreement with regard to the scores given to all proposed potential threats. Comparing the threats to soil fauna, a consensus was reached for all threats except for the use of GMOs that showed a significant difference. Nevertheless, all three groups considered this threat as the least serious. Within the scores of potential threats to biological functions, the only ones that had a significant difference were those assigned to the introduction of invasive species. Nevertheless, all experts ranked this threat as the second least serious.

The risk potential indices, obtained from the expert classifications, revealed a spatial distribution that could allow us to identify the main areas of risk across Europe (Fig. 3). The three maps had diverse patterns, highlighting different levels of potential threats. However, soil microorganisms and biological functions showed the most similar profiles, while threats to soil fauna showed a unique distribution (Fig. 3). Considering each of the European countries individually, more than half of them (14 out of 27) showed more than 40% of soil with moderate-high to high level of risk for all three categories of soil biodiversity (Appendix G). In contrast, only five countries had more than 40% of their surface with low or low-moderate risk.

Land cover showed an impact on the distribution of soil at risk. Agricultural lands showed threats to soils with the highest percentages for all the categories of soil biodiversity (Fig. 4). In contrast, areas covered by forests were those exposed to lowest levels of risk.

Considering the seven European biogeographical regions (EEA, 2011), the steppic areas of Eastern Europe have up to 10.9% of their soils subjected to moderate-high to high level of threat. The boreal region showed the lowest threat with total percentages of soils having low to low-moderate threat ranging from 7.1% for microorganisms to 10% for fauna (Table 1). Considering the soils within currently established protected areas in the 27 European countries, the majority (values range from 45% for microorganisms and fauna to 46% for biological functions) were classified as low to low-moderate level of risks. Low percentages (26%, 29%, and 31% for biological functions, microorganisms, and fauna, respectively) of soils within protected areas had a moderate-high/high risk for soil biodiversity.

4. Discussion

Any appropriate strategy to preserve biodiversity, whether above- or below-ground, requires the availability of tools that allow us to understand the causes of potential reduction/loss of biodiversity and to identify the areas at risk. Researchers whose goal it is to prioritize

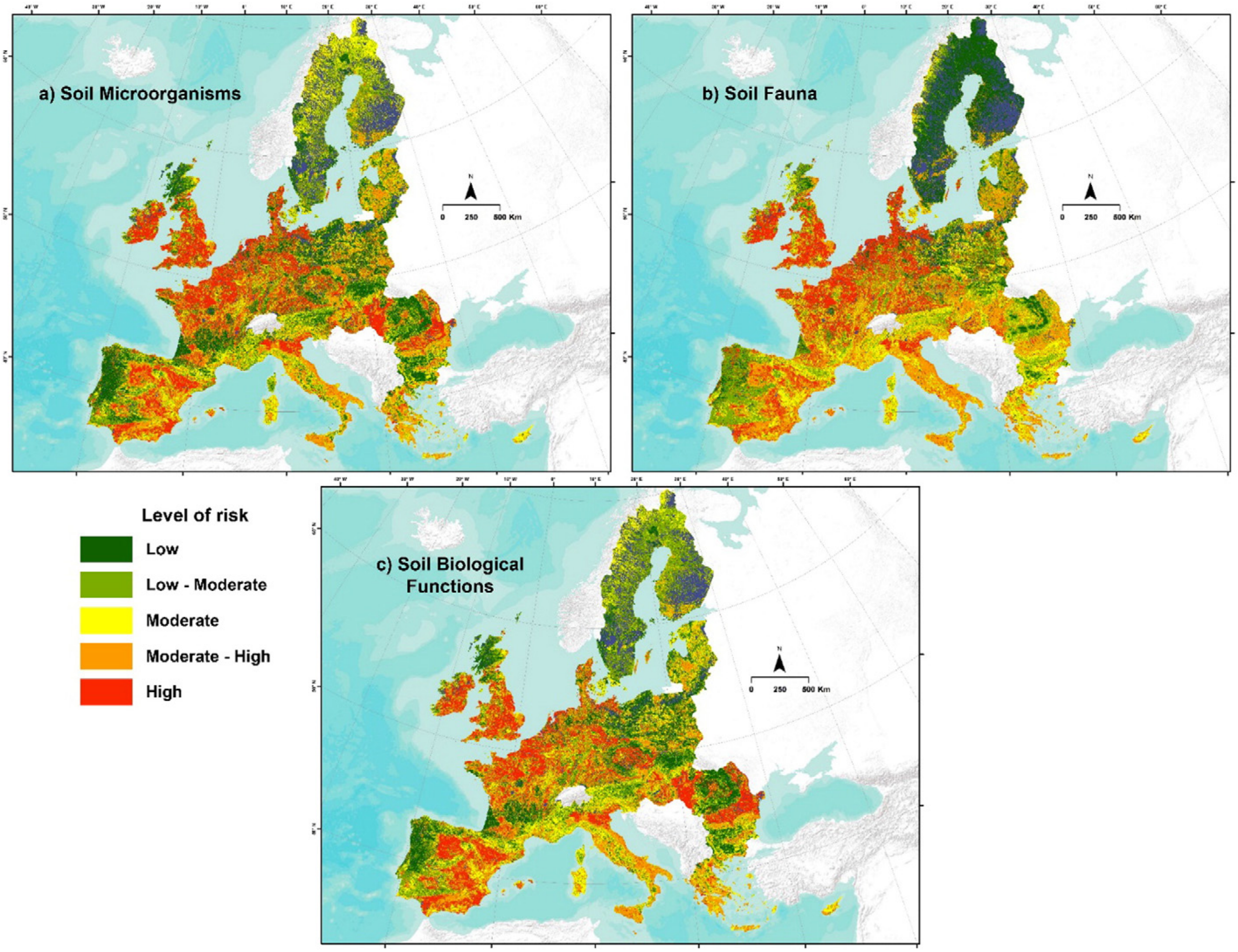

Fig. 3. Maps of potential risk to soil biodiversity in Europe. Distribution of the potential threats to (a) soil microorganisms, (b) soil fauna and (c) soil biological functions predicted for 27 European countries (spatial resolution 500 m).

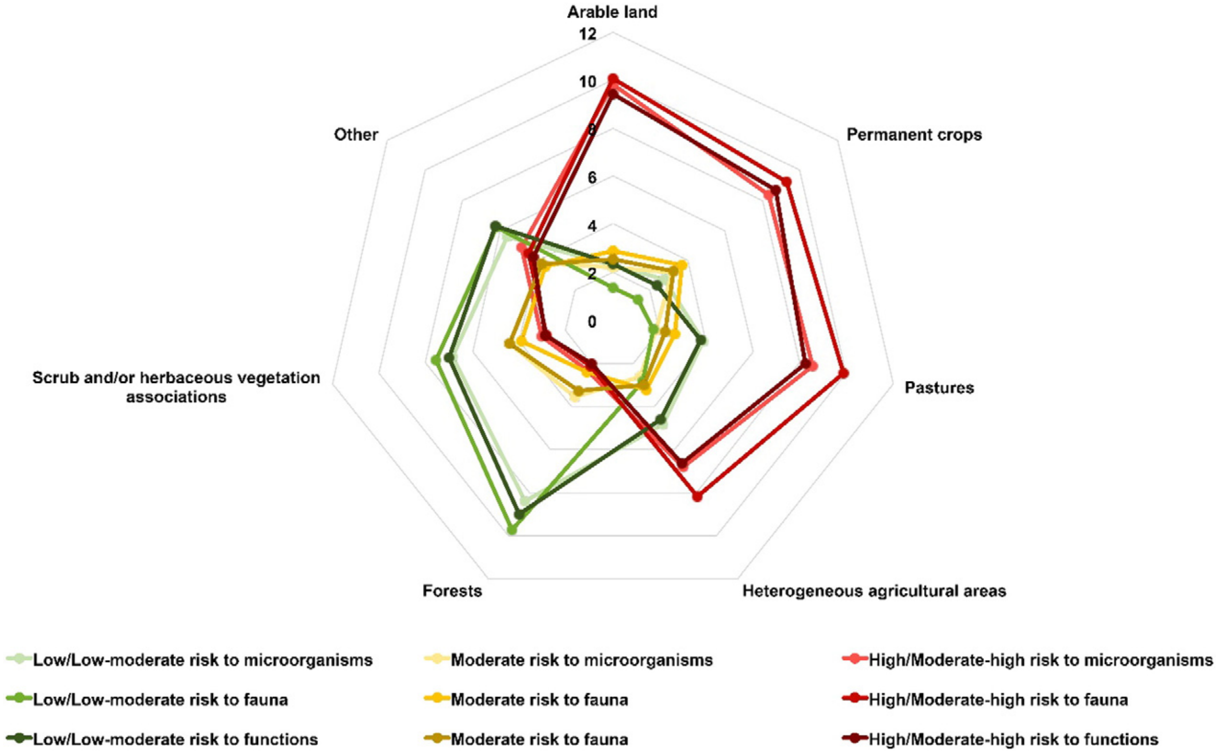

Fig. 4. Distribution of the threats to three components of soil biodiversity by land cover typologies. Values of low/low-moderate threat and moderate-high/high threat are aggregated. Values are weighted and reported as percentage calculated on the average coverage of the seven chosen classes (Arable land, Permanent crops, Pastures, Heterogeneous agricultural areas, Forests, Scrub and/or herbaceous vegetation associations, Other — for detailed description of land cover types included in these classes: http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-2006-by-country/legend) from the level classification of Corine Land Cover 2000 (EEA, 2012) (water bodies excluded).

locations or actions for conservation of soil biodiversity should provide this information. For example, in order to set conservation priorities a global map of biodiversity hotspots was proposed by Myers et al. (2000) on the basis of above-ground biodiversity distribution data. The recognized importance of below-ground biodiversity for ecosystem management (Bardgett and Van der Putten, 2014), proves that it should also be included in future conservation strategies. However, this incorporation is not easy since the factors potentially impacting soil biodiversity are numerous, of varying intensity and controversial effects. Therefore, the evaluation of threats to soil organisms remains an ambitious task. Despite the availability of several studies (Verbruggen et al., 2012; Tsiafouli et al., 2015) assessing the impact of different pressures on specific groups of soil-dwelling organisms, a broad framework mirroring the current level of knowledge is still missing. Expert knowledge is not often properly taken into account for translation into environmental policies (Wesselink et al., 2013), also because it might be influenced by personal interests (e.g. the debate surrounding the use of GMOs). However, the scientific opinion poll can represent a starting and, at the same time, summarizing point and, consequently, help drive the future debate surrounding sensitive issues subjected to controversies. Nonetheless, the uncertainties linked to this approach are numerous. Indeed, there are many different approaches based on expert knowledge for risk assessments (Aspinall, 2010), all with their own strength and weakness. The main issue is related to the need to test inconsistencies of expert opinions. When we decided to apply such an approach to assess the distribution of potential threats to soil biodiversity at European level, we were aware of these issues. Nevertheless, the proposed assessment represents an initial step toward developing a more robust framework. It is time for soil biodiversity to obtain the same level of attention as life above-ground when discussing conservation and sustainability policies. To reach such an ambitious goal, it is necessary to develop methods to (1) better assess the distribution and richness of soil organisms at large scale and (2) identify the areas of risk. Recently, progress has been made toward investigating biogeography of soil biodiversity and creation of databases of soil organisms (Burkhardt et al., 2014; Tedersoo et al., 2014), whereas less has been done in terms of risk evaluation. In the future, these two lines of research should be combined in order to identify the actual risk for soil biota by comparing observed data with reference levels of soil biota stored in databases (i.e. development of a reliable plan of monitoring of soil biodiversity). At the moment, despite the intrinsic limits of expert assessments, the proposed analysis begins to bridge this gap by exposing a new era of soil biota conservation research.

4.1. Threats to soil biodiversity

The first element to consider for the analysis was the high number of threats that may affect soil biota. The analysis of expert opinions showed some trends relevant to all three categories of soil biodiversity. In particular, with the current level of scientific knowledge, scientists do not consider the use of GMOs in agriculture as too risky for soil biodiversity (Verbruggen et al., 2012). The debate surrounding the use of GMOs in agriculture remains a hot topic and decision processes in this field can be problematic. Our assessment does not claim that the use of GMOs is completely risk-free, but confirms that other pressures are more relevant. In particular, the intensive use of soil in agriculture was recognized as the only threat with high potential for all three components of soil biodiversity. It is known and previously proven that agricultural exploitation (e.g. high levels of pesticides and mechanization) can strongly affect the soil-dwelling organisms and functions (Tsiafouli et al., 2015). However, the measures to obtain a more sustainable use of soils in agriculture often do not consider soil biodiversity as a target. Our results suggest that the scientific community recognizes intensive exploitation as one of the key forces impacting below-ground diversity. Therefore, discussions about possible measures to protect soils, should consider not only abiotic aspects (e.g. carbon storage capacity and soil erosion reduction), but also biotic components (i.e. preservation of soil-living community).

Similar rankings were obtained for soil microorganisms and biological functions, while a higher uncertainty was found for soil fauna, with six potential threats for which it was not possible to classify the potential. The similarity between microorganisms and functions could be due to the fact that scientists often tend to only take into account microbe-mediated processes when thinking about functions carried out by soil biota (Nannipieri et al., 2003). The observed difficulty in assessing the risk potential to soil fauna might be due, in some cases as for soil sealing, salinization, and habitat fragmentation, to a real scarcity of knowledge because of the limited number of available studies. Our analysis highlighted that for soil erosion, compaction, and industrial pollution, the uncertainty can also be explained by the lack of agreement among the experts. This can be due to limited effects on soil biodiversity as could be the case for soil compaction. Indeed, it was shown that compaction may impact more the biological process (e.g. burrowing) than the species abundance (Beylich et al., 2010). Despite this ambiguity, the exclusion of these six unclassified threats from the analysis does not have to be considered as a real absence of effects on soil fauna. In contrast, it highlights the need for further investigation to assess the impact of this group of threats.

Another interesting result from the comparison of the three classes of soil biodiversity came from the class “climate change”. Indeed, its potential effects were unclassifiable for both soil microorganisms and biological functions and low for soil fauna. This difficulty in quantifying the impact of global warming on soil biodiversity is likely due to the open controversy featured in the debate surrounding this issue, with some studies presenting a correlation between global warming and alteration of soil life (De Vries et al., 2012), and others showing the opposite (Rousk et al., 2013). Therefore, nowadays we may claim that climate change impacts life below-ground, but not exactly to what extent. The only way to overcome this uncertainty seems to be the development of a specific strategy aiming at understanding actual effects of global warming on life below-ground at large scale.

4.2. Categories of soil biodiversity and groups of experts

A second level of complexity in the analysis was due to the different expertise of the participants that could have influenced the final outcomes. Comparing the opinions given by the three different groups of experts to all potential threats, a general consensus was reached, with only a couple of exceptions. This suggests the presence of a shared point of view in the scientific community dealing with threats to soil biodiversity. Furthermore, the results from the publication meta-search showed the good representativeness of the level of knowledge of the involved group of experts, in terms of the papers published. All this confirms the suitability of the knowledge-based evaluation as a possible approach for risk assessment.

The final level of complexity was represented by the intrinsic variability of soil biodiversity. In this regard, the importance of carrying out a separate assessment for different categories, rather than considering soil biodiversity as a whole, is confirmed by the significant difference, with only three exceptions, in the scores given to soil microorganisms, fauna, and functions, respectively. Of course the ideal situation would be to have a specific assessment for each group, or even better each species, of soil organisms. Another possibility would be to consider threats to different trophic groups of soil organisms (e.g. decomposers and ecosystem engineers). This type of approach is desirable from a scientific point of view aiming to obtain a complete and detailed assessment of threats to soil biodiversity, but could also generate a fragmented scenario with disadvantages in terms of protection of soil biodiversity.

Finally, the proposed assessment can be considered a good reference point for interested scientists as guidelines for setting priorities for future studies, i.e. to focus their attention on the pressures that showed the highest uncertainties. At the same time the rankings may be useful for decision makers in order to target and establish appropriate policies to start protecting soil biodiversity.

4.3. Possible guidelines for preserving soil biodiversity

The development of risk maps is essential to identifying locations for conservation. The maps of threats to soil biodiversity show that the

Table 1

Distribution (percentage weighted on the average area of the eight types of biogeographical region) of soils subjected to different levels of risk aggregated per biogeographical region. The total sum of each box is 100%, covering the whole considered area in Europe.

	Biogeographical region	Level of risk				
		Low %	Low–Moderate %	Moderate %	Moderate–High %	High %
Soil microorganisms	Alpine	3.7	3.1	4.5	1.0	0.2
	Atlantic	2.5	1.3	1.4	2.3	5.0
	Black Sea	1.2	1.8	3.2	5.3	1.1
	Boreal	2.2	4.9	3.7	1.5	0.2
	Continental	3.1	1.8	2.1	2.8	2.7
	Mediterranean	1.5	2.0	2.9	3.9	2.1
	Pannonian	1.1	1.0	1.8	3.8	4.8
	Steppic	0.2	0.3	1.1	3.9	7.0
Soil fauna	Alpine	2.7	4.2	3.7	1.6	0.3
	Atlantic	0.6	2.2	2.2	1.6	5.9
	Black Sea	0.3	3.0	4.7	4.1	0.4
	Boreal	8.4	1.7	0.5	1.8	0.2
	Continental	1.3	2.6	3.2	2.5	3.0
	Mediterranean	0.3	2.2	3.3	5.0	1.6
	Pannonian	0.0	1.2	3.3	6.6	1.4
	Steppic	0.0	1.3	2.7	8.1	0.3
Soil biological functions	Alpine	3.0	4.1	4.6	0.7	0.1
	Atlantic	2.3	1.5	1.8	2.9	4.1
	Black Sea	0.9	1.7	3.7	3.7	2.4
	Boreal	2.2	6.7	2.5	0.9	0.1
	Continental	2.9	2.0	2.5	2.6	2.5
	Mediterranean	0.9	1.9	3.4	3.7	2.6
	Pannonian	0.9	1.0	2.2	3.7	4.7
	Steppic	0.1	0.3	1.3	1.0	9.9

overall distribution of the sensitive areas is quite similar since the two main driving forces, intensive exploitation and organic matter decline, are the same. A greater similarity was found between the patterns of threat for soil microorganisms and biological functions. The reason for this may be the current more in-depth knowledge, expressed also in terms of published articles, of potential effects of threats on microorganisms. The spatial distribution of threats to soil fauna showed a more peculiar and less fragmented pattern due to the different driving forces that shape the distribution. Considering the distribution at country level, differences among the classes of threat were observed, thus demonstrating the need for specific actions to be taken at local level.

The analysis of the spatial distribution of threats demonstrates the urgency with which action should be taken as the majority of the European countries showed the presence of soils with high level of risk. Because of the magnitude of the interested areas, a common strategy seems to be the recommended way forward in order to start thinking about a feasible conservation strategy for soil life or, at least, to increase focus on this topic. A first possible buffer measure to be taken is the reconsideration of the current distribution of protected areas, or at least the criteria for protected area planning. Soil biodiversity is not taken into account in preliminary biodiversity surveys for the creation of national parks (Decaëns et al., 2006). The developed maps might be considered in order to redraw the boundaries of protected areas to include soil with high level of risk. Furthermore, the analysis allowed us also to circumscribe the typologies of soils, in terms of both land cover and biogeographical distribution, which would require more attention. Soil-living organisms of agricultural lands are potentially in danger. In contrast, forests and grasslands presented the lowest levels of risk due to their more natural management and soil parameters. From a biogeographical point of view, the highest risk present in soils of the steppic regions may be related to the combined effects of human activities, i.e. increasing conversion into arable land, and ecological characteristics, i.e. low diversity of vegetation. In contrast, soils of both the boreal and alpine regions are less exposed to threats. This is likely due to the isolation present in these regions. Both the land cover and biogeographical distribution may also be used to recognize the potential factors affecting soil organisms and biological functions and to better circumscribe areas that would need a more urgent intervention.

One of the Aichi Biodiversity Targets to 2020 states that direct pressures on biodiversity need to be reduced (Chase, 2014). Not much time remains to reach such an ambitious goal and soil biodiversity cannot be excluded. At the same time, current knowledge of the spatial and temporal distribution of soil biodiversity is increasing also thanks to the DNA-based technologies (Orgiazzi et al., 2015). The application at large scale of such tools will bring this discipline toward a reliable assessment of soil biodiversity distribution, as has been done for above-ground biodiversity. To assure conservation, the assessment phase must go hand-in-hand with a reliable risk and monitoring analysis. Therefore, the mapping of the risk potential associated to different pressures is needed as it would represent the first step toward a conservation framework. Once the sensitive areas are identified, it is necessary to verify whether the expected threats actually impact the soil biota. In case of need, the process considers the development and then application of measures to promote the restoration of a condition able to guarantee proper levels of soil life. Finally, the applied strategy will need to be monitored in order to assess its effectiveness. The interested parties should move toward the completion of this step-by-step procedure. In doing so, the development of any type of suitable measures should consider that soil biodiversity is a complex player, including an enormous variety of different organisms. Some organisms react better to pressures than others, some are affected by threats differently from those acting on other groups, so conservation actions cannot be homogeneous. Putting all soil organisms together runs the risk of being too simplistic, but it is essential from the point of view of the development of a conservation strategy. A compromise can be found with major components of soil biodiversity identified and treated differently according to their typical features.

In conclusion, the analysis carried out highlights the urgency to start a factual discussion on threats faced by life below-ground. The main intention of our analysis was to clearly provide impetus for further work on this topic as conservation of soil biodiversity deserves as much attention as life above-ground. In this context, the obtained results can be used as preliminary guidelines to set the agenda for the research and policy priorities in order to preserve soil biota. Of course, the possible measures must be inserted into a wider context with economic and social scenarios taking into account the feasibility of the proposed strategies of conservation, in order to plan the most effective actions to safeguard soil biodiversity.

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Appendix A. Supplementary material.

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