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An estimate of potential threats levels to soil biodiversity in EU

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Abstract

Life within the soil is vital for maintaining life on Earth due to the numerous ecosystem services that it provides. However, there is evidence that pressures on the soil biota are increasing which may undermine some of these ecosystem services. Current levels of belowground biodiversity are relatively poorly known, and so no benchmark exists by which to measure possible future losses of biodiversity. Furthermore, the relative risk that each type of anthropogenic pressures places on the soil biota remains unclear.

Potential threats to soil biodiversity were calculated through the use of a composite score produced from data collected from 20 international experts using the budget allocation methodology. This allowed relative weightings to be given to each of the identified pressures for which data were available in the European Soil Data Centre (ESDC). A total of seven different indicators were used for calculating the composite scores. These data were applied through a model using ArcGIS to produce a spatial analysis of composite pressures on soil biodiversity at the European scale.

The model highlights the variation in the composite result of the potential threats to soil biodiversity. A sensitivity analysis demonstrated that the intensity of land exploitation, both in terms of agriculture and use intensity, as well as in terms of land-use dynamics, were the main factors applying pressure on soil biodiversity. It is important to note that the model should not be viewed as an estimate of the current level of soil biodiversity in Europe, but as an estimate of pressures that are currently being exerted. The results obtained should be seen as a starting point for further investigation on this relatively unknown issue and demonstrate the utility of this type of model which may be applied to other regions and scales.

Keywords: BISQ, DISPR, QBS, soil biodiversity, soil degradation processes, soil thematic strategy, threats

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Introduction

Soil biodiversity has often been overlooked despite its importance in global functioning, the sustainability of agriculture, and the high value of the numerous ecosystem services that it provides (Costanza *et al.*, 1997; Pimentel *et al.*, 1997). 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 *et al.*, 2010). Furthermore, there is a paucity of data regarding the current baseline levels of soil biodiversity across scales from field scale in most areas up to regional scales and beyond. This means that it is generally not possible to directly evaluate where, if anywhere, soil biodiversity is decreasing due to anthropogenic influences such as intensive agriculture, land-use change, or climate change.

Many species around the world are under threat, and in many places this threat is increasing (McKee *et al.*, 2004). The Global Biodiversity Outlook three, the flagship publication of the Convention on Biological Diversity, states that 'The target agreed by the world's Governments in 2002, to achieve by 2010 a significant reduction in the current rate of biodiversity loss at the global, regional and national level… has not been met.' (CBD, 2010).

If the extinction process is indeed occurring at an accelerated rate for mammals, birds, reptiles, amphibians, etc., as seems evident from McKee *et al.* (2004), it is probable that it is also accelerated for the variety of organisms living into the soil as evidence shows that many of the pressures affecting aboveground organisms, such as loss of habitat, e.g., through urbanization, and the associated soil sealing (Scalenghe & Marsan, 2009) and agricultural intensification also affect belowground organisms (Jones *et al.*, 2003). The historical records concerning soil organisms are relatively limited and as such quantifying any changes which may have occurred in their prevalence and distribution is problematic. However, some evidence exists of the decline in mushrooms species in some European countries

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(Jeffery & Gardi, 2010). For example, a 65% decrease in mushroom species in the Netherlands was reported over a 20-year period (Condé *et al.*, 2010), and the Swiss Federal Environment Office has published the first-ever 'Red List' of mushrooms detailing 937 known species facing possible extinction in the country (Swissinfo, 2007). Invasive species have been shown to be causing a decline in soil biodiversity in some areas. Garlic mustard (*Allaria petiolata*), an invasive plant in North America, has been shown to be responsible for the decline in arbuscular mycorrhizal Fungi (AMF) in many native hardwood forests (Stinson *et al.*, 2006; Anderson *et al.*, 2010), and in United Kingdom, a flatworm from New Zealand (*Arthurdendyus triangulatus*) is probably one of the main threats to indigenous earthworm populations (Boag *et al.*, 1999; Jones *et al.*, 2001). Furthermore, it has been found that in sampling at the European level, over half of all earthworm species are rare, being found only once or twice across the different sites investigated (Watt *et al.*, 2004). This suggests that local extinctions may well mean regional or even global extinctions.

The main anthropogenic disturbance factors (pressures) have been identified for the three levels of biodiversity: ecosystem, species, and gene (Gardi *et al.*, 2008 after Spangenberg, 2007).

At the ecosystem level, the main pressures derive from:

- Land-use change
- Overexploitation
- Change in climatic and hydrological regimes
- Change in geochemical framework

At the species level, the main pressures on soil biodiversity derive from:

- Change in environmental conditions
- Change in geochemical framework
- Competition with invasive species
- Effects of ecotoxins

At the gene level, the main pressures derive from:

- Change in environmental conditions
- Effects of ecotoxins
- 'Genetic pollution'

Further to each of these pressures, any physical loss of soil, such as erosion, or other soil degradation processes can potentially also lead to a loss of biodiversity. However, other pressure factors which play an important role in governing levels of aboveground biodiversity are often less important for soil biodiversity. For example, habitat fragmentation and the consequent reduction in biotope size can, theoretically, also be detrimental for soil biological diversity. However, detrimental effects usually only occur spatial scales that rarely occur in practice (Rantalainen *et al.*, 2006), such as in the order of few square centimeters, far away from the real-world processes (Rantalainen *et al.*, 2006, 2008).

Although it is thought that the current rate of species extinction is two to three orders of magnitude higher than it would be in absence of human activities (Balmford, 1996), leading many biologists to state that we are currently undergoing the sixth extinction event (e.g., Leakey & Lewin, 1996), this number is derived from studies on aboveground species. However, owing to the close-nit links between aboveground and belowground communities (Wardle *et al.*, 2004) it is likely that the factors which are driving extinction aboveground are likely to affect belowground communities, either directly or indirectly, and lead to increased pressures and extinctions there. For example, increasing land-use intensity is widely reported to reduce aboveground biodiversity (Donald *et al.*, 2001; Kleijn *et al.*, 2009), and other authors (Eggleton *et al.*, 2002; Jones *et al.*, 2003) confirmed that termite assemblages also collapse along land-use intensity gradients with increasing land-use intensity being directly correlated with reduced number and species richness of termite communities, thereby confirming the negative impact of land-use intensity on at least one part of the soil biota. It has been demonstrated that the intensity of land management can alter the resistance and the resilience of soil food webs (de Vries *et al.*, 2012), and consequently the adaptation to environmental changes.

Monitoring programs are often restricted to aboveground biodiversity with indicators related to soil biodiversity being measured only rarely. For example only 5 of 29 countries within Europe have monitoring sites for earthworms (Jeffery *et al.*, 2010) which are one of the main indicators of soil biodiversity identified by Huber *et al.*, (2008), and there is a paucity of soil biodiversity monitoring programs outside of Europe.

Some small steps have been taken toward continual monitoring in some of the EU member states. For example, in the Netherlands, the 'Netherlands Soil Monitoring Network' (NSMN) sampled approximately 300 sites over a 6-year period where they investigated, among other things, the quantity and community composition of earthworms, microarthropods, enchytraeids, nematodes, and microorganisms (Rutgers *et al.*, 2010). These data were then used as part of their 'Biological indicator system for soil quality' (BISQ). In Brittany, France, monitoring of earthworm abundance is ongoing (Cluzeau *et al.*, 2009). Furthermore, in Northern Italy, the 'Biological Quality of Soil Index' (QBS) was developed by Parisi (2001) and built upon by Gardi *et al.* (2008) which allows for the monitoring of soil quality through examination of the soil microarthropod communities. However, this methodology is yet to be applied to a long-term monitoring project.

These relatively small programs are important first steps but also highlight the lack of data and so the difficulty of quantifying soil biodiversity and its changes over time, as well as the lack of monitoring programs both within Europe and particularly globally. Owing to the availability of data at the European scale, available via the EU Soils Data Centre, Europe was used as a test region to test a model and investigate whether it is possible to address the question: In which areas of Europe are soil biodiversity most under pressure and which anthropogenic factors contribute most to such pressures? Should it be possible to answer this question for this test region, the model may then be applied to other regions for which data are available.

Materials and methods

Potential threats to soil biodiversity were selected and ranked on the basis of expert evaluation (Fig. 1). Questionnaires were presented to the 20 expert members of the Soil Biodiversity Working Group of the European Commission on 2nd March 2009.

The experts were asked to give a threat ranking to each of the following potential threats to soil biodiversity:

- Human intensive exploitation
- Soil organic matter decline
- Habitat disruption
- Soil sealing
- Soil pollution
- Land-use change
- Soil compaction
- Soil erosion
- Habitat fragmentation
- Climate change
- Invasive species
- GMO pollution

Threats were each ranked on a scale of 1–10 (1 = low threat, 10 = high threat) by the experts using a budget allocation approach (Nardo *et al.*, 2008). Figure 2 shows the result of the exercise in the form of a box-and-whisker plot. The averages of the experts' scores – expressed as percentage – were used for the subsequent analysis (Table 1). The selection of the proposed threats was undertaken on the basis of the expert judgment and available data.

For each of the parameters listed in Table 1, a map, in the form of a raster layer (1 × 1 km grid cells) was compiled, classifying the range of values present in each grid into five classes. These values were weighted using the coefficients obtained from the expert evaluation. The software used for GIS operations was ArcGIS 9.3.

The final indicator (an index) was calculated, with an operation of map algebra as the sum of the weighted individual raster values. The values shown on the map are related to the

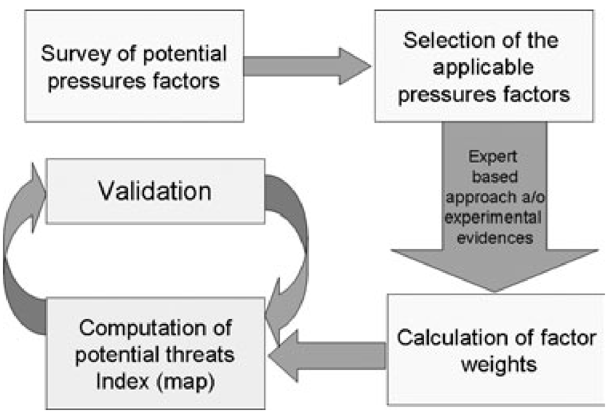

Fig. 1 Conceptual model applied for the evaluation of threats on soil biodiversity.

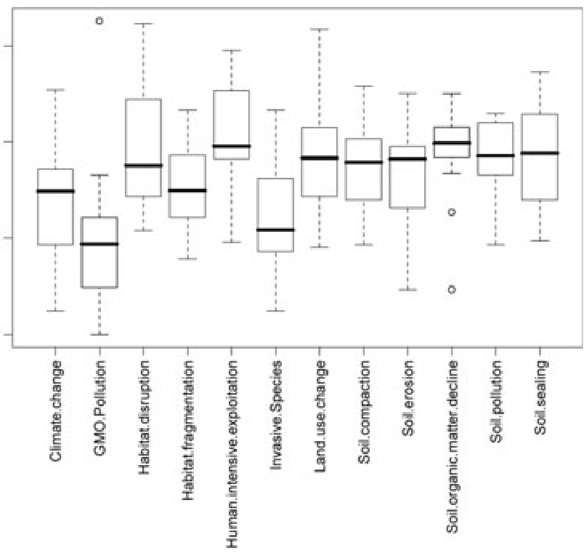

Fig. 2 Box-and-whisker plot of the rankings of soil biodiversity threats as assigned by the experts.

Table 1 Summed threat weightings (expressed as a percentage of the maximum possible score) of the identified potential pressures on soil biodiversity as provided by the Soil Biodiversity Working Group of the European Commission

Pressure to soil biodiversity	Weighting score (%)
Human intensive exploitation	65.0
Soil organic matter decline	63.5
Habitat disruption	61.5
Soil sealing	61.0
Soil pollution	61.0
Land-use change	60.5
Soil compaction	57.5
Soil erosion	56.5
Habitat fragmentation	48.5
Climate change	46.0
Invasive species	38.0
GMO pollution	32.5

potential threats to soil biodiversity, for the 23 of the member states of the European Union countries for which data were available. The composite map was first presented in the European Atlas of Soil Biodiversity (Jeffery *et al.*, 2010) and has been expanded on here to include further statistical analysis.

Thematic maps data

Agricultural intensity. For the evaluation of human intensive exploitation, the average nitrogen load was used as a proxy (Herzog *et al.*, 2006). Data on nitrogen load, at watershed level, were derived from the report on 'Nutrient discharge from rivers to seas for year 2000' (Bouraoui *et al.*, 2009). The values, ranging between 0 (0.2) and 545 kg N ha^{-1}, were classified in five classes, based on natural break interval approach. The score attributed to each class are shown in Table 2. The assigned scores were weighted by multiplying them by 10, according to the experts' judgment.

Compaction. For the evaluation of this specific threat, the map of natural susceptibility of soil to compaction (Houšková, 2008) compiled by JRC (Joint Research Centre) was used. The scores were attributed on the basis of the proposed classification of susceptibility to soil compaction (Classes 0–4), with an additional class for sealed soils (Table 3). The assigned scores were weighted by multiplying them by 8.9.

Contamination. The map of contamination was derived from Corine Land Cover 2000 map, reclassifying the 44 existing third-level classes according to the specification reported in

Table 2 Agricultural intensity calculated using data on nitrogen load, at watershed level, as a proxy measurement. Values ranging between 0 (0.2) and 545 kg N ha^{-1} were classified into five classes based on natural break interval approach

N load (kg N ha^{-1})	Class	Score
0–20	1	1
21–56	2	2
57–98	3	3
99–167	4	4
>167	5	5

Table 3 Soil compaction scores were attributed on the basis of the proposed classification of susceptibility to soil compaction (Classes 0–4), with an additional class for sealed soils

Susceptibility to compaction	Class	Score
Low	1	1
Medium	2	2
High	3	3
Very high	4	4
Sealed soils	5	5

Table 4 Soil contamination scores were derived from Corine Land Cover 2000 map, through reclassifying the 44 existing third-level classes

Class	Level 1	Level 3	Score
1.1.1	Artificial surfaces	Continuous urban fabric	2
1.1.2	Artificial surfaces	Discontinuous urban fabric	1
1.2.1	Artificial surfaces	Industrial or commercial units	5
1.2.2	Artificial surfaces	Road and rail networks and associated land	3
1.2.3	Artificial surfaces	Port areas	3
1.2.4	Artificial surfaces	Airports	5
1.3.1	Artificial surfaces	Mineral extraction sites	4
1.3.2	Artificial surfaces	Dump sites	4
1.3.3	Artificial surfaces	Construction sites	2
1.4.1	Artificial surfaces	Green urban areas	0
1.4.2	Artificial surfaces	Sport and leisure facilities	0
2.1.1	Agricultural areas	Nonirrigated arable land	1
2.1.2	Agricultural areas	Permanently irrigated land	1
2.1.3	Agricultural areas	Rice fields	1
2.2.1	Agricultural areas	Vineyards	1
2.2.2	Agricultural areas	Fruit trees and berry plantations	1
2.2.3	Agricultural areas	Olive groves	1
2.3.1	Agricultural areas	Pastures	0
2.4.1	Agricultural areas	Annual crops associated with permanent crops	1
2.4.2	Agricultural areas	Complex cultivation patterns	1
2.4.3	Agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation	0
2.4.4	Agricultural areas	Agro-forestry areas	0
3.1.1	Forest and seminatural areas	Broad-leaved forest	0
3.1.2	Forest and seminatural areas	Coniferous forest	0
3.1.3	Forest and seminatural areas	Mixed forest	0
3.2.1	Forest and seminatural areas	Natural grasslands	0
3.2.2	Forest and seminatural areas	Moors and heathland	0
3.2.3	Forest and seminatural areas	Sclerophyllous vegetation	0
3.2.4	Forest and seminatural areas	Transitional woodland-shrub	0
3.3.1	Forest and seminatural areas	Beaches, dunes, sands	0

Table 4 (continued)

Class	Level 1	Level 3	Score
3.3.2	Forest and seminatural areas	Bare rocks	0
3.3.3	Forest and seminatural areas	Sparsely vegetated areas	0
3.3.4	Forest and seminatural areas	Burnt areas	0
3.3.5	Forest and seminatural areas	Glaciers and perpetual snow	0
4.1.1	Wetlands	Inland marshes	0
4.1.2	Wetlands	Peat bogs	0
4.2.1	Wetlands	Salt marshes	0
4.2.2	Wetlands	Salines	0
4.2.3	Wetlands	Intertidal flats	0
5.1.1	Water bodies	Water courses	0
5.1.2	Water bodies	Water bodies	0
5.2.1	Water bodies	Coastal lagoons	0
5.2.2	Water bodies	Estuaries	0
5.2.3	Water bodies	Sea and ocean	0

Table 4. The assigned scores were weighted by multiplying them by 9.2.

Invasive species. The information for deriving the map of invasive species was taken from the DAISIE (Delivering Alien Invasive Species In Europe) web database (DAISIE, 2009).

The total number of invasive plants, fungi, and invertebrates, ranging between 188 and 2472, was reclassified into five classes, using the natural breaks method (Table 5). The assigned scores were weighted by multiplying them by 5.8.

Land-use change. Detection of land-use change was based on the comparison between the Corine Land Cover 1990 (CLC 1990) and CLC 2000 (EEA, 2009). The transition of land use was classified as shown in Table 6. The assigned scores were weighted by multiplying them by 9.65.

Organic carbon loss. Data regarding the potential losses of soil organic carbon (SOC) in European soils were derived from data available in the European Soils Data Centre of the Joint Research Centre (JRC) previously published by Stolbovoy & Maréchal (2010). The data utilized refer to the amount of SOC (tC ha^{-1}) that can be lost by a given soil typological unit within a bioclimatic region. The potential for a given soil to lose SOC was estimated by JRC using the following equation:

Potential of SOC loss = Mean SOC − Min SOC.

The values, ranging between 0 and 2586 kg SOC, were classified into five classes, based on the natural break method (Table 7). The assigned scores were weighted by multiplying them by 5.8.

Table 5 The invasive species score was calculated using information from the DAISIE (Delivering Alien Invasive Species In Europe) web database. The total number of invasive plants, fungi, and invertebrate, ranging between 188 and 2472, was reclassified into five classes, using the natural breaks approach

Number of invasive species	Class	Score
0–381	1	1
382–821	2	2
822–1147	3	3
1148–1545	4	4
1546–2742	5	5

Table 6 Land-use change scoring was based on the comparison between the Corine Land Cover 1990 (CLC) and CLC 2000. The transition of land use was classified according to the following table:

From\To	Forest	Grassland	Agriculture	Urban
Forest	0	1	2	3
Grassland	−1	0	1	2
Agriculture	−2	−1	0	1
Urban	−3	−2	−1	0

Soil erosion. The soil erosion map was derived from the Pan European Soil Erosion Risk Assessment (PESERA) and the Revised Universal Soil Loss Equation (RUSLE) model (applied in Finland and Sweden) (Louwagie *et al.*, 2009).

The values, ranging between 0 and 1074 t ha^{-1} y^{-1}, were classified into five classes, based on the natural break method (Table 8). The assigned scores were weighted by multiplying them by 8.4.

Statistical analysis

To apply a sensitivity analysis (Saltelli *et al.*, 2008) to the results of the model, a subset of points were extracted from the thematic maps of the input factors and from the final map produced as a result of the model application. Scatterplots of the seven input factors are given in Figure 3.

A total of 1848 points were extracted, and for each of them the values of all the seven factors and the final indicators were analyzed. Furthermore, a more sophisticated form of sensitivity analysis using a model-free version of the Pearson test (the

Table 7 Scoring of the potential of soils to lose soil organic carbon (SOC) in European soils was derived from data available in the European Soils Data Centre of the Joint Research Centre and the values, ranging between 0 and 2586 kg SOC, were classified into five classes, based on the natural break interval approach

OC potential losses (kg OC ha^{-1})	Class	Score
0–92	1	1
93–233	2	2
234–477	3	3
478–791	4	4
>791	5	5

Table 8 Scoring of the susceptibility of soils to erosion was undertaken using data derived from the Pan European Soil Erosion Risk Assessment (PESERA) and the RUSLE (Revised Universal Soil Loss Equation) model (applied in Finland and Sweden). The values, ranging between 0 and 1074 t ha^{-1} y^{-1}, were classified into five classes, based on the natural break interval approach

Soil water erosion (t ha^{-1} y^{-1})	Class	Score
0–8.4	1	1
8.5–46.4	2	2
46.5–122.2	3	3
122.3–274.0	4	4
>274.0	5	5

Pearson correlation ratio η^2, see Paruolo *et al.*, 2012 for a recent application) was attempted, but results were not appreciably different from the correlation-based one due to the discrete scale of the input variables (0–5) and the concentration of results in few bins (e.g., practically only one bin in the case of land-use change and two bins in the case of contamination). These coefficients give an indication of the relative importance of the selected variables in determining the value of the index (Table 9). Note that this table offers quite a different picture of the relative importance of variables than that from that of Table 1. In other words the importance as perceived from the statistical analysis is different from that wished by the experts. This is a common problem in building composite indicators, see Paruolo *et al*. (2012) for a discussion.

Results

This research presents an expansion of the work first presented in Jeffery *et al.* (2010) showing the first continental (EU) scale analysis of threats to soil biodiversity, presented as a composite indicator and highlighting differences in threat levels, thereby helping to focus areas where resources, research, and monitoring should be directed as well as informing policy. Our framework incorporates all major classes of anthropogenic drivers of stress for which data are currently available, and enables an assessment of their aggregate impact on soil biodiversity utilizing the EU as a region to test the model which may be applied in other regions and at other scales.

Results from the questionnaires used for the budget allocation approach showed the potential threats to soil biodiversity to be, in order of decreasing risk: human intensive exploitation; soil organic matter decline; habitat disruption; soil sealing; soil pollution; land-use change; soil compaction; soil erosion; habitat fragmentation; climate change; invasive species; GMO pollution (see Table 1 from Jeffery *et al.*, 2010).

Use of these data to form weighted layers in GIS as described previously shows that 44% of the EU (25) territory currently has no significant anthropogenic pressures on soil biodiversity. The remaining territory (56%) is characterized by pressure on soil biodiversity of various degrees. The area under high, very high, and extremely high threats are, respectively, the 9%, 4%, and 1% of the EU territory used for this analysis. Conversely low, very low, and extremely low threats cover 14%, 12% ,and 4% of the EU territory, respectively. 13% of the EU territory used in this study showed a moderate threat to soil biodiversity.

A sensitivity analysis based on both Pearson correlation ratio η^2 and its linear equivalent is shown in Table 9. These coefficients relate the final indicator, computed as a weighted linear aggregation of the underlying seven variables, to the individual variables.

Table 9 shows that the relative importance of variable 'Land Use Change' is very small, i.e., this variable does not appreciably affect the value of the index. Erosion and contamination are also weak variables. Hence, as mentioned, the relative importance of the input variables does not correspond to the assigned weights. The order of importance of the variables is thus: agricultural intensity, OC losses, invasive species, compaction, erosion, and contamination. The same information can be directly appreciated from the scatterplots, where, e.g., the plot for land-use change does not show any dependence between this variable and the index, whereas the plot for agricultural intensity shows a clear positive trend (Fig. 3). Table 10 shows the variable-to-variable linear correlation and indicates the existence of both positive and negative associations among some of the input variables. When composite indicators are built using linear aggregation (the present case) positive correlation are desired; this indicates that all variables go in the same direction, i.e., the direction of the unobservable subject of the analysis (soil threat). Negative correlations are instead more of a problem, as these may 'kill' the effect of variables. For example, in our case Land-Use Change is the variable with the smallest

Table 9 A correlation analysis showing the correlation (Pearson) between the index and the unweighted input variables. Pearson correlation ration η^2 is defined as the ration $E(Y|X\_i)/V(Y)$ and squared Pearson correlation coefficient

Name of the variable	η^2	r^2
Agricultural Intensity	0.370	0.365
Compaction	0.119	0.116
Contamination	0.034	0.033
Erosion	0.080	0.070
Invasive species	0.201	0.158
SOC loss	0.309	0.301
Land-use change	<0.001	<0.001

Table 10 The final indicator computed as a weighted linear aggregation of the underlying seven variables, correlates with all variables with the exception of the seventh variable, land-use change; this variable was mostly zero over the sample explored. Furthermore, the weighting applied to the index does not translate automatically into the correlation table, i.e., the final indicator is more strongly associated with agricultural intensity (correlation = 0.60) and to OC losses (correlation = 0.55) than with the other variables, whose importance follows in the order (3rd) invasive, (4th) compaction, (5th) erosion, and (6th) contamination

	Agricultural intensity	Compaction	Contamination	Erosion	Invasive species	OC losses	Land-use change	Final indicator
Agricultural intensity	1.000							
Compaction	−0.023	1.000						
Contamination	0.031	0.035	1.000					
Erosion	0.000	0.012	0.155	1.000				
Invasive species	0.345	−0.116	−0.013	0.072	1.000			
OC losses	0.072	0.012	−0.195	−0.192	−0.061	1.000		
Land-use change	−0.002	−0.020	0.000	−0.051	−0.004	−0.023	1.000	
Final indicator	0.604	0.341	0.182	0.264	0.397	0.549	0.004	1.000

effective weight (Table 9) but also the variable with the least association with the other variables.

Discussion

The present discussion of the soil threats is conditional on the validity of the adopted model; in this case our soil pressure index composite indicator. Model validation is not an easy task because it would involve comparison of a model-based inference with some sort of evidence (Oreskes, 2000). For composite indicators describing complex phenomena (e.g., competitiveness, environmental pressure, innovation, or university performance), 'objective' data describing in a single number the complex phenomenon being measured are not and cannot be available. In these cases the evidence is in the experts and practitioners 'making sense' of the plausibility of the measure as compared with their own perception (Fig. 1). The Doing Business Index of the World Bank derives its success from the fact that businessmen and practitioners alike find it a useful summary measure of a country's receptiveness to doing/opening a business in that country.

The present study is hence itself a step of the validation process as it offers the index up for appraisal to its possible users.

The values of the index, ranging from 25 to 222, were divided into 10 classes and represented as thematic map (Fig. 4).

From the map presented in Figure 4, the high spatial variability in the proposed indicator is evident, with the areas characterized by the highest potential threats to soil biodiversity showing in dark red, and the shade of red getting lighter with decreasing potential pressure. It should be clarified that this specific indicator should not be interpreted as an indicator of the current level of soil biodiversity, but only as an evaluation of the potential threats to soil biodiversity and hence is a proxy highlighting areas where soil biodiversity is most likely to be in decline with respect to the current situation.

The high score (i.e., high potential threats) of several areas of United Kingdom and central Europe is determined by the combined effect of a high intensity agriculture, with a relatively high number of invasive species and an increased risk for the soils present there to lose organic carbon. Conversely, when compared with these situations, the intensive agricultural areas of Southern Europe are less affected by both the risk to lose organic carbon (Stolbovoy & Maréchal, 2010) and by the effect of invasive species (DAISIE, 2009). This means that a lower combined indicator value was found for such regions. However, while some regions within Southern Europe which have intensive agriculture, so as the Po Valley in Italy, have been identified as areas of high threat to soil biodiversity, it should be noted that several small intensive agricultural areas of Southern Europe are likely not to have been properly accounted for, due to problems of scale and to the proxy indicator used for the evaluation of agricultural intensity. In general terms, however, the use of nitrogen input as land-use/agriculture intensity indicator is widely accepted (Herzog *et al.*, 2006). However, some intensive agricultural land uses, such as fruit orchards, vineyards, and horticulture, cannot be properly assessed using the nitrogen load as proxy indicator. The decision to use N-input as a proxy indicator was motivated also by the availability of detailed and up-to-date data for the investigated area. Due to the fact that the sensitivity analysis demonstrated agricultural intensity to be the most important input variable, adding further proxies to better quantify this spatially would enhance the robustness of the model.

The impact of terrestrial invasive species on soil biota is well documented in the scientific literature (Boag

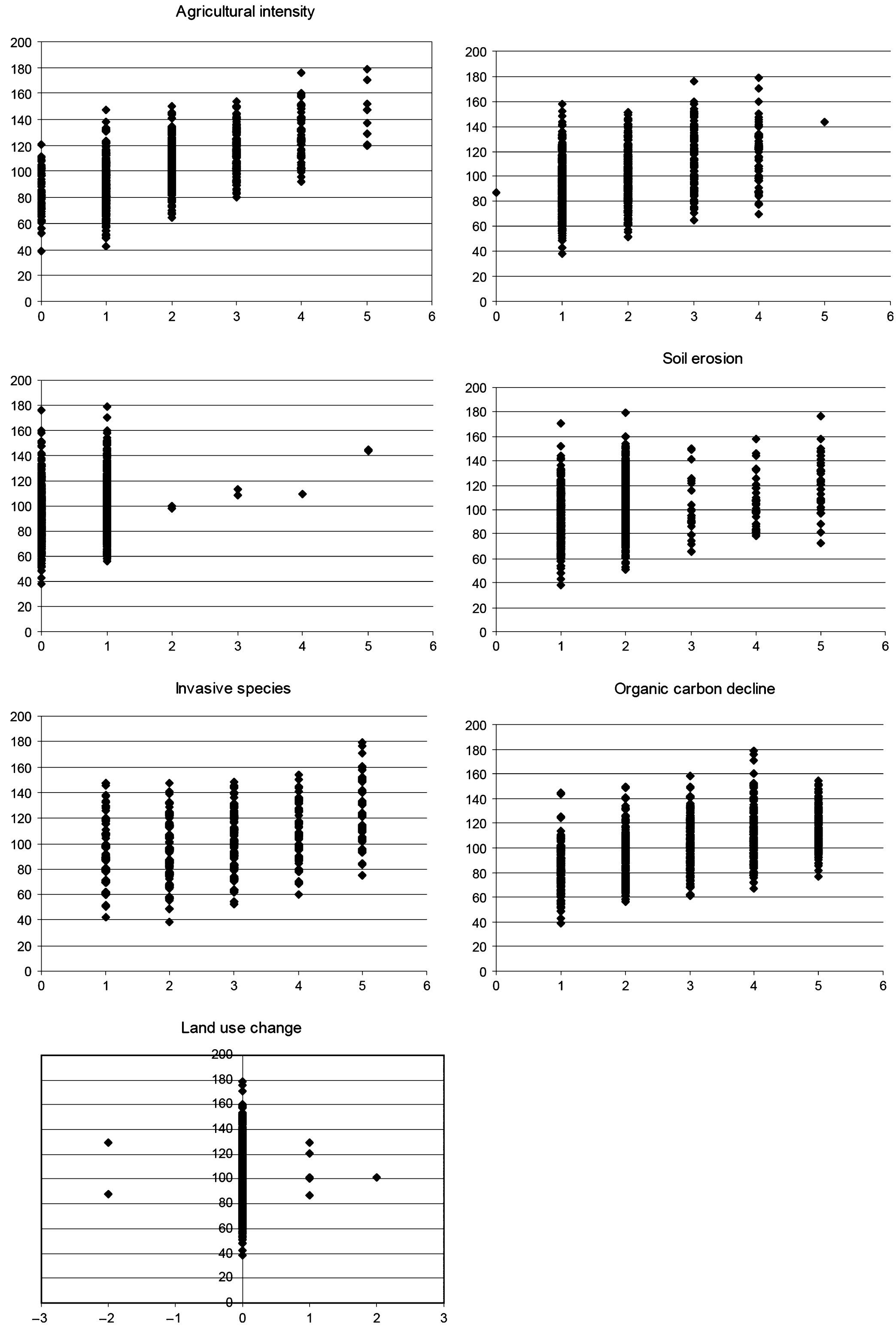

Fig. 3 Scatterplots of the seven factors used to calculate the composite indicator of the potential threats on soil biodiversity.

& Yeates, 2001; Callaway *et al.*, 2004; van der Putten *et al.*, 2007; Weidenhamer & Callaway, 2010). The possible impact of such biological invasions is included in the proposed model, even though the availability of data on the number of invasive species is available only to a very coarse (i.e., country) level. However, as the

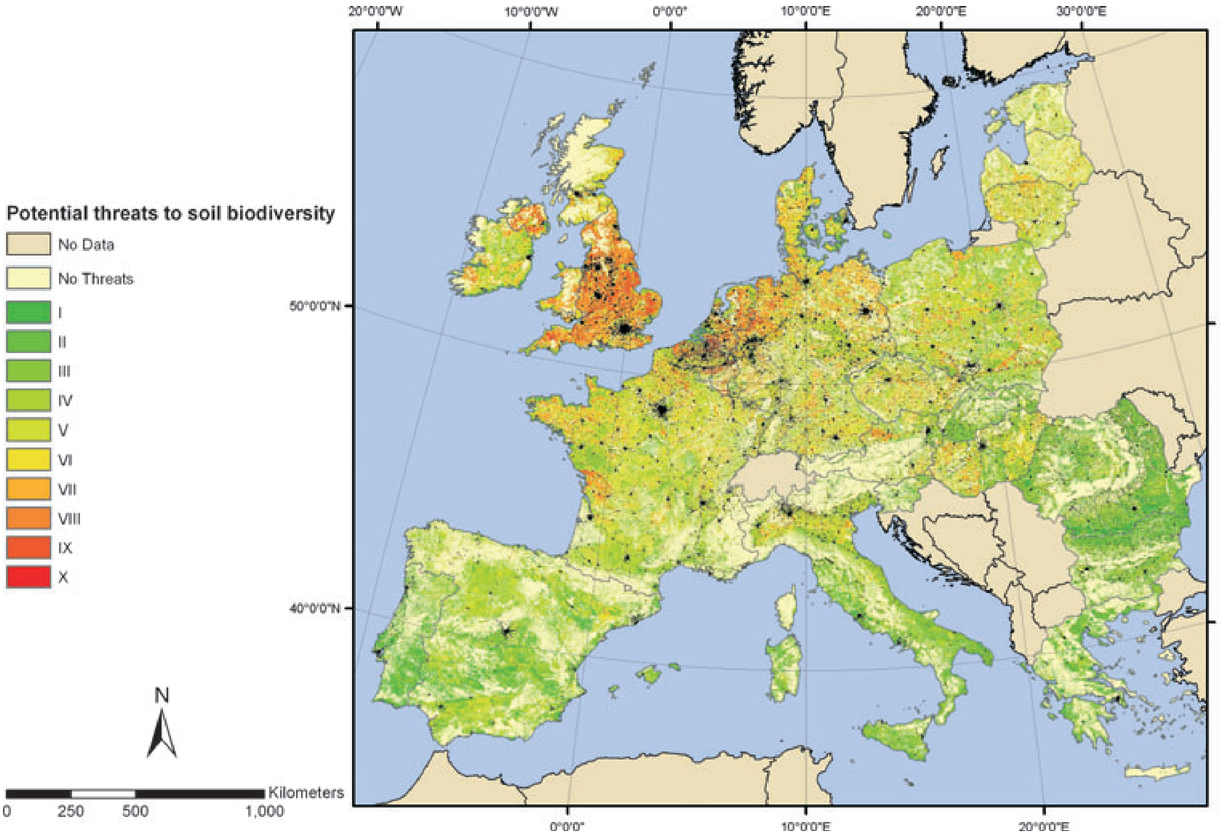

Fig. 4 Map of composite indicator of the overall estimate of pressure on soil biodiversity.

sensitivity analysis showed that invasive species are third in importance in terms of the input variables, it is clear that higher resolution data would enhance the robustness of the model. Unfortunately such data are currently not available.

Furthermore, other potential threats have not been included in this analysis, due to a lack of data or to the spatial resolution of such data not being adequate for the scale of the current investigation (i.e., specific land uses such as greenhouses, intensive horticulture, etc.). A further omitted factor is the potential effect of climate change; in this case, the scientific evidence of the probable effects of climate change on soil biodiversity is not currently sufficient to correctly estimate the impact of this factor.

While this model highlights areas within Europe in which soil biodiversity can be expected to be under relatively high pressure, it makes no predictions as to how the local soil biota responds to such pressures. Soil communities can exhibit strong differences with regard to resistance and resilience in response to pressures (Griffiths *et al*., 2000). This means that the effects of pressures which are considered relatively low risk may have a greater effect on the soil biota, possibly leading to greater loss of biodiversity than areas which are considered relatively higher risk. Therefore, this study can be used to guide future research and monitoring programs through highlighting spatial differences in anthropogenic pressures on soil biodiversity. Furthermore, it can also be used to guide policy owing to the fact that it identifies areas of high potential pressure on soil biodiversity, and hence can aid in the guiding of resources to monitor, research, or protect the biota in such areas as seems appropriate.

Currently this model has been applied at the European scale, but there is nothing to prevent the model being applied at different scales and in different regions where available datasets exist. Owing to the fact that the expert evaluation was conducted with scientists from Europe and North America, a slight bias may exist, however, which may reduce the robustness of the model when applied to regions which may have different pressures and threats or where the same pressures may exist at different levels, such as the developing world. It is advisable, therefore, that an expert evaluation is conducted to obtain threat weightings for the application of the model if applied in such regions.

The ecology of the huge variety of soil organisms can be extremely diverse, and the effects of environmental factors can, in some cases, produce opposing effects on different groups of organism. There are, however, processes that can be generally considered detrimental for the vast majority of soil organisms. The approach used in the proposed model starts from this principle, and it is based on the combined opinions of an internationally renowned group of experts in soil biology and biodiversity (European Commission, 2009). Weighting variables according to experts with a wide range of backgrounds in the area of soil biodiversity reduces the chance of any bias being introduced into the results.

The model predicts a high degree of spatial heterogeneity with regard to the cumulative effects of the different weighted variables on soil biodiversity. Intensive agricultural practices, combined with a relatively high potential for soils to lose soil organic carbon and invasive species combine to produce the highest pressure on soil biodiversity. This work is a first step toward identifying areas within Europe in which soil biodiversity is under most pressure and so at the highest probability of decline. Furthermore, this work provides a framework methodology for modeling threats to soil biodiversity at different scales and provides a tool for guiding future research, the allocation of resources and policy. The sensitivity analysis discussion also suggest that as a result of the present study some more consultation with the experts should take place, e.g., to deal with a redesign of the index which would alleviate the problem of the coexistence of negative and positive correlations.

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