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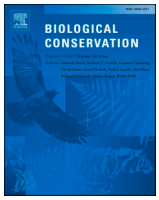

Review

In defence of soil biodiversity: Towards an inclusive protection in the European Union

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ABSTRACT

Since soil biodiversity sustains above-ground life, the European Union (EU) has recently announced its new Soil Strategy to better protect soil ecosystems as part of the Biodiversity Strategy for 2030. Also, the EU's Farm to Fork Strategy and the Zero Pollution Action Plan aim for soil protection. However, the status of soil biodiversity protection has not been comprehensively assessed. Therefore, we explored regulatory, incentive-based and knowledge-based instruments and strategic policy documents at the EU and national levels to determine whether they adequately protect soil biodiversity. Our review of 507 literature references concluded that only eight EU member states explicitly address threats to soil biodiversity in 14 regulatory instruments while 13 countries mainly focus on implicit threats to soil biodiversity, whereas six countries do not consider soil biodiversity. At the EU level, current directives and regulations only tackle individual threats to soil biodiversity. An EU-wide, legally binding protection could ensure a standardised minimum level of soil biodiversity protection while preventing surging costs of not acting. The EU Soil Health Law foreseen for 2023 could couple land management practices beneficial for soil biodiversity with incentive-based instruments. Simultaneously, models should be designed to predict soil biodiversity, considering soil biodiversity's spatial and temporal heterogeneity.

1. Introduction

Soil biodiversity assemblages together with their abiotic and biotic interactions determine the multi-functionality of soils: complex soil food webs recycle nutrients, decompose organic matter, sequester carbon, regulate and filtrate water, provide habitat support, raw and food materials, remediate contaminants, and increase the genetic pools (Wagg et al., 2014). However, soil biodiversity is threatened by intensive agriculture, deforestation, urbanisation, loss of organic matter, soil compaction and sealing, soil acidification and nutrient imbalances, pollution, salinisation and sodification, fire, erosion and landslides, climate change and invasive species (FAO et al., 2020).

Previous studies have claimed that soil biodiversity is under pressure in 56% of the total European land, with 14% being at high risk (Gardi et al., 2013) and another study found 40% of 14 Member States (MS) (EU + UK) under a moderate-high to high potential risk (Orgiazzi et al., 2016b). Despite these risks, the importance of soil biodiversity and its conservation is partially neglected in EU policymaking (Paleari, 2017), and its conservation is excluded from nature conservation targets (Guerra et al., 2021). For example, in the EU Habitats Directive, invertebrates are underrepresented (despite the fact that the great majority of them have a life stage in soils and are therefore considered part of soil biodiversity (FAO et al., 2020)). Further evidence is that they receive 468 times less funding for conservation projects compared to vertebrates (Mammola et al., 2020).

At the global scale, soil biodiversity is still a blind spot: most Parties of the Convention on Biodiversity neither protect soils nor their biodiversity explicitly (Guerra et al., 2021). Protected areas, created to protect aboveground biodiversity, do not necessarily protect soil organisms belowground (Cameron et al., 2018). Ciobanu et al. (2019) found no effect of protected areas on preserving nematode diversity. Despite some indirect "protection spill-overs", specific protection is urgently needed to avoid soil biodiversity losses and in turn, unforeseen consequences due to delayed responses (Veresoglou et al., 2015).

Currently, there is no common soil framework at the EU level setting binding rules for protecting soils and their biodiversity (Frelih-Larsen et al., 2016; Paleari, 2017; Vrebos et al., 2017) and soil biodiversity protection is scattered and hidden across various provisions (Paleari,

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2017). Possibly as a consequence of this, soil biodiversity is excluded from important policy reflections such as the impact assessment of biodiversity in farmland (European Court of Auditors) and the impact assessment of the post-2020 Common Agricultural Policy (CAP 2021–2027).

In contrast, over the last years and compared to the rest of the world, the EU has become a frontrunner in visioning soil biodiversity protection: for example, the European Biodiversity Strategy for 2030 (COM/2020/380) considers soils as a habitat in its own rights and both the Biodiversity Strategy for 2030 and the Farm to Fork Strategy (COM/2020/381) call for better soil protection (Montanarella and Panagos, 2021). In addition, the EU has recently launched the Zero Pollution Action Plan for Air, Water and Soil (European Commission, 2021b) to address concerns about the impact of contaminants on soil condition. Most importantly, in November 2021, the EU Soil Strategy for 2030 was launched, with a view to equalise the legal status of soil to those of water and air through a Soil Health Law, foreseen for 2023.

These recent policy developments expand conservation goals from their previous circumscription to aboveground biodiversity (Glæsner et al., 2014). However, the current status of soil biodiversity conservation is largely unknown. To ensure that the Soil Health Law will adequately protect soil biodiversity, an analysis of EU and national policy instruments and documents in place is needed to assess how well they counteract threats to soil biodiversity and hence, protect or even enhance soil biodiversity.

Therefore, in this paper, we reviewed all existing strategic policy documents and incentive-based, regulatory and knowledge-based instruments to evaluate to what extent EU and MS policy frameworks cover soil biodiversity protection.

2. Materials and methods

The review of conservation activities within European Union policy (EU-27) is based on regulatory instruments (i.e. legally binding instruments such as directives and regulations), incentive-based instruments (e.g., taxes, certificate trading systems and subsidies) and knowledge-based instruments (e.g. the research fund "Horizon Europe" and social learning engagements (e.g., via the eu|academy)) (Fig. 1). In addition, Communications, Strategies and Action Plans, supporting and facilitating achieving policy instruments, were also considered.

While the EU regulations are applied directly and uniformly, superseding conflicting national laws, the EU directives set binding goals, although the Member States are free to accommodate them into their national legislations. In the case of non-compliance, the European Commission can initiate an infringement procedure (Article 211).

Most environmental instruments (e.g., Sewage Sludge Directive, Water Framework Directive and Nitrates Directive) and agricultural policy frameworks (e.g., Common Agricultural Policy) are implemented as regulatory instruments (Terpan, 2015). However, despite the EU envisioning soil biodiversity protection in several policy documents in 2021, the state of current conservation activities for soil biodiversity are not comprehensively known. Therefore, here we reviewed all those activities that indirectly enhance soil biodiversity or protect soil biodiversity by preventing and/or counteracting potential risks to soil life. The threats to soil biodiversity were selected based on the EU Soil Thematic Strategy (Panagos and Montanarella, 2018), the Food and Agricultural Organization's Assessment (FAO et al., 2020) and the available literature (Orgiazzi et al., 2016b, Tibbett et al., 2020). They

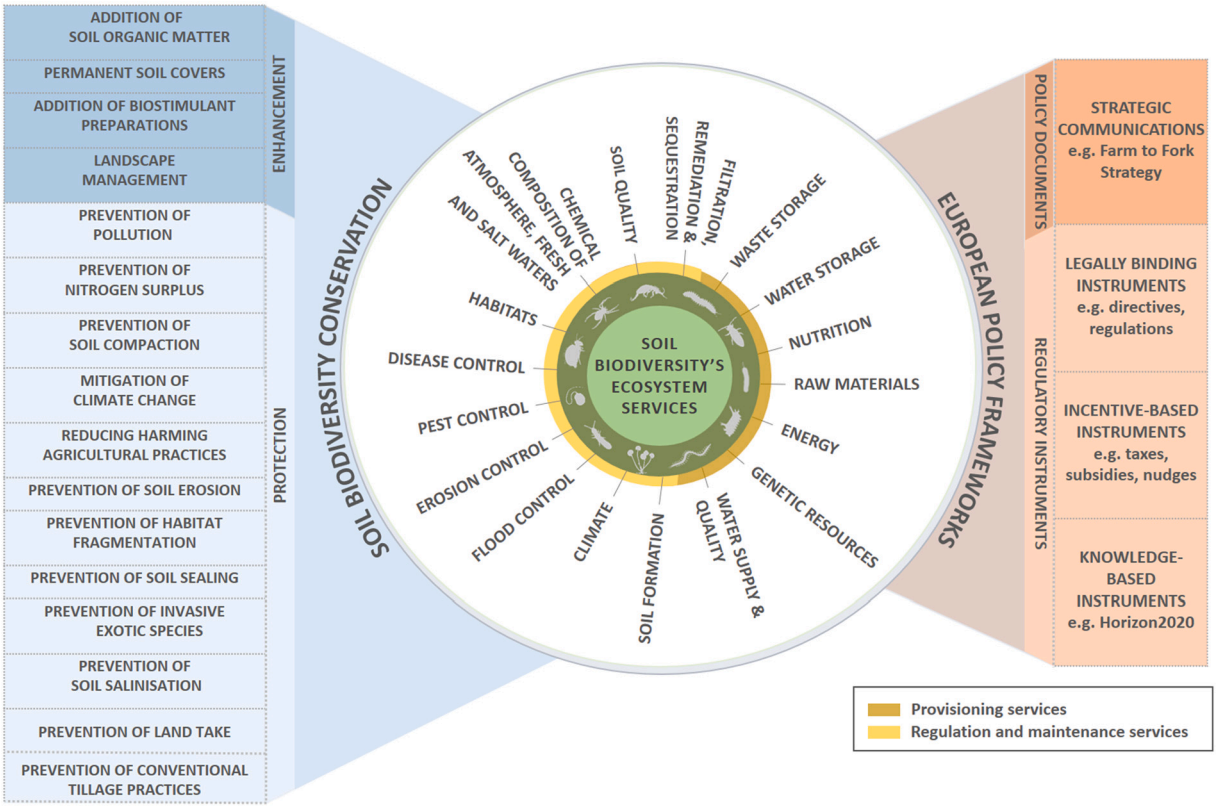

Fig. 1. Policy instruments and various anthropogenic activities protecting and enhancing soil biodiversity, and hence ecosystem multi-functionality (Wagg et al., 2014). Ecosystem services are at the core of soil conservation measures, including soil relevant ecosystem services according to the Common International Classification of Ecosystem Services (Paul et al., 2021). Services are divided into regulating (light yellow) and provisioning services (dark yellow). Raw materials, nutrition and energy include minerals and cultivated/wild plants. We did not differentiate between habitats for different animal life stages (e.g. nurseries). Climate includes air temperature and humidity regulation. Soil quality includes weathering processes and decomposing and fixing processes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

included (i) harmful agricultural practices such as pesticide usage (Prashar and Shachi, 2016), mineral fertiliser usage (several studies found mineral fertilisers' acidifying effect on soils, to harm soil organisms, e.g. de Souza and Freitas, 2018, Chen et al., 2019) and conventional tillage practices (Briones and Schmidt, 2017); (ii) pollution (e.g. by heavy metals, antibiotics or pathogens added via manure from intensively farmed animals (Köninger et al., 2021) or by plastics (Zhu et al., 2018)), (iii) land take (including conversion to agriculture, deforestation and sealing (Geisen et al., 2019)); (iv) climate change (including alterations in soil temperature/moisture and erosion due to extreme events (Coyle et al., 2017)), (v) habitat fragmentation (Brunet et al., 2011) (Fig. 1). The decline of soil nutrients (Tibbett et al., 2020) was not integrated since it does not apply to the EU, facing rather surpluses of nutrients (Svanbäck et al., 2019). The risk of genetically modified organisms was also excluded, since only Spain and Portugal allow their cultivation in a limited area (Brookes, 2019).

In the EU, 80% of the land is either used for agriculture (43%) or forestry (37%) (Eurostat, 2020). Therefore, this paper focuses on soil conservation activities in managed lands. Since the literature ranks harmful agricultural practices as the main threat to soil biodiversity (Tsiafouli et al., 2015; Geisen et al., 2019; Orgiazzi et al., 2016b; Tibbett et al., 2020), conservation activities presented in this paper focus on agricultural land. However, several management practices also apply for forest soil management. Land management practices to protect soil biodiversity by preventing threats on soil biodiversity include: (i) reducing pollutants (pesticides, heavy metals, mineral fertilisers), (ii) permanent soil cover through intercropping, mulching practices, catch crops and no-till/conservation tillage, (iii) preventing soil compaction by avoiding the usage of heavy machinery, (iv) landscape management increasing wildlife reservoirs (e.g., hedgerows, grass margins, agroforestry) (Marsden et al., 2020), (v) addition of organic amendments such as manure (but considering quality, storage, treatment (e.g., composted), and pollutants) and biostimulant preparations (Köninger et al., 2021), either commercial or homemade preparations (Fig. 1).

Therefore, we screened published articles in peer-reviewed journals (2000–2021) using the SCOPUS and Web of Science databases, applying the Boolean search operators: *title-abstract-keywords ("soil biodiversity" or "soil protection") and all ("governance" or "legislation" or "polic*") and all ("European union" or "EU") and all ("soil biodiversity" and "conservation" or "protection")*. SCOPUS retrieved 111 articles and Web of Science 105, of which 56 articles were selected, addressing soil biodiversity conservation at the EU or Member States level (see Supplementary Table A1). To investigate conservation activities at the EU and at the national level, we expanded the literature search by screening the websites of the European Commission. As a result, 14 publications were added as 'grey' literature.

Soil protection in the EU is mainly applied at the national and regional level (Römbke et al., 2016; Ronchi et al., 2019), following the principle of subsidiarity (Vrebos et al., 2017). Therefore, we reviewed policy instruments both at the EU and at the MS levels. Policy instruments at the EU level were screened using the EU-Lex website. The policy instruments at the MS level were selected using the Soil Wiki provided by the European Commission, which lists existing national policies and instruments applied by various MS, differentiating between instruments explicitly referring to risks of soil biodiversity losses and those implicitly protecting soils (Frelih-Larsen et al., 2016). In total, the analysis included 33 policy instruments at the EU level and 406 legislative instruments at the MS level. Data sources considered were papers selected according to the literature explained in the previous paragraph, regulatory instruments (EU level), incentive-based instruments, policy documents (EU level), grey literature and policy instruments at the MS level (for more details see Supplementary Table A2 and Supplementary Fig. A1).

The information compiled on the impact of EU policy frameworks (Fig. 1, section on the right) was analysed by considering potential threats leading to activities protecting (in light blue) and enhancing (dark blue) soil biodiversity (Fig. 1, section of the left) and their potential implications on soil functioning (Fig. 1, core of the figure). These categories were developed based on the current knowledge (FAO et al., 2020).

The aims of these analyses were to: (i) evaluate whether existing policy instruments adequately address the protection and enhancement of soil biodiversity; (ii) identify knowledge gaps in current instruments and how these omissions could affect the protection and enhancement of soil organisms; and (iii) assess how the Soil Health Law can best contribute to fully protect soil biodiversity.

3. Soil biodiversity conservation in the European Union

3.1. EU level (EU-27)

Until 2021, the most crucial policy instrument advocating for soil biodiversity protection in the European Union was the Soil Thematic Strategy adopted in 2006 (Panagos and Montanarella, 2018). This Strategy included the proposal for its implementation as a directive, which was withdrawn in 2014 by the European Commission after it had been blocked by five MS due to concerns about costs, administrative burden, and preference for soil protection to remain under the subsidiarity principle at the national level (Glæsner et al., 2014). Despite that, the Strategy has raised soil conservation awareness and public concerns on the ecological implications of soil biodiversity losses (COM/2006/0231). For example, the Soil Thematic Strategy reinforced the implementation of an EU soil monitoring scheme, born in 2009 and named LUCAS Soil (Land Use/Cover Area frame statistical Survey), which, as of 2018, also includes soil biodiversity among measured parameters (Orgiazzi et al., 2018). Due to limited data available at the time, in 2006, the Strategy did not include any quantifiable targets.

Under the recent EU Soil Strategy, published in November 2021, which updates the Soil Thematic Strategy (COM/2021/699), the Commission announced that it will:

i) limit the drainage of wetlands/organic soils and restore managed/drained peatlands
ii) consider measures for mineral soils to enhance biodiversity in agricultural land
iii) limit land take by implementing ambitious national, regional and local targets by 2023
iv) propose a set of sustainable soil management practices, maintaining soil health, yielding multiple benefits.

Finally, under the Mission 'A Soil Deal for Europe', the Commission will continue providing substantial funding to i) research solutions to increase soil biodiversity; ii) prevent soil degradation; iii) pilot innovative technologies for decontamination and restoration.

It also announced a proposal for a Soil Health Law, foreseen for 2023 (COM/2021/699). According to the Commission, this will be the first EU-wide law protecting soils, implementing the monitoring of soil biodiversity and a 'passport for excavated soil' (COM/2021/699). Also, legally binding provisions should be provided to identify, register, monitor and remediate contaminated soils. Preventing and mitigating contaminated soils will be crucial for soil biodiversity conservation, reducing pressure on soil organisms.

The Soil Strategy is part of the Biodiversity Strategy for 2030 (COM/2020/380), which is among other political documents under the umbrella of the Green Deal, the EU action plan towards climate neutrality, by 2050 (COM/2020/0036, 2020). In addition, it includes the Farm to Fork Strategy (F2F Strategy) (COM/2020/381), the Zero Pollution Action Plan (aiming to reduce soil pollution to no-harmful levels, European Commission, 2021g), the Chemicals Strategy (COM/2020/667), and the Circular Economy Action Plan (COM/2020/98). The latter is the main driver for nutrient recycling, replacing mineral fertilisers with organic fertilisers, which protect and enhance soil biodiversity.

Both the Biodiversity Strategy for 2030, and the Farm to Fork Strategy (F2F) address threats to soil biodiversity indirectly. They aim to reduce fertilisers by 20%, nutrient losses by at least 50%, reduce the overall use and risk of chemical pesticides use by 50% and hazardous pesticides by an additional 50% and increase organic farms to 25% by 2030 to prevent soil pollution and, on the other hand, enhance the use of organic fertilisers (Appendix Table A2). The F2F proposes a revision of the Sustainable Use of Pesticides Directive to significantly reduce use, risk and dependency on pesticides and enhance integrated pest management. The Biodiversity Strategy explicitly addresses land degradation and restoration of soil (protected areas +30%, aiming to plant more than 3 billion trees by 2030). Furthermore, increasing implementation of agroecological practices and reducing deforestation are encouraged to mitigate climate change, which in turn will benefit soil biodiversity (Lemanceau et al., 2015). One of the key measures announced by the Biodiversity Strategy 2030 is the regulatory nature restoration targets. The European Commission will propose targets during 2022, including several soil protection measures that will indirectly protect soil biodiversity. Also, the F2F Strategy announced a proposal for a legislative framework for an EU sustainable food system, foreseen for 2023.

While the Biodiversity Strategy for 2030 included the aim to protect soil ecosystems, there is currently no uniform definition of soil biodiversity protection at the EU level (Orgiazzi, 2021). Also, the Biodiversity Strategy for 2030 does not address the risks associated with soil compaction and conventional tillage. The F2F Strategy does not explicitly consider soil compaction, tillage, soil organic matter loss, soil erosion, sealing and habitat fragmentation but does call for a more sustainable EU food system. Additionally, some of the proposed actions might have contrasting effects. For instance, for more sustainable manure management, both the F2F Strategy and the Circular Economy Plan see anaerobic digestion as a solution for reducing greenhouse gases emissions, but this does not integrate the negative effects of carbon availability and heavy metal/antibiotic contents on soil biodiversity (Köninger et al., 2021).

Looking into the European regulatory legislation that indirectly protect soil biodiversity, there is a set of regulations targeting different aspects (e.g., plant protection products and invasive alien species) that could also affect soil biodiversity protection (Table 1). For instance, the European Climate Law (EU 2021/1119) came into force as a regulation in 2021. It sets the Carbon Farming initiative, aiming to promote higher soil organic carbon stocks and, thus, be beneficial for soil organisms.

Also, the regulations for organic production (Organic Production Schemes (EEC) No 2092/91) and fertilising products schemes (European Commission 2019/1009) promote the use of organic fertilisers and prevent the additions of pollutants. Organic Production Schemes could address six threats to soil biodiversity (prevention of pollution, N surplus, harmful agricultural inputs for soil biodiversity (e.g., mineral fertilisers and pesticides), soil salinisation, and the application of soil organic matter and biostimulants). The establishment of a Framework to Facilitate Sustainable Investment (known as the Taxonomy Regulation) is one of the outstanding delegated acts on the environmental objectives. Its 'do no harm' vision comprises criteria that soil biodiversity (and soil fertility) should be assessed prior to new building development, based on the LUCAS soil survey of the European Commission's Joint Research Centre (European Commission, 2021c, Annex 2, p. 239).

Besides regulations, we identified 17 EU directives with the potential to protect and enhance soil biodiversity (Table 1). Most of these regulatory instruments address soil pollution issues that could benefit soil biodiversity indirectly (Table 1). However, none of these directives includes any direct actions on soil biodiversity. For instance, no soil-living species are included in the list of threatened species of the Habitats Directive.

Looking at the EU incentive-based legislation, the Common Agricultural Policy (CAP) provides subsidies for different management choices for land management. The CAP also includes a few incentives for foresters. It is the main EU tool regulating (soil) management practices (Simoncini et al., 2019). This is a consequence of the high share of agricultural land in the EU and the dependence of EU farmers on agricultural subsidies (for the period 2015–2017, on average, the CAP contributes to 36% of farms' yearly net income, Coppola et al., 2020). The CAP distributes the biggest share of its financial payments based on farm size and animal count (77% for the CAP 2014–2020) (Brady et al., 2009). Those payments are tied with minimum standards and requirements for environment, animal welfare and food safety (conditionality-based). The CAP reform was discussed for the last three years before the EU Council and the Parliament reached an agreement (to enter into force in 2023). Conditionality in the post-2020 CAP comprises Statutory Management Requirements (SMRs) and Good Agricultural Environmental Conditions (GAEC) (see Supplementary Fig. A2 (European Commission, 2020b)). While GAECs are standards aiming to achieve sustainable agriculture, SMRs include rules on public, animal and plant health, animal welfare and the environment that need to be kept healthy to receive financial support from the CAP. For example, the Nitrates Directive, Habitats Directive, Plant Protection Products Directive and the Hormone Directive are interwoven as SMRs. Following the rules set therein are pre-requirement to receive direct payments. Member States can decide on GAECs, which will be mandatory for farmers (Montanarella and Panagos, 2021). Besides direct payments, the CAP subsidises agri-environmental-climate measures (AECMs) targeting more specific objectives to mitigate environmental and climatic challenges (e.g., preserving permanent grasslands, promoting organic agriculture and reducing nutrient losses; Scown et al., 2020). AECMs are voluntary for farmers and foresters (Pe'Er et al., 2019). However, once signed up for an AECM, they are contractually binding.

The post-2020 CAP provides several tools to promote the sustainable use of soils (European Commission, 2018) and safeguard soil biodiversity (for a full list, see Table 2). For instance,

(i) banning the burning of organic material (GAEC 3),
(ii) encouraging conservation tillage management and reducing the risk of soil degradation, including slope consideration (GAEC 6), no bare soil in the most sensitive period(s) (GAEC 7) and crop rotations (GAEC 8);
(iii) advocating for keeping landscape features by a minimum share of agricultural land for non-productive features and preventing the spread of invasive species (GAEC 9);
(iv) banning the conversion or ploughing of permanent grassland in Natura 2000 sites (GAEC 10);
(v) moving from conventional to reduced tillage and the creation and maintenance of grasslands (AECMs);
(vi) supporting organic farming (EC Evaluation 2020);
(vii) proposing eco-schemes, which are a list of voluntary agricultural practices beneficial for the environment (European Commission, 2021f) and for soil biodiversity (decided upon by the MS).

Various impact indicators monitor the environmental performance of the post-2020 CAP, such as erosion and soil organic carbon. However, for soil biodiversity, no indicators could be provided in 2018 due to missing data.

The implementation of beneficial conservation activities within the CAP depends on various decision levels. While the EU decides upon the distribution of subsidies flowing into funds and defined activities, national and regional administrations (e.g. in the case of Germany) decide upon subsidised measures (eco-schemes and AECMs) and specify preconditions of eligibility for area-based subsidies (GAECs). Farmers decide upon implementing AECMs or eco-schemes through a very complex process. The number and complexity of decisions require an adequate knowledge distribution (Stupak et al., 2019). For example, the difference between eco-schemes and AECM often is unclear: Economically, eco-schemes are much more attractive for farmers (they consist of 22–25% of direct payments, while AECM cannot surpass average implementation and opportunity costs (the value of alternative

Table 1
Soil biodiversity conservation in current European Union regulatory instruments based on the literature review. Impact on soil biodiversity is reported for each possible conservation activity: + Protection (light green), ++ Enhancement (dark green), 0 Not relevant (white). Types of EU legal instruments: regulation (darker blue) and directive (light blue).

Legally binding instruments \ Soil biodiversity conservation	- Prevention of pollution	- Prevention of N surplus	- Prevention of soil compaction	- Mitigation of climate change	- Limiting harmful agricultural practices	- Prevention of soil erosion	- Prevention of habitat fragmentation	- Prevention of soil sealing	- Prevention of invasive exotic species	- Prevention of soil salinisation	- Prevention of land take	- Limiting conventional tillage practices	- Addition of soil organic matter	- Permanent soil covers	- Addition of biostimulant preparations	- Landscape management
Fertilising Products Regulation 2019/1009	+/++	0	0	0	0	0	0	0	0	0	0	0	+/++	0	+/++	0
Market and Use of Biocidal products (Regulation (EU) No 528/2012)	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant Protection Products (Regulation EC 1107/2009)	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+
Organic Production Schemes (EEC) No 2092/91	+/++	+/++	0	0	+/++	0	0	0	0	+/++	0	0	+/++	0	+/++	0
Sustainable finance taxonomy Regulation (EU) 2020/852	+	0	0	0	0	0	+/++	+/++	0	0	++	0	0	0	0	0
Prevention and management of invasive alien species Regulation 1143/2014	0	0	0	0	0	0	0	0	+	0	0	0	0	0	0	0
Veterinary Medicinal Regulation EU/2019/6 repelling Directive 2001/82/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
European Climate Law EU/2021/1119	0	0	0	0	0	0	0	0	0	0	0	0	+/++	0	0	0
Air quality framework Directive 2008/50/EC	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GMO Directive 2001/18/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hormones Ban Council Directive 96/22/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Emissions Directive 2010/75/EU	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill Council Directive 99/31/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
The Habitats Directive 92/43/EEC	0	0	0	0	0	0	+	0	0	0	+	0	0	0	0	+
Nitrates directive Council Directive 91/676/EEC	+	+/++	0	0	0	0	0	0	0	0	0	0	0	+	0	+
Packaging and Packaging Waste Directive 94/62/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Environmental impact assessment directive	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Environmental Liability Directive 2004/35/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Single Use Plastics Directive EU 2019/904	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Strategic environmental assessment directive 2001/42/EC	0	0	0	0	0	0	0	+	0	0	0	0	0	0	0	0
Usage of sewage sludge in agriculture 86/278/EEC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste Directive 208/98/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste from extractive industries Directive 2006/21/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water Framework Directive (2000/60/EC)	+	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0

Table 2
Soil biodiversity conservation activities and the EU Common Agricultural Policy (considering the CAP post-2020). The list of voluntary eco-schemes that could be chosen by the Member States are presented in violet, light blue the Good Agricultural Environment Conditions within the Conditionality of Pillar I based on the literature review. Regulatory instruments as Statuary Mandatory Requirements within the Conditionalities are presented in dark blue (blue = directives, dark blue = regulations). + Protection (light green), ++ Enhancement (dark green), 0 Not relevant (white). Agri-environmental measures were excluded since they are not set yet for the upcoming CAP. *Predictions for potential eco-schemes' effects on soil biodiversity are based on comparable literature findings of such practices. However, their efficiency and implementation are currently unknown.

Policy instruments \ Soil biodiversity conservation	- Prevention of pollution	- Prevention of N surplus	- Prevention of soil compaction	- Mitigation of climate change	- Limiting harmful agricultural practices	- Prevention of soil erosion	- Prevention of habitat fragmentation	- Prevention of soil sealing	- Prevention of invasive exotic species	- Prevention of soil salinisation	- Prevention of land take	- Limiting conventional tillage practices	- Application of soil organic matter	- Permanent soil covers	- Application of biostimulants preparations	- Landscape management
Eco-scheme: Organic farming practices*	+/++	+/++	0	0	+/++	+/++	0	0	0	+/++	0	0	+/++	0	+/++	0
Eco-scheme: Integrated Pest Management practices*	+/++	0	+/++	0	+/++	0	0	0	0	0	0	0	0	0	+/++	+
Eco-scheme: Agro-ecology*	+/++	0	+/++	+/++	+/++	0	0	+/++	0	0	0	+	+/++	+/++	+/++	+
Eco-scheme: Husbandry and animal welfare plans*	+/++	0	+	+/++	0	0	0	0	0	0	0	0	0		0	0
Eco-scheme: Agro-forestry*	+	0	+/++	++	+/++	+/++	0	+/++	0	+/++	+	+	+/++	+/++	0	+/++
Eco-scheme: High nature value (HNV) farming*	+	0	+/++	0	+/++	+/++	0	0	0	0	+	+	0	+/++	0	+/++
Eco-scheme: Carbon farming*	+	0	0	++	0	0	0	0	0	0	0	+	+/++	+/++	0	+/++
Eco-scheme: Precision farming*	+/++	+/++	0	0	0	0	0	0	0	0	0	+	0	0	0	+
Eco-scheme: Improve nutrient management*	+/++	+/++	0	+/++	0	0	0	0	0	0	0	0	+/++	0	0	+
Eco-scheme: Protecting water resources*	+	0	0	+/++	+/++	0	+/++	0	0	0	+/++	0	0	0	0	+/++
Eco-scheme: Other practices beneficial for soil*	+	0	0	+/++	0	0	0	0	0	0	0	0	0	0	0	+
Eco-scheme: Other practices related to GHG emissions*	+	0	0	+/++	0	0	0	0	0	0	0	0	0	0	0	0
GAEC 1 requires permanent pastures	0	0	0	0	+	0	+	0	0	0	+	+/++	0	0	0	+/++
GAEC 2 requires the protection of wetlands and peatlands	0	0	0	+	+	0	+	0	0	0	0	0	0	0	0	+/++
GAEC 3 bans the burning of arable stubble	0	0	0	++	++	0	0	0	0	0	0	0	++	0	0	+/++
GAEC 4 requires buffer strips along with water tables	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+/++
GAEC 5 calculates nutrient budgets for nutrient requirements	+	0	0	0	+	0	0	0	0	0	0	0	0	0	0	+
GAEC 6 requires conservation tillage practices	0	0	0	0	+	+	0	0	0	0	0	+/++	0	0	0	+
GAEC 7 requires soil covering during sensitive periods	0	0	0	0	+	+	0	0	0	0	0	+/++	0	+	0	+/++
GAEC 8 requires crop rotation	0	0	0	0	+	+	0	0	0	0	0	+	0	0	0	0
GAEC 9 requires areas that are not cultivated	0	0	0	0	+	+	+	0	+	0	+	+	0	0	0	+/++
GAEC 10 bans ploughing/land conversion in Natura 2000 areas	0	0	0	+	+	+	+	0	0	0	+	+/++	0	0	0	+/++
Habitats Directive Council Directive 92/43/EEC	0	0	0	0	0	0	+	0	0	0	0	0	0	0	0	+/++
Hormones Ban Council Directive 96/22/EC	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Natura 2000 on wild birds Directive 2009/147/EC	0	0	0	0	0	0	+	0	0	0	+	0	0	0	0	+/++
Nitrates Council Directive 91/676/EEC	+	+	0	0	0	0	0	0	0	0	0	+	0	+	0	+
Plant Protection Products Regulation EC 1107/2009	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+

activities)).

However, independent of available knowledge, farmers might choose the cheapest option, which is not always the most beneficial for soil biodiversity and not the cheapest in the long term (Świtek and Sawinska, 2017; Zinngrebe et al., 2017). Indeed, decision-making also depends on social, cognitive and dispositional factors such as attitude, peers and experience but also on local knowledge (Dessart et al., 2019, Bartkowski and Bartke, 2018).

In recent knowledge-oriented EU programmes, the level of attention towards soil biodiversity has risen among the priorities in the EU policy agendas (Montanarella and Panagos, 2021). Knowledge on soil biodiversity has gained relevance in the EU after the publication of the Global Soil Biodiversity Atlas (Orgiazzi et al., 2016a) and several international reports (EASAC – the European Academies' Science Advisory Council, 2018; FAO et al., 2020). Consequently, ad-hoc scientific funding for research has increased within the EU research funding programme (Panagos and Montanarella, 2018). For example, the recently adopted mission area "Soil health and food", within the EU Horizon Europe funding programme, is designed to enhance knowledge and awareness of the importance of soils (European Commission, 2020a).

Additionally, plans for monitoring soil biodiversity have been expanded (Guerra et al., 2021; Römbke et al., 2016). The EU is the only continent aiming to include a standardised soil monitoring programme as part of its LUCAS soil survey across all MS (Eurostat, 2018). In 2018, for the first time, the LUCAS soil survey included a new soil biodiversity module consisting of 1000 samples to be analysed through metabarcoding and metagenomics (Orgiazzi et al., 2018). Finally, the recently launched EU Soil Observatory will monitor goals for all current and future EU soil-related policy initiatives (Montanarella and Panagos, 2021). Also, in April 2021, the European Parliament (the elected body of the EU) approved a motion for a resolution on soil protection, which invites other EU institutions or Member States to act (European Parliament, 2021a).

3.2. Member State level

To date, only a few Member States have implemented national regulations for soil protection that also include soil biodiversity conservation, such as the additional support for sustainable farming practices (Ronchi et al., 2019).

According to our analyses, 14 MS aim to protect soil and its functioning in national strategies: Austria, Finland, Germany, Poland and Portugal address soil biodiversity explicitly in their strategies, while Bulgaria, Croatia, Ireland, Italy, Lithuania, Malta, the Netherlands, Romania and Sweden implicitly address the protection of soil biodiversity (Supplementary Table A4). Only 15% out of a total of 406 national instruments addressing threats to soil biodiversity had a regulatory character, and only 29% of them do so explicitly and 71% implicitly (Fig. 2).

In addition, 8 MS (Bulgaria, Croatia, Finland, Germany, Hungary, the Netherlands, Poland and Slovakia) protect soil biodiversity explicitly in 14 regulatory instruments (Fig. 3) and 19 MS address the threats to soil biodiversity implicitly in 48 regulations by extending protection measures set by the EU (Supplementary Table A5). Based on available information, Cyprus, Estonia, France, Greece, Luxemburg, Malta and Sweden address threats to soil biodiversity neither implicitly nor explicitly.

In addition, several MS have implemented further incentive schemes implicitly protecting soil biodiversity. Among them, Denmark applied a tax on harmful pesticide products as a measure to acknowledge negative effects on earthworms; Ireland provided state aid funding to increase forest areas between 2014 and 2020; Latvia compensated farmers for restricting agricultural and forestry activities in protected areas; Romania provided financial support for environmental projects, including afforestation or the recovery of polluted sites; Spain subsidised the land transformation from agricultural land into forests; and Sweden provided state aid for the remedial and compensation for damages due to contamination.

At the national level, another key element for ensuring soil biodiversity protection is to increase farmers' knowledge of the EU and national legislations. Indeed, the degree of acceptance of voluntary financial measures provided by the CAP or national laws may depend on farmers' knowledge and awareness (Stupak et al., 2019). For a more integrative knowledge transfer to farmers, since 2007, MS are required

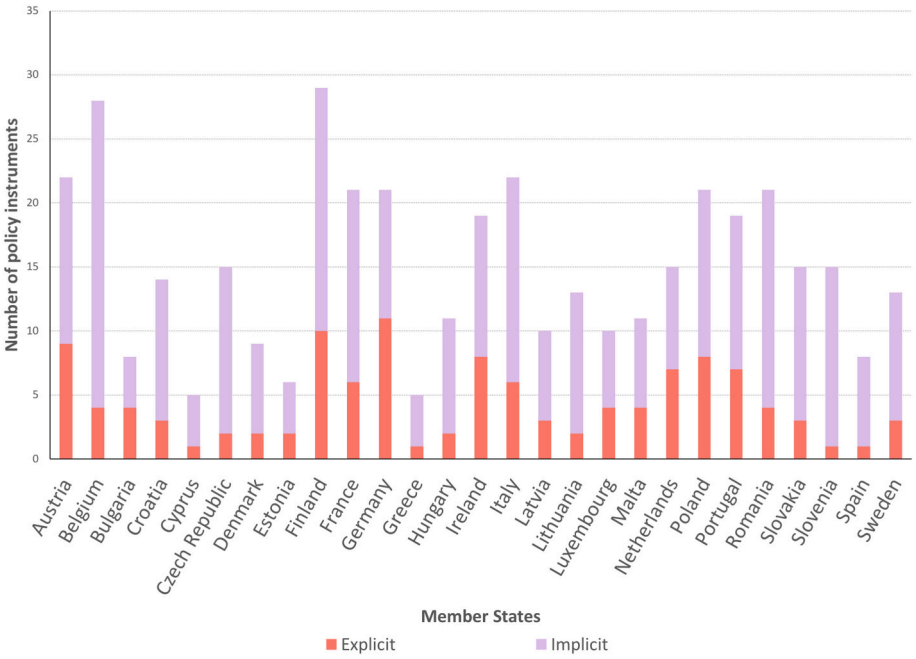

Fig. 2. The number of EU policy instruments per Member State addressing threats to soil biodiversity (implicitly and explicitly) according to the Soil-Wiki (Frelih-Larsen et al., 2016).

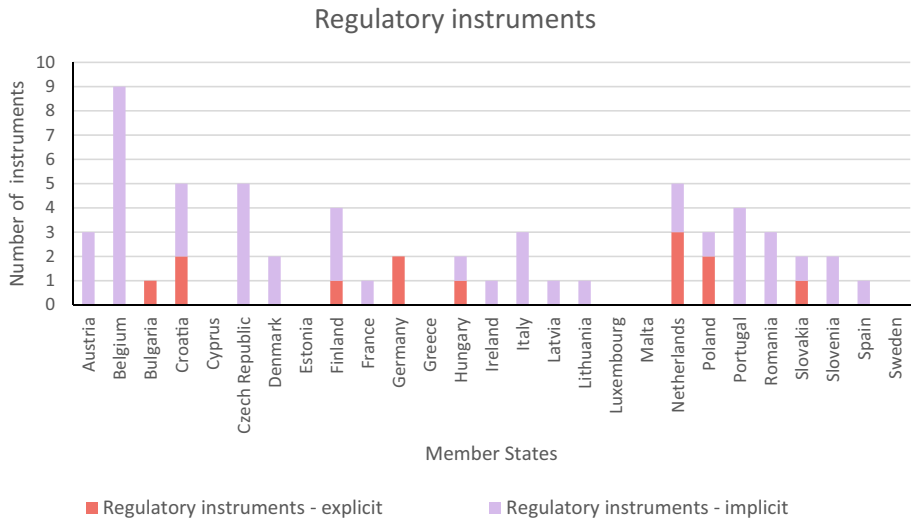

Fig. 3. Member State regulatory instruments addressing threats to soil biodiversity (implicitly and explicitly) according to the Soil-Wiki (Frelih-Larsen et al., 2016).

to provide a national farm advisory service (FAS) (Council Regulation (EC) No 1782/2003), for advising farmers on land and farm management that comply with climate change mitigation and adaptation, protection of water and biodiversity legislation. The organisation of FAS is very heterogeneous, responding to farmers' specifies (Knierim et al., 2017). They were found to strongly influence farmer behaviour for forestry measures and carbon management practices (European Commission, 2021e). For example, Bulgaria has implemented consultancy packages addressing manure management. A third of Spanish advisory activities address organic fertilisers, irrigation and minimum tillage practices (European Commission, 2021e). Portugal focuses on water and soil conservation by targeting soil erosion reduction and soil protection against pollution. Despite these positive examples, farm advisory services give low priority to sustainable soil management (Ingram and Mills, 2019).

Soil biodiversity monitoring schemes differ significantly between MS (Römbke et al., 2016), often only focusing on chemical and physical parameters, while soil biology is rarely measured (except Belgium, Denmark, Estonia, Finland, France, Germany and Luxemburg; Supplementary Table A5). Sweden started to measure soil fungal diversity, while Austria integrated monitoring goals for soil biodiversity in its national Biodiversity Strategy.

To raise the awareness for the importance of soil biodiversity and reach both citizens and policymakers, several initiatives have been adopted over the last years. To combine monitoring with awareness-raising, France has launched a "participatory observatory for earthworms", the Netherlands has engaged the public in the project "Sustainable Soil" and Finland has implemented a citizen science platform enabling the recording, managing and sharing of soil observation data. Also, Austria and Germany have designed awareness-raising campaigns for soil biodiversity. Italy organised several educational events during the International Year of Soils 2015.

Given all these, it is possible to conclude that the policy initiatives for soil biodiversity protection at the national level are too fragmented and not fully designed to focus on the target, revealing a legislative gap for the conservation of soil-living organisms. Despite several protection activities initiated or still ongoing, MS's conservation activities come particularly short in (i) the prevention of soil pollution (e.g. antibiotics, pathogens and heavy metals added via untreated manure of intensively-farmed animals), (ii) the enhancement and conditionality of sustainable farming practices and (iii) the restoration of contaminated soils.

4. Legislative and knowledge gaps and the way forward

Since soil biodiversity sustains above-ground life (for its regulating and provisioning ecosystem services; see Fig. 1) and since the extent of soil biodiversity losses and the ecological tipping points of diminishing soil biodiversity are unknown (Veresoglou et al., 2015), soil protection is the cheaper and safer option to ensure future food security (Bach et al., 2020) and to prevent soaring costs for the remediation of degraded soils. In Europe, the costs of inaction on soil degradation surpass the costs of actions by a factor of six (European Environment Agency, 2018).

Our review found that only 30% of MS address threats to soil biodiversity in their regulatory policies to date. Current implemented binding instruments address neither multi-functionality nor the manifold threats to soil biodiversity. A significant number of MS do not have laws that explicitly address threats to soil biodiversity.

At the EU level, in the scientific arena, there is the perception that the EU is not adequately protecting soils: For instance, the EU's agri-environmental policy has been criticised for being "soil-blind" (Bartkowski et al., 2021a), the post-2020 CAP for favouring sustainable soil management practices via voluntary approaches (Pe'er et al., 2019), which are not often widely adopted by farmers/land managers (Świtek and Sawinska, 2017; Zinngrebe et al., 2017). Several scientists called for actions in the CAP to address sustainability (Pe'er et al., 2020). However, the EU's awareness of the importance of soil and its biodiversity increased. That, for instance, is represented by several recently published policy documents (such as the EU Biodiversity Strategy for 2030) but particularly by the Soil Strategy for 2030. The latter considers several EU policies related to soils and proposes a series of actions that, in turn, may positively affect soil biodiversity. Also, to maintain and enhance healthy soils under the CAP, the Soil Strategy calls to adopt ambitious CAP strategic plans "containing sufficient interventions under the green architecture" (Section 4.1., COM/2021/699). The Soil Strategy aims for "a set of 'sustainable soil management' practices, including regenerative farming in line with agro-ecological principles, adapted to the wide variability of soil ecosystems and types, and identify unsustainable soil management practices" (Section 4.1., COM/2021/699). These sustainable farming practices are framed as the new normal. Due to the importance of soil biodiversity, such practices should include beneficial practices for soil organisms.

The effect of agricultural practices on soil biodiversity varied between European regions. However, responses towards the different management approaches were found to be highly consistent (Tsiafouli et al., 2015). Despite the recent start of EU-wide soil biodiversity assessments (Orgiazzi et al., 2018) and the increased relevance of soil

biodiversity in the context of social-ecological challenges over the last ten years (FAO et al., 2020), there are still significant knowledge gaps in monitoring soil biodiversity. While more research is needed on temporal and spatial variables, the knowledge of threats to soil biodiversity (e.g. FAO et al., 2020) allows to determine which practices are harmful or beneficial for soil biodiversity. Therefore, it is essential to put commitments into action that protect and enhance soil biodiversity by considering ecological interactions occurring in the soil food webs and by accounting for the multi-functionality of soils (Wagg et al., 2014; see Fig. 1). For example, Organic Production Schemes mitigate several threats to soil biodiversity, which was confirmed by the literature (Bender et al., 2016; Bengtsson et al., 2005), particularly if combined with conservation tillage practices (Wittwer et al., 2021). However, threats through conventional tillage practices are currently not yet mitigated by Organic Production Schemes.

To efficiently implement beneficial practices in policies, subsidising beneficial methods were promoted by Jeffery and Verheijen (2020). They called to "pay for practices" protecting soils, which would also facilitate monitoring practices compared to monitoring indicators. This strategy is applied in the United Kingdom, where soil protection measures will be subsidised starting from 2022 (The Guardian, 02.12.2021). In the EU, practice-based incentives are currently already in place, dominating the second pillar of the CAP. However, pillar 1 is the CAP's priority, receiving >70% of the post-2020 budget (depending on MS decisions, the allocation for pillar 1 can be increased/decreased by 15%). 94% of pillar 1 consists of direct payments (European Parliament, 2021b). The majority of direct payments do not have specific provisions for environmentally friendly practices (including beneficial practices for soil biodiversity). Moreover, area-based payments were found to indirectly favour input-intensive monocultures (e.g. Pe'er et al., 2019). Yet, even direct payments have to consider the national CAP strategic plans, which will include environmental and climate objectives. Therefore, we support the model of practice-based incentives, however, we propose to better implement such practices. Regulatory soil protection legislation should be coupled to incentive-based instruments such as direct payments of the CAP as Statutory Management Requirements, mandatory to receive direct payments. This would contribute to a "greener" design of the CAP, making it fit for purpose, which has been heavily questioned in the literature (Pe'er et al., 2019, Pe'er et al., 2020, Bartkowski et al., 2021a). Only recently, the mandatory use of Farm Sustainability Tool for Nutrients (FaST) was removed from GAEC 5, untying the financial incentives of direct payments with the monitoring of the nutrient status of soils. However, in the aims of the Soil Strategy to better understand soils, the Commission calls to encourage and support MS to set up farm sustainability tools for nutrients (FaST), as part of the farm advisory services under the new CAP (EU COM/2021/699).

Over the last years, the aim for quantifiable goals in the form of integrative and reliable quantitative indicators has slowed down if not even prevented protecting soil biodiversity, as was shown in the previous CAP agreements, when environmental indicators for soil biodiversity were meant to be integrated comparable to CAP biodiversity indicators in place. However, soil biodiversity indicators could not be included due to no commonly accepted indicators in science. It is not clear how realistic and reliable indicators for soil life will be due to complex dynamics of climate, regional differences in soil properties and land-uses but also not when such indicators will be available. While indicators ignore the uncertainty of current predictions, models allow closing this gap.

Bartkowski et al. (2021b) proposed to couple payments with a modelled design predicting results. Particularly for soil biodiversity, this suggestion might allow subsidising soil biodiversity protection. Since soil biodiversity varies with environmental conditions (climate, soil type, organic inputs, etc.) and also since the knowledge on soil biodiversity is still in an early stage (only 10% of species have been identified), a certain flexibility is required, which could be answered by subsidising beneficial soil biodiversity management based on a model as suggested by Bartkowski et al. (2021b). Agricultural practices should be among the main parameters of the models predicting the richness and abundance of soil organisms. For farmers, a list of possible practices and their effects would provide flexibility to respond to spatial and temporal heterogeneity (Bartkowski et al., 2021b).

Since soil biodiversity sustains above-ground life, soil biodiversity protection should not be delayed due to data or knowledge gaps. Proxy indicators, such as land management practices that are beneficial for soil biodiversity, could be used as a reference for soil protection coupled to subsidies until models become available, predicting soil biodiversity considering its spatial and temporal variability.

To implement proxies or models into EU subsidies, a supranational regulatory instrument would best allow coherence with other incentive-based instruments (such as the CAP) and quickly bring all MS at least to a minimal level of soil biodiversity protection. Due to the transboundary effects of environmental protection but also due to the enormous costs for not protecting the environment, the EU has developed a range of environmental policy initiatives addressing different environmental media (e.g. via the Water Framework Directive (2000/60/EC), Ambient Air Quality Directive (2008/50/EC) or the Climate Law that came into place in 2021 (2021/1119)). Also for soils, the Commission calls for a common approach due to "transboundary impact of soil degradation and set measures across the EU" (European Commission, 2021g).

While in 2006, five MS opposed EU-wide protection (Glæsner et al., 2014), in the meantime, the demand for EU-wide soil protection has increased. For example, just shortly before the Soil Health Law was announced, the European Parliament approved a resolution calling for a common legal framework for soil protection, representing European citizens. The proposal was supported by the Committee of the Regions and the European Court of Auditors (European Commission, 2021g). An EU-wide, legally binding soil protection could:

- Complement the national protection (Stankovics et al., 2018), ensuring a certain minimum level of soil protection.
- Face the high costs of soil protection (considering monitoring and research needed) that only the EU can bear. Not protecting soil biodiversity at least at a minimum level will come at a high cost for all MS.
- Allow to execute and ensure coherence and quality standards (Stankovics et al., 2018), answering transboundary effects of soils (e.g. caused by water erosion or the export of excavated soils within the EU).

The Soil Health Law and the legislative framework for an EU sustainable food system both foreseen for 2023 could fill gaps in soil biodiversity protection at the national level. However, it will be crucial that soil biodiversity will be adequately protected. The law should prioritise gaps of soil biodiversity protection at the national level, including the mitigation of soil pollution as well as the promotion of beneficial farming practices for soil biodiversity and the restoration of contaminated soils. To fill the national gap and realise the listed protection priorities, the legislative frameworks needs to translate those goals into applicable practices, protecting and enhancing soil biodiversity. Relating subsidies to proxies of beneficial land management practices or models could simplify the monitoring compared to result-based payments based on indicators (Jeffery and Verheijen, 2020), avoiding an unbearable administrative burden. Models predicting soil biodiversity considering its spatial and temporal variability could provide the flexibility required due to current knowledge gaps preventing burdens to update legislative frameworks constantly.

Solutions are more likely adopted if the grassroots, the national and the supranational are brought to the same table. Since knowledge on soil biota is very heterogeneous (Hervé et al., 2020), the methods to be followed should also be heterogeneous. The rigid top-down regulation should meet a dynamic bottom-up approach. This will likely cause tensions, requiring well-balanced compromises (see Fig. 4). However, a

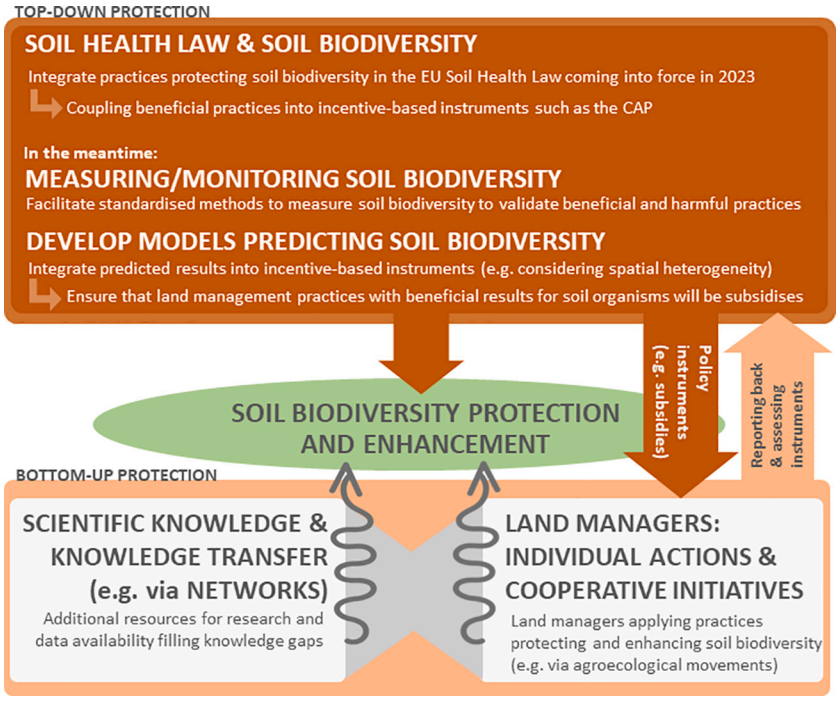

Fig. 4. Towards soil biodiversity conservation: political top-down protection meeting bottom-up protection and the enhancement of soil biodiversity led by networks of scientists and stakeholders such as agroecological farming movements. The dynamic process that is involved in finding common scientific ground and grassroots knowledge of land managers (wavy arrows) bottom-up meet rigid top-down regulation (straight arrows), which is likely causing tensions, requiring compromises from both directions.

close interaction between top-down regulatory instruments and bottom-up activities enables the exchange of knowledge and the intervention and mitigation to ensure the success of conservation activities. Local/national authorities should subsidise tying ecological processes with social and financial benefits (e.g., funding for agroecological community farming, creating local labour and food, see Ajates et al., 2018). The new Soil Strategy announced to involve various stakeholders to define sustainable farming practices and to set up a network of practitioners aiming to connect different stakeholders by building "Living Labs" and Lighthouses of the Mission 'A Soil Deal for Europe' (Section 4.1., COM/2021/699). Also, international networks of scientists, farmers/foresters and other stakeholders (Guerra et al., 2021, Bartkowski et al., 2021a) help to fill knowledge gaps at the national level, such as the Global Soil Biodiversity Initiative, the global Soil Biodiversity Observation Network (Soil BON), the EU Soil Observatory (European Commission, 2021d) and the FAO's recently launched Global Soil Biodiversity Observatory (GLOSOB).

The urgency for protecting soil biodiversity is timely if we aim to comply with Sustainable Development Goals (SDGs) (Bach et al., 2020). Protecting soil biodiversity will have positive spill-offs to other sustainability goals, including food security, water quality and human health. Since SDGs are global goals, the EU should try not to outsource environmental harmful food production (Fuchs et al., 2020), likely threatening soil biodiversity in other parts of the world that are probably even more likely to be hit by weather extremes caused by climate change. Despite importing one-fifth of all food to the EU, the Green Deal does not envision import limitations (Fuchs et al., 2020). Since higher imports are also a consequence of the extensification of agricultural land (e.g. since organic farming requires more area), the EU needs both: more sustainable food production, preventing land degradation, but also more efficient practices for sustainable food production (e.g. by enhancing soil biodiversity, Huang et al., 2021). Inclusive decision-making is needed (e.g. in terms of multidisciplinary teams, property rights) that holistically protects soil biodiversity while considering global consequences.

5. Conclusions

Our findings revealed that threats to soil biodiversity are not adequately addressed in current EU policy frameworks. To maintain the health and fertility of soil and its ecosystem services, soil biodiversity cannot be sacrificed for the sake of ensuring a high primary production. Striving for the most efficient protection of soil biodiversity should be in the interest of every Member State to prevent escalating soil remediation costs but also to comply with the demands from the European citizens, represented by the European Parliament.

We found soil biodiversity protection best achieved as a common action at the EU level. An EU-wide, legally binding protection could complement national law to guarantee an EU-wide minimum level of soil biodiversity protection following coherence and quality standards while preventing surging costs of not acting. The Soil Health Law foreseen for 2023 opens doors to ensure healthy soils and holistic soil protection. It should prioritise gaps in national soil biodiversity protection, preventing pollution while promoting contamination remediation and beneficial farming practices for soil biodiversity. Therefore, it should couple soil biodiversity protection to other policy instruments regulated at the EU level (for example, within the CAP as Statutory Management Requirements that are mandatory to receive direct payments, comparable to the Nitrates Directive). Due to the importance of soil biodiversity, its protection via subsidising beneficial land management practices should not be delayed.

However, since soil biodiversity varies with spatial conditions (climate, soil type, organic inputs) and since the knowledge on soil biodiversity is still in an early stage, a certain flexibility is required. We suggest, therefore, to integrate beneficial practices for soil biodiversity into payments by modelled-results, as suggested by Bartkowski et al. (2021b), considering the spatial and temporal heterogeneity of soil biodiversity. Payments based on models would allow considering the uncertainty of predictions while providing room to adjust or elaborate on advised practices in place if needed. At the same time, we call the scientific community to advance the quantitative assessment of soil biodiversity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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