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REVIEW ARTICLE

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Forty years of soil research funded by the European Commission: Trends and future. A systematic review of research projects

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Abstract

The European Green Deal with its high ambition has set the European Union (EU) on a promising path towards greater soil protection. The EU Soil Strategy 2030, the Biodiversity Strategy 2030, the Farm to Fork Strategy, the Zero Pollution, the Nature Restoration Law and the European Climate Law, among others, include actions to protect our soils. Research and Innovation (R&I) will play a key role in developing new knowledge and tools enabling the transition to healthy soils. The main aim of this paper is to analyse past and near-future trends in EU's funding for R&I on soil-related issues. For this purpose, a review of EU-funded soil projects was conducted based on the data available in the Community Research and Development Information Service and the official portal for European data. Our analysis shows that over the past 40 years, the EU has invested significantly in developing integrated knowledge about the relationships between soil functions and ecosystem services and how human-induced pressures affect soil health. Following the adoption of the EU Soil Thematic Strategy in 2006, there was an increase in research funding for soil-related research. Furthermore, our analysis also illustrates an interesting interplay of permanent and changing soil themes. The Horizon Europe Mission 'A Soil Deal for Europe', which aims to establish a network of 100 living labs and lighthouses to lead the transition towards healthy soils and safeguard human and planetary health by 2030, provides a further incentive for soil research. Together with the EU Soil Strategy 2030 and the new proposal for a Directive on Soil Monitoring and Resilience (Soil Monitoring Law), and the EU Soil Observatory (EUSO), the three instruments set up the political framework, concrete measures, and a monitoring system needed for the protection, restoration and sustainable use of soils.

KEYWORDS

EU research and innovation, EU soil observatory, EU soil strategy, horizon Europe, open science, soil Mission, soil policies

1 | INTRODUCTION

1.1 | European Union research and innovation funding

The involvement of the European Union (EU) in research activities (outside the coal and nuclear fields) began in the 1970s with the adoption by the Council of the first Community Research Programmes (pre-FP) (Guzzetti, 1995). These were low-budget programmes, adopted individually by unanimity in the Council without a strategic approach. At the beginning of the 1980s, the European Commission (EC) proposed to carry out research through Framework Programmes (FP) for research as a strategic tool to programme and carry-out research funding in a more systematic and coherent way. EU FPs for Research and Innovation (R&I) continue to the present day as the current FP (Horizon Europe) is the ninth in a row.

The first FPs (FP1-FP3) focused primarily on supporting pre-competitive, more basic research with the intention to close the research knowledge gap between Europe and other regions of the world (Reillon, 2017). With FP4 and FP5, the scope of the FPs was enlarged to address societal challenges and support a wider range of activities in the innovation process, thus reflecting the global technological and economic landscape. Recognizing knowledge and innovation as key drivers of economic development, in FP6 and FP7 the support for collaborative innovation activities was put on equal footing with the funding exploratory research. The adoption of the Europe 2020 strategy and the Innovation Union flagship initiative in 2010 (COM, 2011) influenced the structure of FP8, which was adopted in 2013 and named Horizon 2020 (H2020) (Reillon, 2017). The most recent programme named Horizon Europe (HE) is the EU's largest R&I programme with EUR 95.5 billion budget for 2021–2027. Building on almost 40 years of R&I programmes, HE is expected to strengthen the scientific and technological bases of the EU to contribute to the tackling of global challenges. In addition, HE introduced the concept of EU Missions to increase the impact of European R&I, grasp the public imagination and make real progress on complex challenges (EC, 2018). One of the five missions launched under HE, 'A Soil Deal for Europe', targets soil health (Soil Mission).

1.2 | EU soil policies: From the 2006 soil thematic strategy to the European green deal

Although there were more than 200 environmental directives and regulations, which directly or indirectly affected soil management, there was no specific instrument directly concerned with soil protection at the EU level until the adoption of the Soil Thematic Strategy in 2006 (Heuser, 2022; Paleari, 2017). The Soil Thematic Strategy consisted of a Communication from the Commission, a proposal for a framework directive (a European law), and an Impact Assessment. However, the proposal for a framework directive was blocked by five EU member states and withdrawn formally in 2014 (Chen, 2020; Panagos & Montanarella, 2018).

Almost 10 years later, the EC adopted, as part of the EU Biodiversity Strategy for 2030, the new EU Soil Strategy for 2030 with the aim to bring all EU soil ecosystems in good condition by 2050 (COM, 2021a). The new Soil Strategy calls for action to gain more knowledge on soil data and monitoring of soils. Actions for soil data harmonization entail efforts on identifying and harmonizing soil data, soil indicators, soil mapping and databases across Europe. Harmonization of soil data enables streamlining data and information flows, reporting and accounting of functional properties of soils. As part of this, a new Soil Monitoring Law has been proposed to ensure a level playing field and a high level of environmental and health protection(COM, 2023).

A central role in the implementation of the Strategy is assigned to the newly established EU Soil Observatory (EUSO), providing the necessary data and indicators for the regular assessment of soil health in the EU (Panagos, Montanarella, et al., 2022). The Soil Mission will allow stepping up efforts on soil health, in line with Green Deal commitments for climate, biodiversity, zero pollution, and sustainable food systems (EC, 2021a). Funding for the Soil Mission amounts to about EUR 320 million for the period 2021–2023 and a further 135 million for 2024.

In this context, the analysis of soil research is particularly relevant, given the long history of the soil file in the EU and the increased political attention on soils not just in the EU but also at global levels. The Soil Mission attracts a lot of interest in soil-related research.

Highlights

- The EU has invested considerably to support soil research.
- This paper provides a refined database of all EU Research projects in soils during the last 40 years.
- The political agenda has influenced EU research on soils.
- Soil scientists have worked over the past four decades to confront major global challenges.

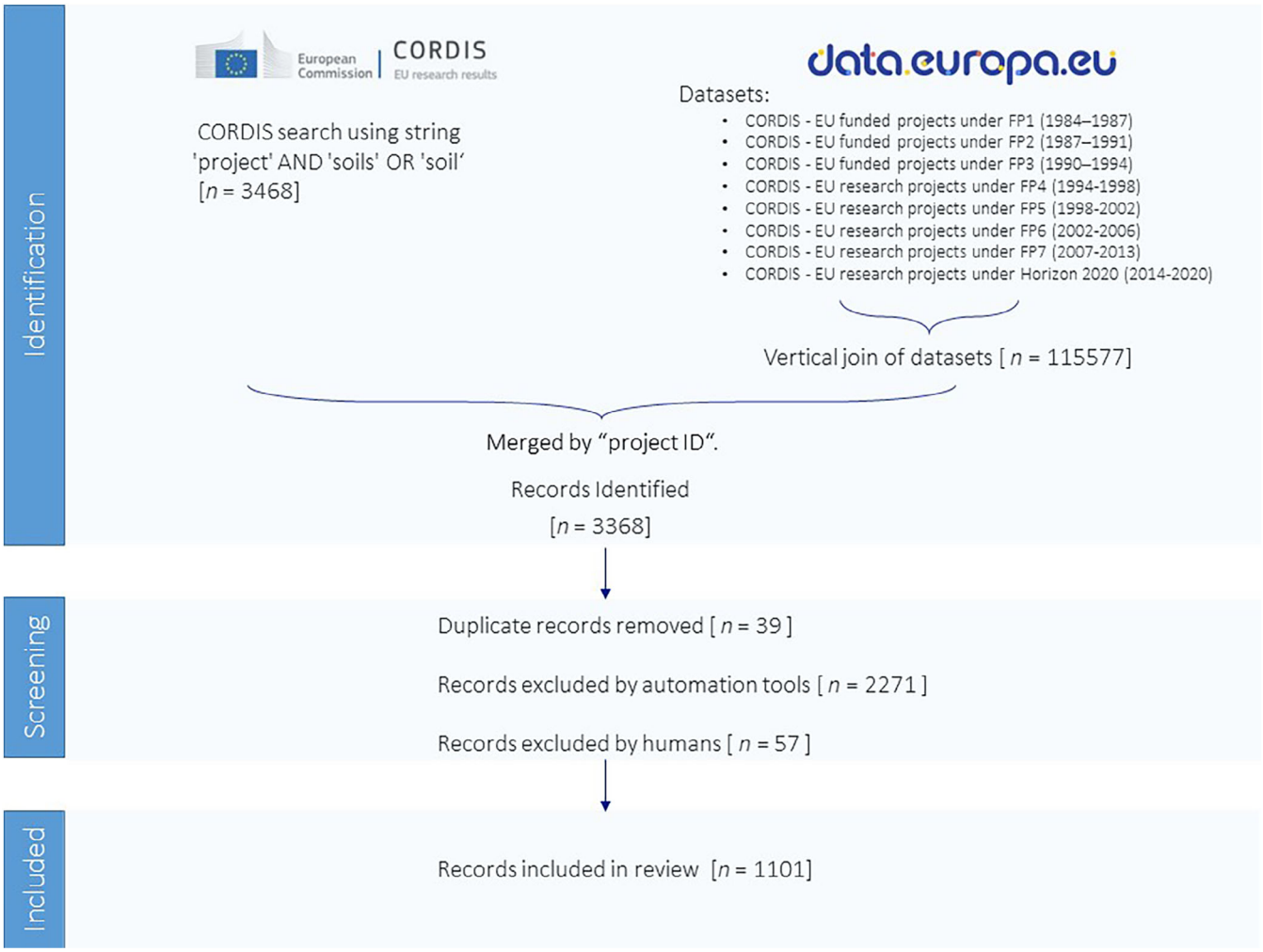

FIGURE 1 Flow diagram showing the steps involved in the systematic review of the soil-research projects and related datasets.

This paper provides an extensive overview of the R&I programmes that were at the origin of this renewed interest.

The aim of this paper is to highlight trends in soil research at EU level and the relation between policy and soil research. We conducted a systematic review of projects that come under the banner of soil funded by successive EC FPs for R&I. We applied semantic analysis to investigate the evolution of soil research themes over time, which ones remained in the mainstream and which ones disappeared or newly emerged. A comprehensive and detailed review of all funded soil projects was not an objective of this manuscript.

2 | MATERIALS AND METHODS

2.1 | Soil research projects

The Community Research and Development Information Service (CORDIS) has a rich public repository with information held by the EC on projects funded by the EU's FP for R&I (García-holgado et al., 2020). In addition, the EC has a solid legal framework for the re-use of its own data available at data.europa.eu, managed by the Publications Office of the European Union. In this data portal, users can have access to almost 2 million datasets available also from international, EU, national, regional, local and geo data portals.

A keyword-based stocktaking of soil-related research projects has been conducted, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). First, we used CORDIS to identify soil projects funded by the EC with the search terms 'project' AND 'soils' OR 'soil' in their CORDIS record (Figure 1). In the second step, we used data.europa.eu (https://data.europa.eu/data/datasets) to obtain public grant information for each project identified (legal basis, topics, cost, coordinator, country, participants, etc.). After removing the duplicates, the projects were screened based on their title and summary.

We discarded 2271 records, using automation tools, which are projects that did not include the word 'soil' in the title or in the summary. We did not consider projects which have used other terms than soils as the purpose of the investigation was to determine trends over time, rather than to provide a comprehensive record of all projects on the topic. The rest of the projects ($n = 1172$) were manually assessed for eligibility. The authors inspected the title and the project summary and excluded those projects that were not related to soil science ($n = 57$). Another 14 duplicated records were manually removed. Finally, $n = 1101$ projects were included in the study. Figure 1 shows the steps followed in the systematic review of the research projects. It maps out the number of records identified, included and excluded. Supplementary material S1 includes a PRISMA Flow Diagram and a description of the datasets used to select the projects.

2.2 | Textual analysis

To analyse the trends in soil themes covered by EU funding, we used the text analysis program *CorTexT Manager* (Breucker et al., 2016). *CorTexT Manager* allows for correlation of large volumes of data (El Akkari et al., 2018). Specifically, the Network Mapping script automatically identifies locally dense groups of nodes. Different definitions/algorithm of these 'communities of nodes' are possible. In this study, we used Louvain hierarchical community detection algorithm, efficient on large networks (Blondel et al., 2008). It is based on an optimisation of the modularity, where modularity measures the density of edges within communities compared to the number of edges connecting each community. Textual analyses were performed using the title and the summary of 1101 projects. Separate analysis were conducted including set of projects belonging to each FP. To identify trends in soil research, we define the frequency distribution of words (topic modelling) (Sievert & Shirley, 2015) for uncovering the underlying semantic structure of the projects collection based on a hierarchical Bayesian analysis of the original texts (Griffiths & Steyvers, 2004). Supplementary material S2 includes statistics, results of the topic modelling, frequency tables of terms and the cluster maps of the main terms for each FP.

3 | RESULTS

3.1 | Number of soil projects and budget

Over the years, the total budget allocated to the successive FP has continually increased, which is also reflected in an increase in funding for research in soil science. Our results show that until the end of 1990's (FP4), soil-research projects were a small portion of the total EU research FP budget (around 0.10%) (Table 1). After the year 2000 (FP5), this portion has been around 0.50% of the total FP budget. There is a tendency in the last 20 years to have higher funding per project and more soil projects funded (Table 1, Figure 2). However, in FP6 (2002–2006) the number of projects and the total EC contribution to those projects was reduced as compared with FP5. This is related to an overall decrease in agricultural and more applied research in FP6 (Reillon, 2017). It is assumed that the adoption in 2006 of the EU Soil Thematic Strategy led to an increased research funding for soil-related research, as of FP7 (2007–2013). One of the four pillars of action of the 2006 Soil Thematic Strategy was to intensify targeted research in order to close the knowledge gaps to support soil protection in the EU and the sustainable use of soils. Before that time, funding soil research was rather unpredictable, and particularly low in FP6 with its focus on enabling technologies (Reillon, 2017). H2020, covering the period 2014–2020, funded more than 200 soil-related projects with an amount of about EUR 350 million (Table 1), and more than 30% of the projects with a EC contribution higher than EUR 1 million (Figure 2). In soil research, the highest EC contribution, EUR 40 million, has been granted to the European Joint Programme on Soil (EJP SOIL). The EJP SOIL is a co-fund action between the EC and EU countries to support coordinated national R&I programmes on soil. The EJP Soil is implementing activities, ranging from R&I projects to training and dissemination.

3.2 | Trends on soil themes

The textual analysis allowed assessing which terms appear most frequently in title and project description, which appear most frequently together, and organizing them into groups of related main terms (soil themes). The main terms appearing in descending order are 'climate change', 'contaminated soil', 'soil organic carbon', 'soil organic matter', 'soil erosion', 'soil pollution', 'heavy metals', 'soil quality', 'soil fertility', 'soil and water'. The contingency matrix (Figure 3) shows the distribution of main soil terms of the full corpus. There is strong correlation between 'climate change' and 'soil erosion', 'soil fertility' and 'soil organic carbon' and between 'contaminated soils' and 'soil and water'. To uncover the main soil themes and their linkages, we produced a semantic map as shown in Figure 4. The proximity between words on the map is reflective of their spatial proximity (co-occurrence). We observe that each term can belong to several different soil themes—the classification is not exclusive. The main terms coalesce in four

TABLE 1 Summary of public grant information of soil projects funded by the European Commission under different Frameworks Programmes (FP) for research and innovation.

Framework Programme	Period[a]	FP budget (billion €)	Soil projects (million €)	% of FP budget	Number of soil funded projects	Mean EC contribution (million €)	Average number of participants per project
pre-FP	1970s–1983	[b]	[b]	NaN	119	[b]	[b]
FP1	1984–1987	3.8	[b]	NaN	69	[b]	1.5
FP2	1987–1991	5.4	[b]	NaN	54	[b]	3.7
FP3	1990–1994	6.6	12.56	0.19	102	0.6	4.6
FP4	1994–1998	13.2	12.94	0.10	130	0.9	4.9
FP5	1998–2002	15	98.24	0.65	157	0.6	4.0
FP6	2002–2006	16.3	71.04	0.44	80	0.9	6.0
FP7	2007–2013	50.5	206.23	0.41	181	1.1	4.8
H2020	2014–2020	77	356.40	0.46	209	1.7	5.1
Horizon Europe	2021–2027	95.5	[c]	[b]	[b]	[b]	[b]

Note: Call for proposals 2021: total budget €62 million. Call for proposals 2022: total budget €95 million.
[a]Period covered by the Framework Programme. It does not correspond with the time of the projects. Several H2020 projects are still ongoing.
[b]Data not available.
[c]Horizon Europe will invest €320 million from 2021 to 2023 to support the implementation of the Mission: 'A Soil Deal for Europe'.

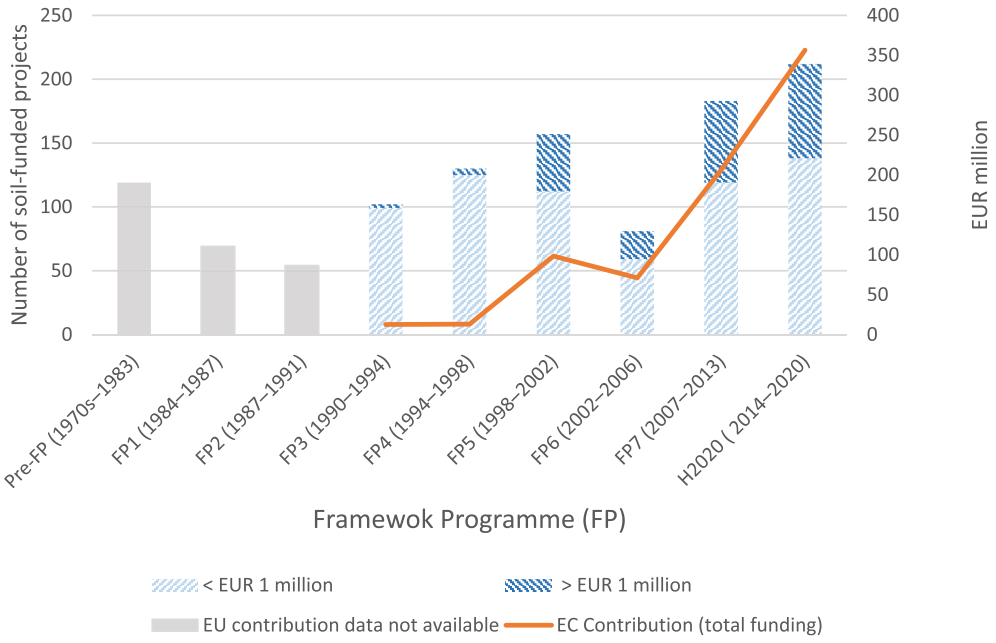

FIGURE 2 Evolution of the EU Framework Programmes (FP) for Research and Innovation. Number of soil projects and funding.

nodes around the themes 1: 'contaminated soil', 2: 'soil and water', 3: 'climate change' and 4: 'soil conservation'. There are some overlaps between themes 1 and 2 and some minor connectivity was evident between themes 1 and 3 (Figure 4).

To identify trends on soil research, that is, how the soil themes have evolved over time, we aggregated mean proportions per FP of all projects (Figure 5). Topic modelling results show that during the pre-FP projects the most relevant theme was 'Contaminated soil', accounting for more than 30% of the projects. After a peak in FP5, the importance of the theme decreased having the lowest proportion in H2020. During the first FPs (from FP1 to FP4), 'Soil and water' has been the most important theme addressed in soil research. While 'Soil conservation' research has remained stable throughout the FPs (accounting on average for 25% of the projects), 'Climate change' has exponentially increased over the time. 'Climate change'

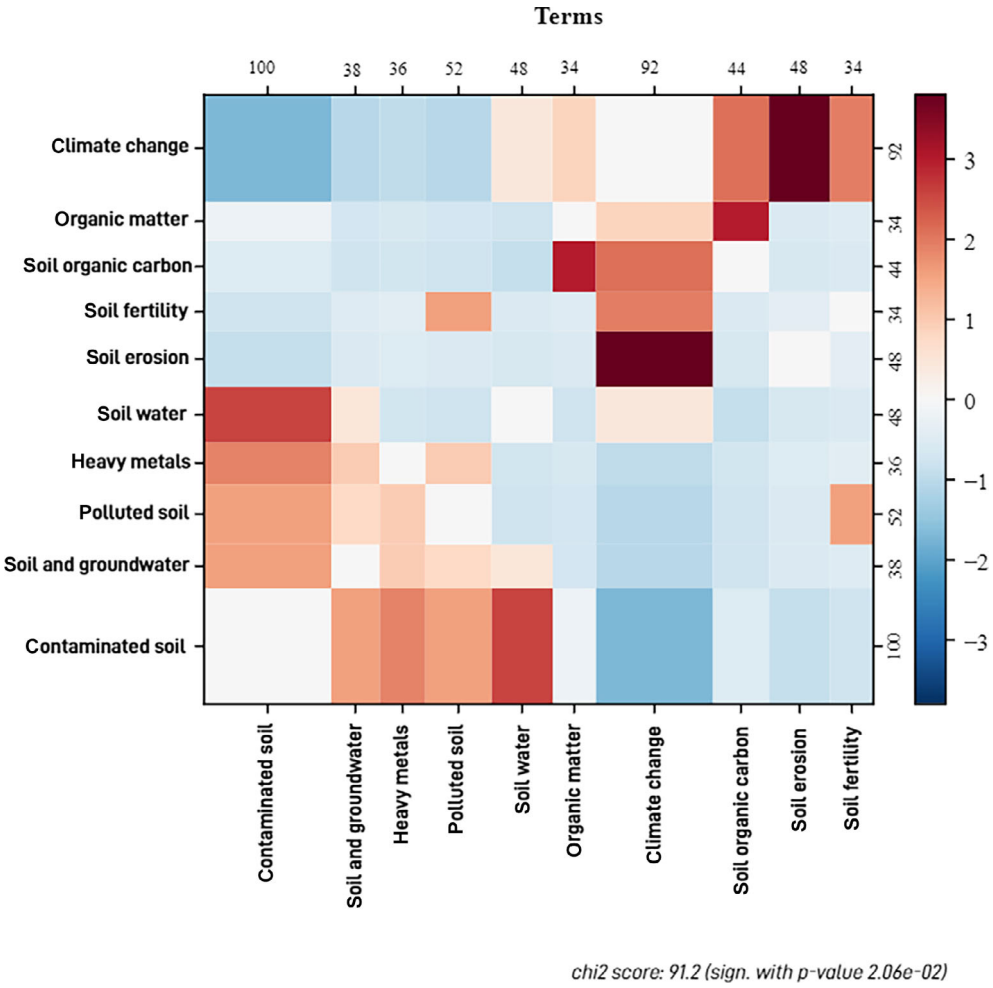

FIGURE 3 Joint distribution of main soil terms in the corpus. The contingency matrix shows the degree of correlation between any pair of terms. Red cells are the most correlated (many documents mentioning term A(i) also mention B(j)). Blue ones are anti-correlated (few documents mentioning A(i) also mention B(j)).

has become the most important theme in soil research from FP7, accounting for more than 40% of the soil research in H2020.

From the multi-term statistics (Table S2.1) we observe that traditionally, most of R&I projects have focused on agricultural soil. The textual analyses show that the terms 'European agriculture', 'agricultural land' and 'agricultural soil' are among the 100 most frequent terms. Under H2020, the frequency of terms associated with agricultural soils increased with respect to the previous FPs ('agricultural soil', 'agricultural production', 'agricultural practices', and 'agricultural crops') (Table S2.10). This fact can be explained partially because in H2020 soil research responsibility was transferred to the Commission DG for Agriculture and Rural Development, which defined research topics from an agriculture perspective. In addition, soil protection (mainly in agricultural soils) has been recognized recently as one of the objectives of the EU Common Agricultural Policy (CAP) (Panagos et al., 2020). Soils are the foundation of agriculture, and our results show that the CAP and its reforms may have played an important role in the EU research funding on soils. The main term 'agriculture' appears for the first time under FP3 (Table S2.5), just after the MacSharry reforms (1992) which changed the CAP from market support to producer support. During FP3-FP6, 'agriculture' is associated with 'soil fertility', 'crop production' and 'food production' (Figure S2.5 to Figure S2.8). The 2013 CAP reform included the 'greening' of farm payments, through the introduction of environmentally sound farming practices, such as crop diversification, and maintaining ecologically rich landscape features (Alan Matthews, 2013). Thus, under H2020 we observe a shift towards 'sustainable intensification' and 'soil health' (Figure S2.10). Furthermore, a growing interest in agricultural 'data sharing' as required by the CAP Integrated Administration and Control System has also enabled some additional funding streams in H2020 (e.g., NIVA project). The Open Data Directive (2019) together with its implementing regulations should further enhance data sharing. The importance of soils is reflected in the new CAP (2023–2027), not just because one of its key objectives is to 'Foster sustainable development and efficient management of natural resources such as water, soil and air' but because targeted improvements in soil management help improve farm sustainability in economic and environmental

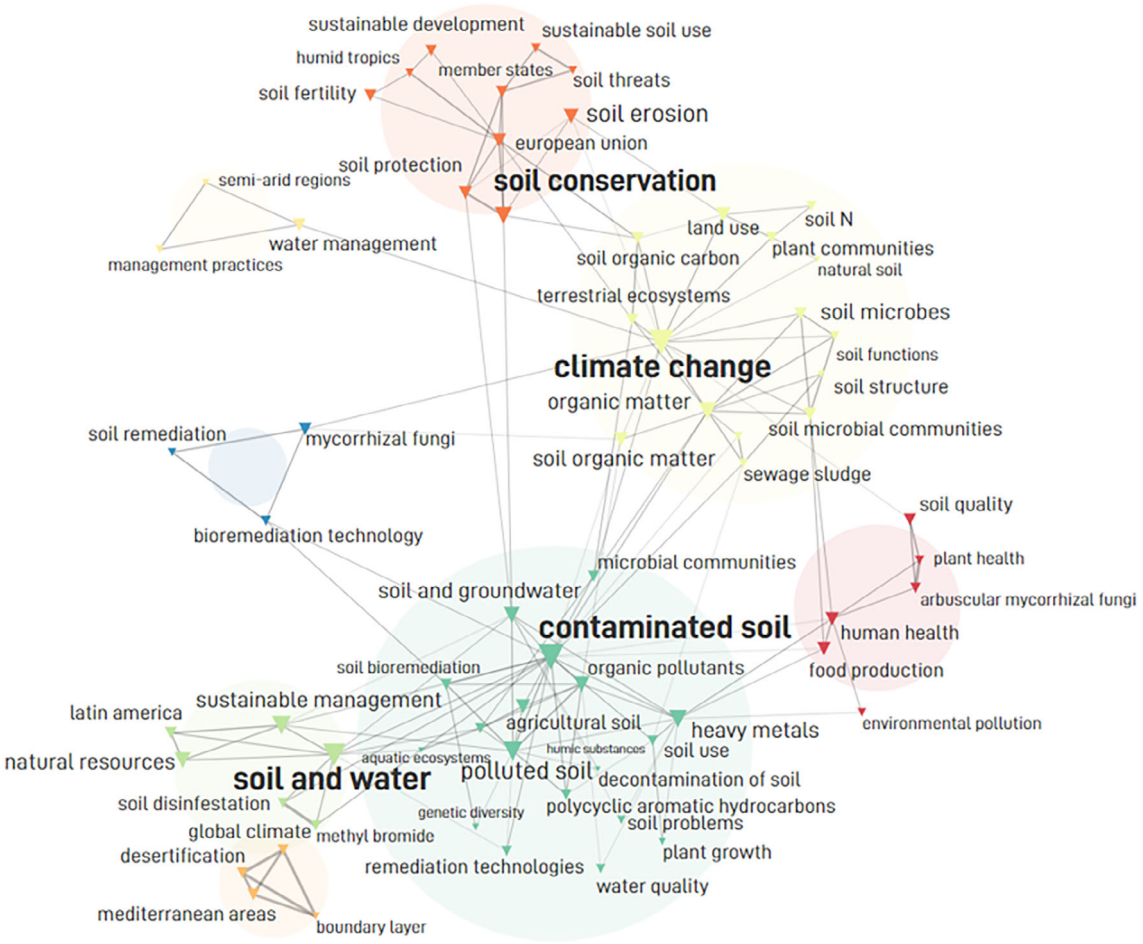

FIGURE 4 Network map presenting groups of related main soil terms found in the title and objective of the 1101 soilprojects included in the review. The main terms coalesce in four nodes around the themes 'contaminated soil', 'soil and water', 'climate change' and 'soil conservation'. Network maps for each Framework Programme (from FP1 to Horizon 2020) are accessible in Supplementary material S2.

terms (EU, 2021). As part of its commitment to support R&I in agriculture, the Commission has proposed to set aside EUR 10 billion from the HE programme for projects relating to food, farming, rural development and the bioeconomy.

Soil is also an important component of the forest ecosystem and the EU has funded research on forest soils over its various FPs. Forest soils research during the first FPs was focused on 'soil chemistry', 'organic matter', and 'acid rain'. During the 1980s, acid rain was considered one of the largest environmental threats of the time (Johnson et al., 2018; Menz & Seip, 2004). During the first FPs (1–3), 'forest soils' and 'acid deposition' were among the main terms in soil research (Table S2.2. to Table S2.5). Acidic deposition severely affected major forested areas of Europe leading to declines in aquatic biodiversity and forest growth (Vet et al., 2014). The legacy of the acidification research became a game changer both politically and policy-wise (Rosseland, 2021). Acidification has been greatly reduced since its peak (Evans et al., 2001) when almost half of the sensitive ecosystem area in the EU Member States was affected (EEA, 2014).

At the beginning of the 21st century, the number of research topics increased, with more ecosystem-related subject areas ('climate change', 'water quality', 'carbon'). The negotiations under the UNFCCC since 2005 included considerations of a mechanism that could ensure reduced greenhouse gas emissions by reducing deforestation and forest degradation and by enhancing forest carbon stocks (REDD+). Consequently, the EC funded several projects on REDD+ (e.g., I-REDD+ project) under the specific programme 'Cooperation': Environment (including Climate Change). Under FP7 (2007–2013) 'forest soils' was one of the main terms associated with 'global climate change', 'greenhouse gases' and 'soil carbon storage' (Figure S2.9, Table S2.9) and forest soils became a truly global research area.

Forest soils have been important in EU research, although sometimes as an afterthought relative to agricultural soils. However, as forests became more important as

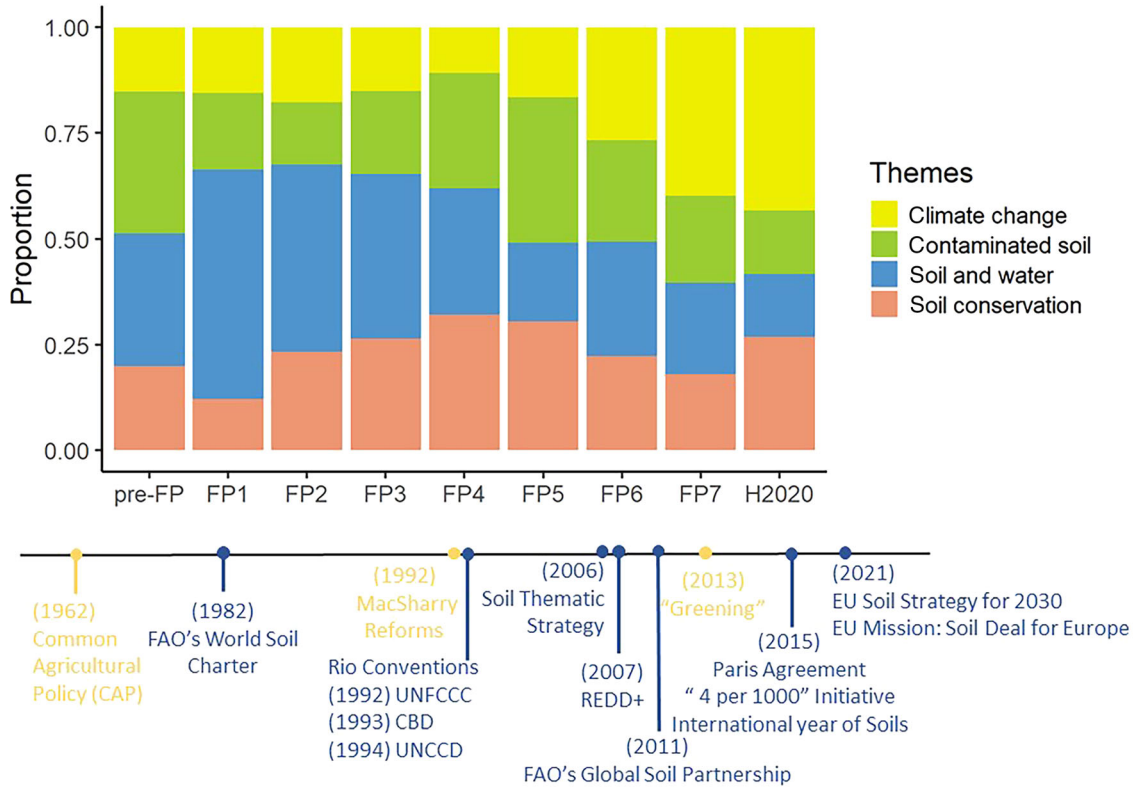

FIGURE 5 Historical perspective of European Union (EU) Framework Programmes (FP) for Research and Innovation. The figure provides an overview of the proportion of four soil themes (climate change, contaminated soil, soil and water, soil conservation) addressed in EU funding over time. Policy milestones important for soils are marked in blue. Common Agricultural Policy (CAP) reforms are marked in yellow.

sources of fuel, wood products, research began to evolve to consider forest soils separately, and in light of their capacity to provide important products, and more recently important ecosystem goods and services. While the number of forest soil indicators has considerably increased in the literature, there are significant knowledge gaps on forest soil processes and soil monitoring is not sufficiently harmonized (Gatica-saavedra et al., 2022), which limits the EU's ability to soil-related ecosystem services and to reach climate policy targets.

The term 'climate change' became a main term in soil research projects already in FP4 (1994–1998). From FP6 (2002–2006), 'climate change' is the term that appears most frequently (Supplementary material S2). The year 2015, was the year in which the world defined and committed itself to striving towards the UN Sustainable Development Goals (SDGs), in which the historic Paris Climate Agreement was signed under the UNFCCC, and it was also the UN International Year of Soils (UN, 2015) (Figure 5). Our results show that under H2020 (2014–2020), soil science achieved new prominence with 'climate change' associated with 'soil organic carbon' (Figure S2.10). An increase of soil organic carbon (SOC) sequestration has been promoted as a prospective additional opportunity to partly counterbalance increasing atmospheric carbon dioxide concentrations and gained political momentum after the '4 per1000' initiative was launched at the 21st Conference of Parties of the UNFCCC (Rumpel et al., 2020). This initiative was proposed to increase global soil carbon stocks by an aspirational 0.4% per year, underlining the role of SOC in addressing the threefold challenge of food and nutritional security, adaptation of food systems to climate change and mitigation of human-induced greenhouse gas emissions (Soussana et al., 2019).

3.3 | Research and innovation cooperation

The network maps from individual FPs (Supplementary material S2) show that EU soil research was very fragmented, with no connection between research themes until FP6. However, our results show that FP6 was effective in breaking down soil research silos (Figure S2.8). One of the thematic priorities in FP6 was to enhance stronger links with national, regional and other European initiatives in the field of research. We observe in FP6 an increased

collaboration with an increased average number of participants per project and an average number of participant's countries per project (Table 1). FP6, FP7 and H2020 also fostered EU international soil research cooperation among Member States with Africa, Latin America and China (Table S2.8, S2.9, and S2.10). The adoption of the Europe 2020 strategy for a smart, sustainable and inclusive economy and the Innovation Union flagship initiative in 2010 influenced the structure of H2020 going beyond interdisciplinary (COM, 2011). In the case of soil research, the multi-terms statistics show that H2020 was effective in fostering more inter-disciplinary research, increased R&I collaboration and fostered transdisciplinary research (Figure S2.10, Table S2.10).

4 | DISCUSSION

4.1 | Stability and change in the soil themes-policy milestones important for soils

The increasing pollution of the environment over the last decades has been one of the greatest concerns for the European Union (EU). Water and soil pollutants represent two major categories of environmental pollution and the results reported here show that both research themes (‘*contaminated soil’* and ‘*soil and water’*) are highly interlinked (Figure 4). Water- and soil-polluting substances are often due to man-made wastes such as agricultural wastes, fertilizers used by farmers, oil spills, and radioactive materials (Ainsworth et al., 2018) representing a serious threat to humans and other organisms (Ahmed & Sulaiman, 2001). The EC has funded research focused on investigating measures for remediating soil contamination (activities related to industry, mining, and industrial waste disposal and treatment) since the first Community Research Programmes. The EC was also at that time a pioneer in investigating soil pollutants, such as polycyclic aromatic hydrocarbons (PAH). Scientific interest in PAHs has remained high during recent decades (Tsibart et al., 2014). Although soil contamination in Europe is a widespread problem, the issue of historical contamination remains an important gap in European policymaking on soils (Van Liedekerke et al., 2014). Currently, the EC recognizes it and urges to deal with pollution through its Action Plan ‘Towards a Zero Pollution for Air, Water and Soil’ (COM, 2021b) and more specifically to act on soil pollution which is mentioned in the new EU Soil Strategy (COM, 2021a). The Zero Pollution monitoring and outlook framework aims to monitor all types of pollution for air, water and soil (COM, 2021b). The zero pollution outlook analyses synergies and trade-offs between different EU policies and translates ‘early warnings’ into recommendations on pollutants of increasing concern based on the latest research findings (JRC, 2022).

‘*Soil conservation*’ has been a central theme in EU-funded research. Soil Conservation research covers multiple aspects of the sustainable use of soil resources, including soil biology, nutrient management, water-use efficiency, soil fertility, hydrology, and ecosystem services. Soil conservation in Europe started to gain political attention during the last decade of the 20th Century and it became rapidly obvious that soil conservation was a complex issue, particularly in Europe, where long historical development has had a deep impact on European soil resources (Imeson et al., 2006). Due to the potential of soil for carbon sequestration, protecting biodiversity and for increasing the resilience of agro-ecosystems to external changes like climate change, soil conservation has been progressively a central theme of the three environmental conventions of the United Nations (UN). Thus, soil conservation research in the EU has been directed towards addressing emerging global challenges such as climate change. In addition, the research in soil conservation proposed management practices to reduce soil loss and protect soils.

Findings from soil conservation research projects have introduced new management practices (e.g., cover crops, mulching, grass margins, etc) to reduce soil loss and enhance soil health. Some of those practices have been introduced in the Good Agricultural and Environmental Conditions (GAECs) of the CAP (Panagos et al., 2016).’*Climate change’* has become the main soil theme in EU-funded research. At the EU level, the EU budget makes a crucial contribution towards the fight against climate change. In the 2014–2020 multiannual financial framework, the EC implemented an innovative approach to dedicate resources to the fight against climate change: ‘climate mainstreaming’. Over the course of 2014–2020, the EU delivered on its ambition of spending 20% of available funds on climate-related measures putting EUR 20.3 billion into climate-related research projects (EC, 2021b). Our analysis shows that in H2020, 43% of the soil projects were linked with climate change, which equates to around 1.75% of the funds available for climate-related research projects. To support the commitment to make the EU the world's first climate-neutral continent by 2050, HE will direct a minimum of 35% of the funding available to climate objectives. These funds will be used for projects that advance the science of climate change, develop solutions to reduce greenhouse gas emissions, and to adapt to the changing climate (EC, 2021a). Given the key role of healthy soils in the carbon cycle (Lal et al., 2021) and the expanding policy

attention to SOC research, we can expect that there will be an increasing amount of funds for research projects that will help to improve soil health and foster more sustainable soil management practices.

4.2 | Research and innovation cooperation-from interdisciplinary to transdisciplinary research

In recent decades, soil scientists have increasingly recognized the importance of working with other disciplines through the exchange of concepts, methodologies and data to sustain soils globally (Cimpoiasu et al., 2021). Such interdisciplinary networks are essential for tackling large-scale, cross-disciplinary objectives such as the UN Sustainable Development Goals (Bouma & Montanarella, 2016; Hou et al., 2020). In the area of agricultural research, a main novelty in H2020 was the introduction of the so-called multi-actor approach and the attention given to linking research and practice. Multi-actor projects are projects in which end users and multipliers of research results such as farmers' groups, advisers, enterprises, are closely cooperating during the course of the whole research project period. Putting together actors working in the field with complementary knowledge has proven positive in H2020 multi-actor projects (e.g., BEST4SOIL project).

Soil scientists have worked over the past four decades to confront major global challenges, including climate change, food security, water security, ecosystem functioning and biodiversity. In spite of advancements, there remains a large number of knowledge gaps and research questions. Among all knowledge types, those addressing socio-economic interrelations with soil health and associated policies represent the biggest bottleneck (Löbmann et al., 2022). The current challenge for the scientific community is to focus on solutions to the societal issues of our time together with a broad range of soil stakeholders and ensuring the transfer of solutions and their use. Achieving this will require transdisciplinary collaboration, dialogue between scientists and diverse stakeholders and engaging citizens in R&I activities dealing with grand societal challenges.

4.3 | Future soil research

R&I is essential to achieve the objectives set by policy, therefore the EU is stepping up efforts on soil health research. The HE Soil Mission through its comprehensive, co-created R&I roadmap, combined with a robust, harmonized soil monitoring framework and increased soil literacy and communication to engage with citizens, comes at the right time. The mission proposes a novel approach to R&I based on open science and interactive, participatory innovation with strong stakeholder and citizen engagement. Special attention will be given to innovations in carbon farming, soil pollution (including pesticides) and restoration, soil biodiversity and the circular economy (EC, 2021a). The main goal of the Mission is to establish 100 living labs and lighthouses to lead the transition towards healthy soils by 2030. Soil health living labs will be partnerships between different actors, like researchers, farmers, foresters, spatial planners, land managers, and citizens who come together to co-create innovations for a mutually agreed objective. Living Labs will be established at territorial, landscape or regional scale, with several experimental sites covered underneath. Lighthouses are places for demonstration and peer-to-peer learning where researchers work hand in hand with land managers to ensure that research responds to concrete needs encountered in the field.

While R&I is a key enabler for change, only its interaction with other instruments and practices will result in major breakthroughs and deliver added value. The EUSO will contribute to the Soil Mission and to the development of a harmonized EU Soil Monitoring framework. Soil data and indicators are made available to all stakeholders over the EUSO indicator dashboard. As a dynamic and inclusive platform, EUSO supports policymakers by (1) providing the Commission Services and the broader scientific community with the soil knowledge and data flows needed to safeguard soils, (2) reinforcing EU Research & Innovation on soils and (3) raising societal awareness of the value of soils. Together with the EUSO, the Soil Mission will help to make data widely accessible to all types of users, also in view of supporting the self-assessment of soil health by land managers and citizens alike.

In addition, the Soil Mission is essential for the success of the EU Soil Strategy for 2030 and the new Soil Monitoring Law. While the strategy provides the political framework for action on soils, the Soil Mission will be an operational arm of the strategy, providing the R&I capacity and creating effective interfaces between research-policy and R&I. The Soil Mission, the EU Soil Strategy and the EUSO mutually reinforce each other and would have limited impact if implemented in isolation.

4.4 | How EU policies can capitalize from research funding?

R&I outcomes are needed to ensure optimal policy development, or eventually adaption, based on robust evidence. However, developing and enforcing sustainable soil management practices and policies is complex

(Helming et al., 2018) in particular since land and soil-related science, policy, and practice communities are often operating in isolation with little synergies (Löbmann et al., 2022). Although soil governance in the EU has gained increasing importance, and it is indirectly addressed in different policy areas (agriculture, water, and climate) (Dazzi & Papa, 2022), the ongoing land degradation processes that are visible across Europe (Panagos et al., 2021) raise the question whether policies are effective enough to face current trends and their possible exacerbation due to climate change.

Implementing research into policy and practice is a key challenge, yet so far, an under-achieved objective. Undoubtedly, much of this hinges on the actions of policymakers, but soil scientists should acknowledge their responsibility to build strategic relationships with them to support policy delivery, while considering new ways of engaging public consciousness about the challenges facing soils. Increased stakeholder engagement, multi-actor, inter-disciplinary and multi-scale operational R&I are of crucial importance for overcoming trade-offs and to allow informed decision-making (Löbmann et al., 2022). Innovation for societal impact and innovation with citizens, academics, entrepreneurs, and public administrators as co-designers, co-developers, and co-implementers is a cross-cutting priority in HE (EC, 2022).

4.5 | Global trends

Soil governance in the EU has gained increasing importance. Similarly, there has also been a marked acceleration in the number of national plans and initiatives around the world. For instance, China released in 2016 the national action plan for prevention and control of soil pollution aiming to improve soil quality (Li et al., 2019). By 2021 in the United States, 20 states formalized soil health initiatives through resolutions and laws by 2021(Gelardi et al., 2023). Similarly, Australia's first national policy on soil was released in 2021 (DAWE, 2021). Those initiatives highlight the importance of science and technology advancement, encouraging R&I.

There is a large increase in the number of soil science journals and publications. The average rate of increase is about 1900 papers per year (from 15,000 soil papers in 2003, to over 42,000 papers in 2018) (Hartemink, 2019). Although the number of papers from the United States increases annually and is larger than most countries, the number of papers from China surpasses the United States (Hartemink, 2019). This could be attributed, among other reasons to a greater financial and researcher's support in China (Zhang et al., 2023). Our results show that in the EC there has been an increase in funding for research in soil science. We can assume that the global increase in publications is somehow the result of more funding so the trends that are noticeable over the past 40 years in the EC are comparable to what happens in the world (Heyard & Hottenrott, 2021).

4.6 | Caveats to the analysis

The main problem to implement a systematized review process with research projects is their differences from the scientific literature. CORDIS does not enhance project findability with metadata, and the search tool provided is simple. Nevertheless, this database fulfils the following requirements: (a) results are publicly available; (b) it is a reference database in the research scope; and c) it allows searching using a string similar to the ones used in the selected scientific databases (García-holgado et al., 2020). We may have missed or inappropriately excluded some relevant projects however; a comprehensive and detailed review of all funded soil projects was not an objective of this manuscript. Our results need to be understood as a first attempt to develop a database of soil-related research projects funded by the EU. This can be improved and better refined in the future as the database will be available in the European Soil Data Centre. Looking beyond the descriptive statistics presented here, additional insights could be gained by a closer look at the projects and FP subprograms that supported them, as well as their main characteristics.

While semantic analysis is a powerful tool, the following caveats apply. First, judging the relative importance of the soil themes is not straightforward on the basis of semantic analysis only. Changes in terms could reflect changes in the semantic content or could just be superficial changes, as terms can be subject to some types of academic or political mode (Gokhberg et al., 2022). In the case of soil science, concepts have emerged at different times, often changing in the frequency of their use and their meanings over time (Mizuta et al., 2021). Overall, the analysis shows that thematic areas overlap and interrelate, but no causality can be derived from this. The statistics capture the occurrence and co-occurrence of terms in project descriptions but this does not reflect the semantic dynamics. For that purpose, it is necessary to constitute wider themes by grouping the terms, to analyse the connections between these groupings, and to embed this evidence into a broader knowledge of the corresponding policy developments.

5 | CONCLUSIONS

Europe has a long tradition of scientific excellence and has built a worldwide reputation in research and unlocked its innovation potential in various domains including soil science. The EU has spent around 1 billion Euro for research in soil with more than one thousand projects during the last 40 years. In addition, the Soil Mission, with an unprecedented budget of 1 billion Euro for 7 years will fund R&I in order to protect and restore soils in Europe and beyond. The findings reported here underpin the enormous effort by the EU to support soil research in the past and in the near future.

Soil research funding has evolved over time, depending on external crises in society/environment (e.g., global climate change, food security). Whether soil concepts persist or will be replaced reflects real societal needs and improved scientific understanding. Our results also show that EU-funded soil research has fostered interdisciplinary and transdisciplinary research and increased Europe-wide R&I collaboration and networking. In the future, researchers who successfully secure HE funding are expected to extend the novel breakthroughs they achieve as far and wide as possible in order to take full advantage of their contribution to societal, environmental and economic impacts. To put it simply, if the research and its results do not successfully extend beyond the specific scientific domain, the impact of soil research will be hampered and minimized.

The Soil Mission, with the establishment of 100 living labs and lighthouses will engage with people, create effective partnerships across sectors and territories to protect and restore soils, leading the transition towards healthy soils by 2030. The Soil Mission together with the new Soil Monitoring Law and EUSO form a unique and robust framework to address soil and land stewardship at the necessary scale and pace and across all types of land use and sectors.

AUTHOR CONTRIBUTIONS

Cristina Arias-Navarro: Conceptualization; methodology; investigation; validation; formal analysis; writing – original draft; writing – review and editing; visualization. **Panos Panagos:** Conceptualization; supervision; validation; writing – review and editing; resources; funding acquisition. **Arwyn Jones:** Funding acquisition; project administration; writing – review and editing; supervision; resources. **María José Amaral:** Writing – review and editing. **Annette Schneegans:** Writing – review and editing. **Marc Van Liedekerke:** Writing – review and editing. **Piotr Wojda:** Writing – review and editing. **Luca Montanarella:** Writing – review and editing; supervision; funding acquisition; project administration; resources.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the European Soil Data Centre (ESDAC) at https://esdac.jrc.ec.europa.eu/.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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