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Unravelling the Drivers of Soil Health: A Standardised Typology and Evidence Synthesis Across Europe

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Abstract:

Diverse and dynamic drivers shape European soils, and with most soils considered unhealthy, understanding these drivers is essential for effective soil management. Yet inconsistent terminology and classification across studies limit comparison and synthesis of evidence. This study addresses this gap through a systematic synthesis of 451 studies and an iterative standardisation process involving expert-based classification of soil health drivers, resulting in a standardised typology. The typology groups drivers into six categories: technology and management, nature and environment, demography, policy and institutional arrangements, socio-cultural context, and economy, and provides a basis for examining patterns in driver representation across land use types, locations, and Soil Health Objectives (SHOs) defined by the Horizon Europe Soil Mission. Technology and management drivers, together with climate-related drivers within the nature and environment category, are the most frequently represented across agriculture, forest, nature, and urban land uses. The evidence base is geographically uneven, revealing where research attention has concentrated across Europe: Mediterranean countries are strongly represented, while Baltic, Balkan, and Eastern European countries remain comparatively underrepresented. Driver categories are also shown to interact rather than operate in isolation. For example, policy instruments such as the Nitrates Directive have stimulated the development and adoption of fertiliser recovery and replacement technologies, illustrating how institutional drivers can influence technological and management responses relevant to soil health. By providing a standardised typology and evidence map, this study reduces conceptual fragmentation, identifies concrete regional and thematic gaps, and provides an empirical basis for more integrated soil health research, monitoring, and governance.

Keywords:
Soil health; Soil health drivers; Typology; Evidence synthesis; Land use; Soil Health Objectives; Climate change; Soil management

Highlights:

- Developed a standardised typology of soil health drivers from 451 studies.
- Six driver categories support consistent analysis across European contexts
- Technology and management and climate-related drivers dominate the evidence base.
- Mediterranean region is strongly represented, while Baltic, Balkan, and Eastern Europe remain underrepresented.
- Interactions among driver categories highlight the need for integrated soil-health assessment and management.

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1 Introduction

Land use in Europe has gone through major transformations throughout the centuries. As one of the most intensively used continents, Europe´s landscape has been shaped by a long interplay of human activities, with around 80% of the continent's land surface bearing the mark of human interventions in the forms of agricultural use, industrialisation, and urbanisation (EEA, 2024a, 2024b). Such continuous use of the surface has strained the health of the soil below, with an estimated 60–70% of soils considered degraded (ESDAC, 2024). Soil is a fragile resource that needs to be carefully managed and safeguarded for future generations. That is why the EU Soil Strategy for 2030 ("COM(2021) 699 final," 2021) provides the framework and concrete steps towards protecting and restoring soils, and ensuring that they are used sustainably. Following the concrete set-up by the strategy and the soil mission (Panagos et al., 2024), the soil monitoring law was adopted in 2025 to establish soil health targets up to 2050 and introduce a comprehensive system for soil monitoring and assessment ("Soil Monitoring Law," 2025). It applies to all soils: in forests, agricultural land, urban areas, and natural areas, providing a legal framework to help achieve healthy soils by 2050.

Land use in Europe has undergone profound transformations over many centuries, and the pattern and intensity, as well as the triggers behind such changes, have varied throughout (Jepsen et al., 2015; Kuemmerle et al., 2016). Today, land use continues to change, and so do the driving forces behind the changes, and they can have varied implications for soil health. Understanding the underlying drivers of land use change is therefore integral in ensuring the effective integration and adaptation of soil-related policies to achieve the targets for healthy soil (Bouma et al., 1998). The DPSIR (Drivers, Pressures, States, Impacts, and Responses) framework adapted for land use and soil management offers a structured way to do this by linking drivers and their effects on soil health, and thus, helping to design responses to guide soil health towards the desirable state (Chowdhury et al., 2025; Lewison et al., 2016). Soil health in Europe is not only tied to the biophysical processes but also to a wide array of socio-economic forces shaping the use and management of the soil and land resources (Bouma et al., 1998; Chowdhury et al., 2025). Because these forces interact across scales, identifying and categorising drivers provides the necessary structure to analyse their combined effects. Without such classification, soil-related research remains fragmented, and producing targeted output for policy integration remains difficult. Beyond identifying individual drivers, understanding how research attention is distributed across drivers, locations, and soil-health dimensions can reveal important patterns in the production of knowledge and highlight areas where evidence remains limited.

To support the vision of healthy soils in the EU by 2050, this study combines the development of a standardised typology of drivers with an analysis of how these drivers are represented across European contexts, land use types, and Soil Health Objectives (SHOs). This approach not only supports the harmonisation of driver terminology but also enables an examination of patterns in how different drivers are emphasised across countries, land uses, and soil health dimensions. This, in turn, allows researchers and decision-makers to distinguish between direct and indirect influences, long-term trends and short-term triggers, and global forces versus context-specific conditions. Categorisation also improves communication across scientific fields by harmonising terminology that is often used inconsistently in the literature. To build such understanding, a comprehensive review of the relevant literature was undertaken following the PRISMA protocol. Since drivers are not often directly addressed in the literature, this study required periodic standardisation of driver terminology throughout the data collection and analysis process. This methodological process underpins the development of a standardised typology of drivers, capturing the range of

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demographic, economic, socio-cultural, institutional, natural, and technological factors that influence soil health.

Despite extensive research on drivers of soil and land-use change, no harmonised framework currently exists for systematically classifying and comparing soil-health drivers across diverse contexts. By establishing a structured and standardised overview of the drivers affecting soil health in the EU, this study attempts to clarify existing conceptual ambiguities, highlight areas of insufficient or inconsistent evidence, and provide a basis for further analysis of their implications for soil and land management. Rather than focusing on narrowly defined quantitative evidence for a single topic, this approach supports a more integrated understanding of soil health as a product of interconnected human, economic, environmental, and technological dynamics. By mapping patterns in driver representation across regions, land uses, and SHOs, the study identifies not only knowledge gaps but also areas where scientific attention has concentrated, providing insight into current priorities and blind spots in European soil-health research.

2 Methods

2.1 Systematic literature review

A systematic literature review was conducted following the PRISMA protocol (Page et al., 2021). The review was undertaken across four land use categories: agriculture, forest, nature, and urban and industrial land use. Separate working groups using harmonised standards for publication period, database selection, language, and geographic scope carried out data collection in parallel. The review focused primarily on peer-reviewed literature indexed in Scopus and published between 2010 and 2023, with limited inclusion of relevant grey literature where appropriate.

Following title, abstract, and full-text screening according to predefined eligibility criteria, 451 studies were retained for analysis. Studies were required to address factors influencing current or future changes in use, management, or intensity of soil and land resources and to provide information relevant to soil health, linked specifically to SHOs. Detailed search strategies, screening criteria, and PRISMA workflows are reported in Chowdhury et al. (2024b).

2.2 Analytical framework and driver classification

The review was structured around the DPSIR (Drivers, Pressures, State, Impact, Response) framework, adapted to the context of soil health in the European Union (Chowdhury et al., 2025; Chowdhury et al., 2024b). In this adapted model, the ´states´ represent SHOs, including eight mission objectives ("COM(2021) 699 final," 2021) and soil biodiversity, while ´drivers´ are understood as the underlying forces influencing the use and management of soil and land.

Drivers were rarely identified explicitly in the reviewed literature and therefore required interpretative identification through qualitative coding. The substantive categorisation of drivers drew on existing classifications proposed by van Vliet et al (2015) and Mitter et al. (2020), which provided the initial basis for coding and the resulting six categories: Technology and Management, Nature and Environment, Demography, Policy and Institutional Arrangements, Socio-cultural Context, and Economy. An initial list of candidate drivers was established prior to the review to guide extraction and classification. As coding progressed, the classification was refined iteratively to accommodate drivers not represented in the source frameworks.

Given the interpretive nature of driver identification, classification relied on the collective judgement of subject-matter experts across the four land-use working groups rather than on formal inter-coder reliability testing. This approach prioritised domain expertise and contextual interpretation over

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statistical consistency measures, which we consider appropriate for a first standardisation of a fragmented and inconsistently reported evidence base, while acknowledging that the resulting typology reflects expert judgement rather than a fully reproducible coding protocol. Divergences in classification were resolved through iterative discussion in the standardisation workshops described in Section 2.3, rather than through quantitative agreement metrics.

2.3 Data standardisation and synthesis

Because data collection was conducted independently across four land use groups, a multi-stage standardisation process was implemented to ensure consistency in terminology, interpretation, and categorisation. Recurring online and in-person standardisation workshops were held throughout the review process to reconcile differences in driver definitions, resolve overlaps between categories, and establish a common classification framework. This standardisation process reconciles independently coded classifications from separate land use working groups through structured expert deliberation. This is an important methodological component of this study, developed to accommodate the scale and interdisciplinary breadth of the review within the time and resource constraints of a large multi-partner EU research project.

The resulting standardised typology was subsequently applied to all studies. Each study was linked to the identified drivers, geographic locations (primarily at NUTS0 level), land use types, and SHOs based on the Horizon Europe Soil Mission. The dataset was then used to analyse patterns in driver representation across locations, land uses, and SHOs. Detailed methodological procedures, coding protocols, and the complete dataset are available in Chowdhury et al. (2024).

2.4 Limitations

The literature review was conducted using a specific database and keyword set; other databases, particularly for grey literature, were not considered, which could have resulted in a different and larger set of studies. The review was conducted separately across four land use types, and although search keywords and filtration criteria followed a shared data collection protocol, some variation existed between working groups.

Driver identification relied on interpretive qualitative coding rather than formal inter-coder reliability testing, with consistency instead achieved through iterative discussion in standardisation workshops. Given the scale and interdisciplinary breadth of the review, this expert-based approach was prioritised over more resource-intensive statistical validation procedures. Geographic information was harmonised primarily at country level, enabling consistent comparison across Europe. This approach supports the identification of broad patterns in driver representation but does not capture all regional variability reported in the literature.

3 Results

A total of 451 studies were analysed at the full-text level to identify drivers influencing soil health. The drivers are categorised into six groups based on the frameworks by van Vliet et al (2015) and Mitter et al. (2020): technology and management, nature and Environment, Policy and Institutional Arrangement, Demography, Socio-cultural contexts, and Economy. Within each category, drivers are structured into more encompassing generic drivers and more precise specific drivers. Table 1 presents the complete list of drivers.

Three characteristics are associated with the identified drivers: geographic context (location), land use type, and soil health parameters. The geographical scope includes EU Member States (EU27) as well as other mainland European countries (Switzerland, Norway, Albania, Serbia, Bosnia and

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Herzegovina, and North Macedonia). While many studies are location-specific, a considerable proportion address drivers at broader spatial scales, referring to the EU, Europe, or other regions defined by geographic, environmental, or climatic characteristics. The literature review focuses on four land use types: agriculture, forest, nature, and urban (including industrial areas), following the classification applied by Nougues & Brils (2023) for the EU Soil Mission Support Project. Soil health parameters are defined according to the SHOs of the EU Soil Mission (EC, 2021). These extend beyond biophysical indicators to include land-related parameters (land degradation), soil characteristics (soil organic carbon, soil biodiversity, soil structure), soil threats (soil erosion, soil pollution, soil sealing), and socio-economic dimensions (EU global footprint on soil, soil literacy). Figure 1 shows the distribution of driver categories and their links to SHOs in the geographic context.

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Table 1: Consolidated typology of drivers influencing soil health, structured into six categories (technology and management; nature and environment; policy and institutional arrangements; demography; socio-cultural contexts; and economy). Within each category, drivers are organised into generic and specific drivers to preserve the hierarchical structure identified in the literature. Technology and management drivers are further grouped into thematic domains (management and planning; soil amendments and machinery; waste and pollution; and water), while policy and institutional drivers are classified according to governance scale (global, EU, and national). The table presents the complete list of drivers identified across the reviewed studies.

Driver category	Generic drivers	Specific drivers
Technology and management		
	Adoption of nature-based solutions for climate change mitigation (Sustainable practices)	Management and planning: Adoption of digital platforms for soil health monitoring and information sharing; Soil amendments and machinery: Advancement and adoption of precision agriculture technologies; Waste and pollution: Advancement of waste management practices; Water: Advancement in the monitoring and management of water resources
	Advances in tools and models for soil monitoring and land management	Management and planning: Advancement in artificial surfaces; Advancement in remote and proximal sensing and imaging; Soil amendments and machinery: Advancement and adoption of efficient fertiliser replacement and recovery technologies; Promotion and acceptance of the use of organic fertiliser, treated sludge and wastewater; Waste and pollution: Advancement in monitoring and management of contaminated sites
	Current land management practices	Management and planning: Current soil management practice during construction; Soil amendments and machinery: Use of fertiliser; Frequency and timing of machinery use; Increased size of machinery; Waste and pollution: Current waste management practices; Current management and regulations about contamination and contaminated sites; Emerging novel pollutants (micro- or nano-plastics); Research and implementation of soil remediation techniques on contaminated sites; Water: Increasing demand for water
	Recognition of the need and progress towards standardisation of soil health indicators	Cross-cutting: Promotion and integration of ecosystem services in spatial planning; Promotion and integration of resilience building through spatial planning
	Recognition of the need for efficient spatial planning strategies across all land uses	Management and planning: Recognition of monetary benefits of ecosystem services in spatial planning; Promotion and integration of green infrastructure in urban and industrial areas; Cross-cutting: Promotion and integration of improved soil sealing and stabilising strategies
Nature and environment	Climate change	Sea level rise; Shift in precipitation, temperature, and wind patterns; Decreased precipitation; Increased precipitation; Increased temperature; Prolongation of the growing season due to a warming climate
	Extreme weather	
	Invasive species	
	Abiotic factors	
Demography	Aging	Decline in active labour in agriculture; Changes in ownership and tenure
	Migration	Declining rural population; Decreasing population density in rural areas; Internal migration
	Increasing population	
	Household size and per-capita land consumption	

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Policy and institutional arrangements	Laws or regulations regarding sustainable development	Global: Sustainable Development Goals (SDG); EU: European Green Deal (including circular economy action plan); Renewable Energy Directive (EU) 2023/2413
	Laws or regulations regarding climate	Global: COP26 Glasgow Climate Pact; EU: European Climate Law 2021/1119; Industrial Emissions Directive; National: Renewable Energy Act (German: EEG); Stratégie Nationale Bas-Carbone 2020 (France)
	Laws or regulations regarding waste and pollution	Global: United Nations Environmental Program (UNEP), Society of Environmental Toxicology and Chemistry (SETAC); EU: Zero pollution action plan; Sewage sludge directive; Urban wastewater directive; Water Framework Directive; Strategic Approach to Pharmaceuticals in the Environment COM/2019/128 final
	Laws or regulations regarding conservation	EU: Biodiversity strategy for 2030; Birds Directive 2009/147/EC; Habitats Directive 92/43/EEC; Nature Restoration Law 2022/0195; National: Spanish Forest Plan
	Laws or regulations regarding agriculture	EU: Common Market Organisation regulation for wine production (CE 555/2008); Nitrates Directive 91/676/EEC; Common Agricultural Policy (CAP); Common Agricultural Policy (CAP) - Pillar 1 support payments and trade liberalisation; Common Agricultural Policy (CAP) - Pillar 2 Natura 2000; National: German Fertiliser Ordinance
	Laws or regulations regarding soil and land	Global: UNCCD's Land Degradation Neutrality Programme; EU: EU soil strategy; Proposed EU soil monitoring law 2023/0232; Reform of the Landfill directive; Horizon Europe soil mission - funding for research
	Combined effect of Global, EU, and National measures	
	Research demands by the European Commission (EC)	
	Conflicts between regional and local policies	
	Unspecified laws. Regulations and strategies	
Socio-cultural contexts	Increasing societal demands for food security	Increased interest in urban agriculture
	Increasing awareness and literacy of soil-based ecosystem services	Growing concerns about soil health in industrial and urban areas; Participatory decision-making for land use planning and management; Need for soil-related policies to reflect the need for societal demand.
	Land managers' attitudes and willingness	
	Lack of knowledge transfer between scientists and stakeholders	
	Changes in consumption patterns and demand	
Economy	Increasing demand for renewables	Increasing demand for bioenergy; Increasing demand for solar energy; Emerging carbon markets
	Market pressure and volatility	Market volatility; Decreasing market price; Increasing market price
	Expansion of built-up areas	Urbanisation; Increasing demand for industrial areas; Non-favourable economic conditions in rural areas; Expansion of rural settlements
	Historical mining	
	Armed conflicts	
	Improved access to the global market	
	Increasing demand for tourism and recreational use	
	Increasing demand for food	

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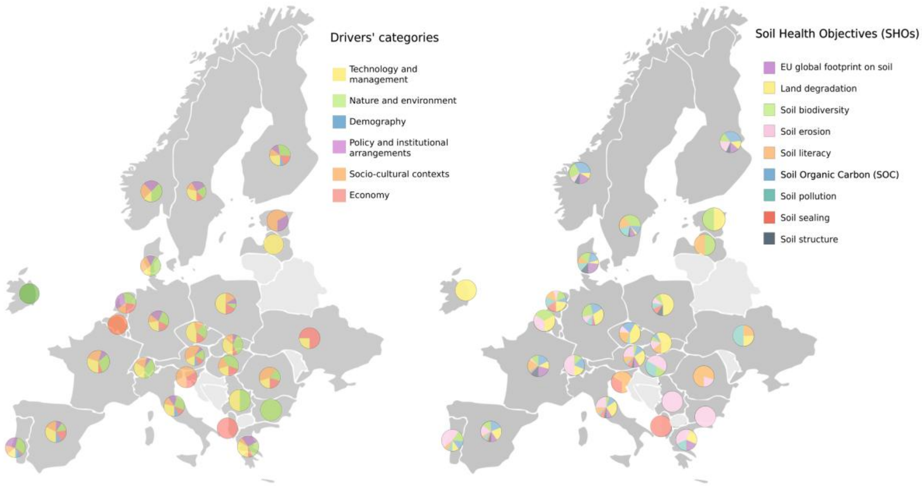

Figure 1: Spatial distribution of driver categories and Soil Health Objectives (SHOs) across the study region. Left: Distribution of the six driver categories; Right: Distribution of SHOs. Pie charts represent the relative contribution of categories and SHOs at each location, based on the number of studies. Colours correspond to the categories and SHOs indicated in the legend.

The analytical framework is structured to preserve the hierarchical nature of the identified drivers. In particular, Technology and Management drivers are further organised into thematic domains (management and planning; soil amendments and machinery; waste and pollution; and water), while Policy and Institutional Arrangement drivers are distinguished by governance scale (global, EU, and national). This structuring maintains the analytical depth of the original data while enabling synthesis across categories. The detailed methodology and data analysis protocol are summarised in the Methods section. The systematic review process and compiled dataset are presented in Chowdhury et al. (2024b), with full data availability through the BonaRes Repository (2024a).

The following six subsections provide an in-depth analysis of each driver category. Each subsection first presents the standardised set of drivers (generic and specific), followed by an analysis of their associations with location, land use, and SHOs. To support interpretation, three types of visualisations are used. Sankey diagrams (Figures 2–7, top panels) illustrate the distribution and relative contribution of drivers across locations, with flow thickness proportional to the number of associated studies. Bar plots (Figures 2–7, middle and bottom panels) show the distribution of drivers across land use types and SHOs, respectively. In these plots, segment size represents the number of studies, the x-axis indicates study counts, and colour coding links drivers consistently across all visualisations.

Individual studies may be associated with multiple drivers across different categories, and drivers may simultaneously relate to multiple geographic contexts, land uses, and SHOs. The underlying dataset, available via the BonaRes Repository (2024a), provides detailed attribution at the study level.

3.1 Technology and management

Technology and management drivers refer to the use of existing and the need for or adoption of efficient and nature-based knowledge, tools, models, and strategies for soil use and land management. There are five generic drivers in the technology and management drivers category,

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with specific drivers grouped within the four thematic domains: management and planning, soil amendments and machinery, waste and pollution, and water (see Table 1 for the full list).

This category is the most represented in the dataset (n = 186) and is consistently identified as highly influential across Europe (n = 86) and at the EU level (n = 27) (Figure 2, top). At the national scale, Spain shows the highest number of associations (n = 29), followed by Italy (n = 14), Germany (n = 12), and France (n = 7). Across studies, the adoption of nature-based solutions for climate change mitigation (sustainable practices; e.g. cover crops, reduced tillage) is the most frequently identified driver (n = 75), particularly in Mediterranean regions. Advances in tools and models for soil monitoring and land management also feature prominently (n = 68), alongside current land management practices (n = 65). Additional drivers include the recognition of the need and progress towards standardisation of soil health indicators (n=27) and efficient spatial planning strategies across all land uses (n=28).

Agriculture is the most associated land-use (n = 90), with studies linking it to all major drivers, particularly adoption of nature-based solutions for climate change mitigation (n = 60) and advances in tools and models for soil monitoring and land management (n = 42) (Figure 2, middle). Urban land use (n = 41) is primarily associated with the drivers related to waste and pollution, and management and planning. Forest land use (n = 32) is mainly linked to current land management practices (n=20) (e.g. use or size of the machinery). Nature land uses show the lowest association (n = 23), with a stronger focus on current land use practices than on technological innovation.

Technology and management drivers are broadly linked to all SHOs (Figure 2, bottom). Soil pollution (n = 40) and soil literacy (n = 36) are most frequently addressed, though through different drivers: pollution is primarily associated with current land management practices, while soil literacy is driven by advances in tools and models for soil monitoring and land management (n=21). These two drivers also play a prominent role in land degradation, soil organic carbon, soil biodiversity, and erosion. The least associated SHOs are soil sealing (n=7), followed by soil structure (n=9).

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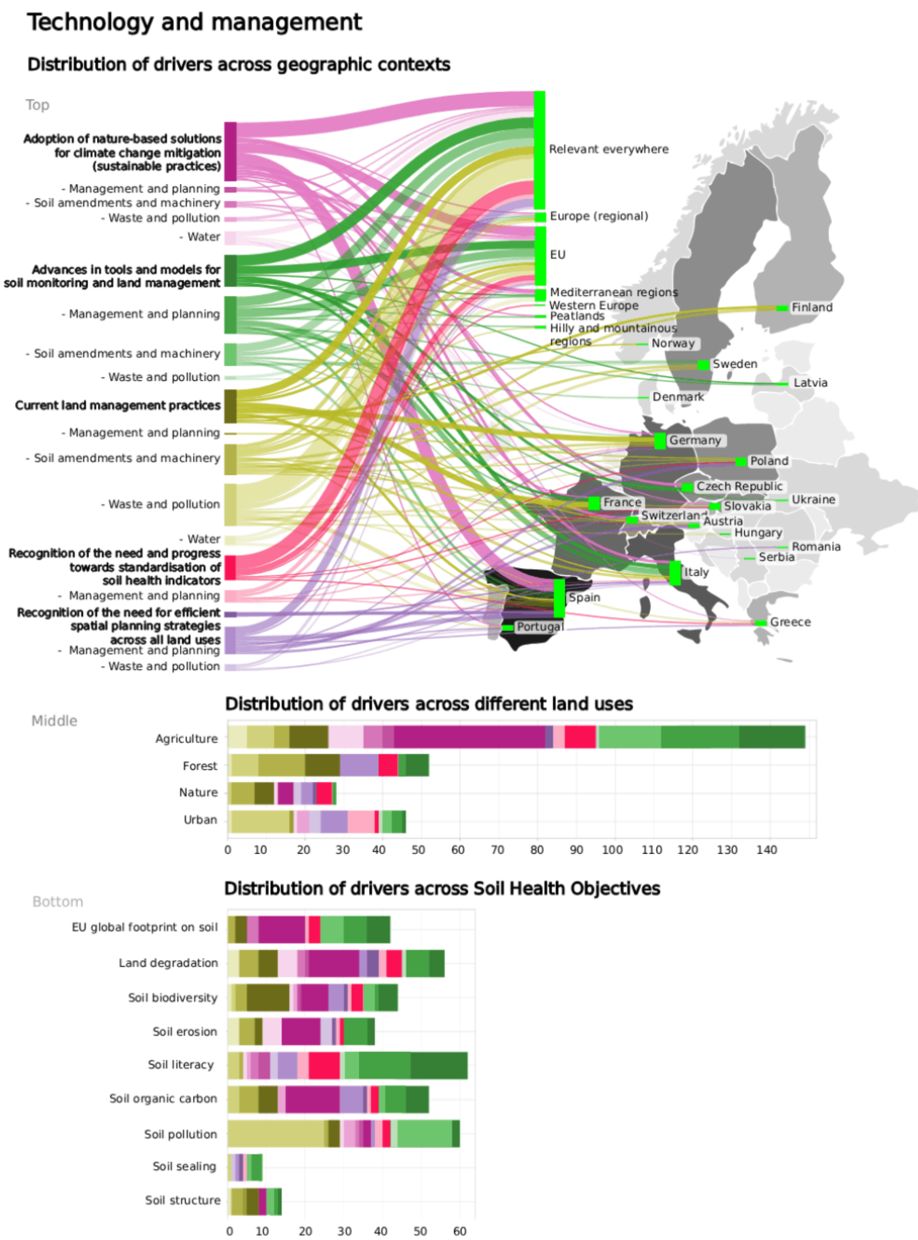

Figure 2: Distribution of technology and management drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Technology and management drivers are further organised into four thematic domains (management and planning; soil amendments and machinery; waste and pollution; and water). Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

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3.2 Nature and environment

Nature and environmental drivers include climate-related processes and biophysical factors affecting soil systems (see Table 1 for the full list). This category is highlighted by 144 studies, and climate change and the associated specific drivers account for the vast majority of studies (n = 139) (Figure 3, top). Among the specific drivers of climate change, shifts in precipitation, temperature and wind patterns (n = 60) and extreme weather events (n = 33) are the most explored. These drivers are consistently identified as globally relevant, with strong regional expression in Mediterranean countries. Prolongation of the growing season (n=3), however, is linked to the countries exclusively in the north, Sweden (n=2), Finland (n=3), Denmark (n=2), and Norway (n=2). Studies explore sea level rise (n=3) in relation to soil and land use change and their impacts on soil health, with the Netherlands being the only member state individually linked. Other specific drivers, invasive species and abiotic factors are comparatively underexplored.

Natural land use shows the strongest association with this category of drivers (n = 86), followed by agriculture (n = 46), reflecting the direct exposure of these land uses to climatic variability (Figure 3, middle). Forest and urban land uses are less frequently studied, with most attention focused on climate change as well. Nature and environment drivers are most strongly associated with land degradation (n = 44), soil erosion (n = 38), and soil organic carbon (n = 30) Figure 3, bottom). Soil biodiversity is uniquely linked to invasive species, while abiotic factors are linked to land degradation and soil literacy as well. Other objectives, particularly soil structure and pollution, are less frequently addressed within this category.

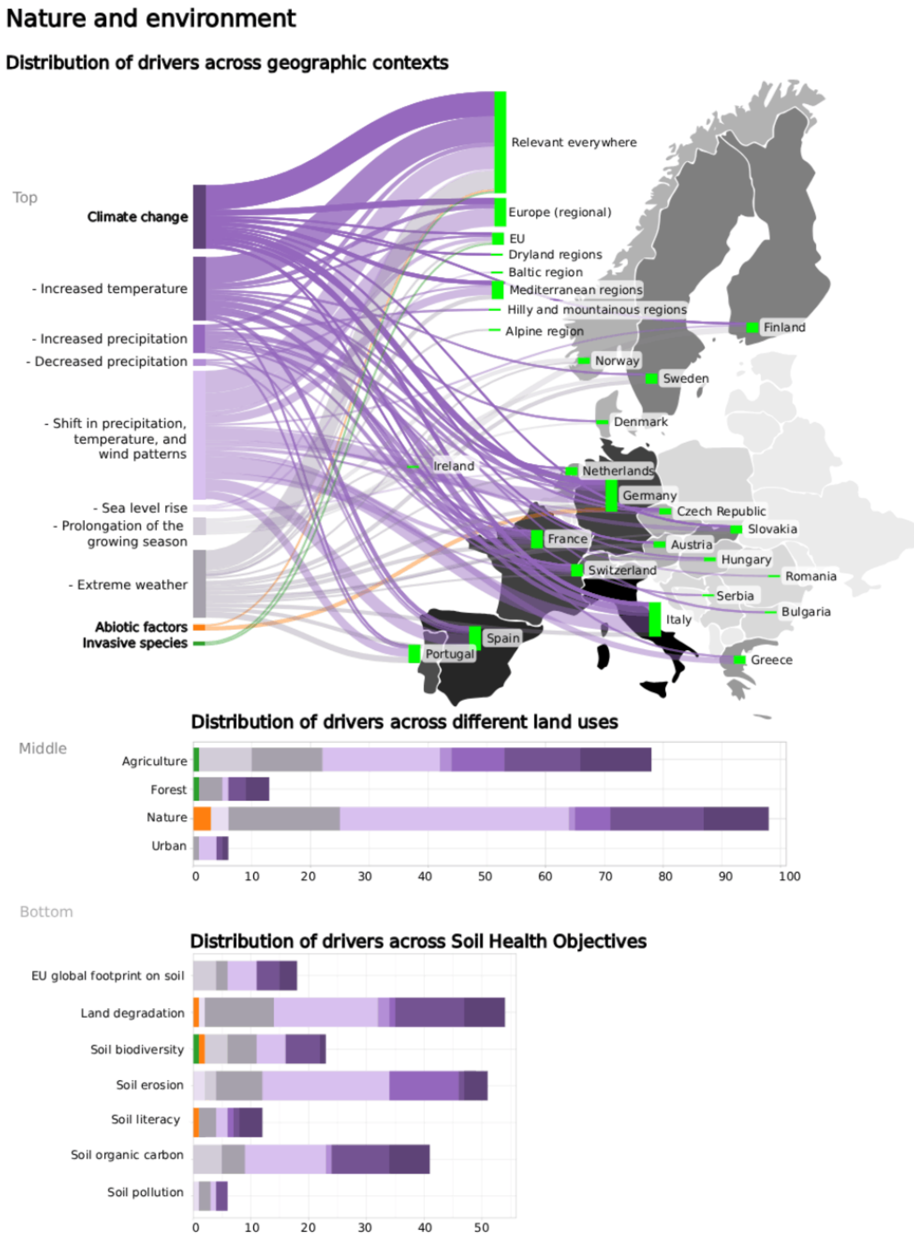

Figure 3: Distribution of nature and environment drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Drivers are presented as generic categories with grouped specific drivers. Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

3.3 Demography

Drivers in the demography category include population size, age, structure, and growth, all of which can influence the use of soil and land and, consequently, soil health (see Table 1 for the full list). Overall, this category is less represented than other categories (n = 40), but still reveals clear and contrasting spatial trends (Figure 4, top). Increasing population (n = 21) is the most frequently identified driver and is often framed as a broadly relevant influence across Europe. In contrast, migration (n = 15) and the associated specific drivers, particularly declining rural population, are strongly linked to Mediterranean regions, highlighting a dual dynamic of urban growth and rural decline. Ageing (n = 5) is less frequently studied but is associated with structural changes in land use and soil management, agricultural labour, and land tenure.

Agricultural land use dominates the evidence base (n = 24) and is linked to all demographic drivers except household size and per-capita land consumption, as the corresponding studies associate this driver primarily with urban land use (Figure 4, middle). Urban land use (n = 3) is further associated with population increase and migration, which are the only two drivers linked to natural land use (n = 9). Nature (n = 9) and forest (n = 4) land use are less represented, while urban land use (n = 3) is mainly associated with population increase and migration. Forest land use (n = 4) is associated with both population increase and ageing.

Demographic drivers are most frequently associated with land degradation (n = 12) and soil erosion (n = 7), reflecting the effects of both intensification and land abandonment (Figure 4, bottom). Population increase is the only driver linked to soil biodiversity and the EU global footprint on soil, while migration and ageing are more closely associated with soil erosion. Other SHOs, including soil structure, soil sealing, and soil pollution, are weakly represented, and no studies explicitly link demographic drivers to soil literacy.

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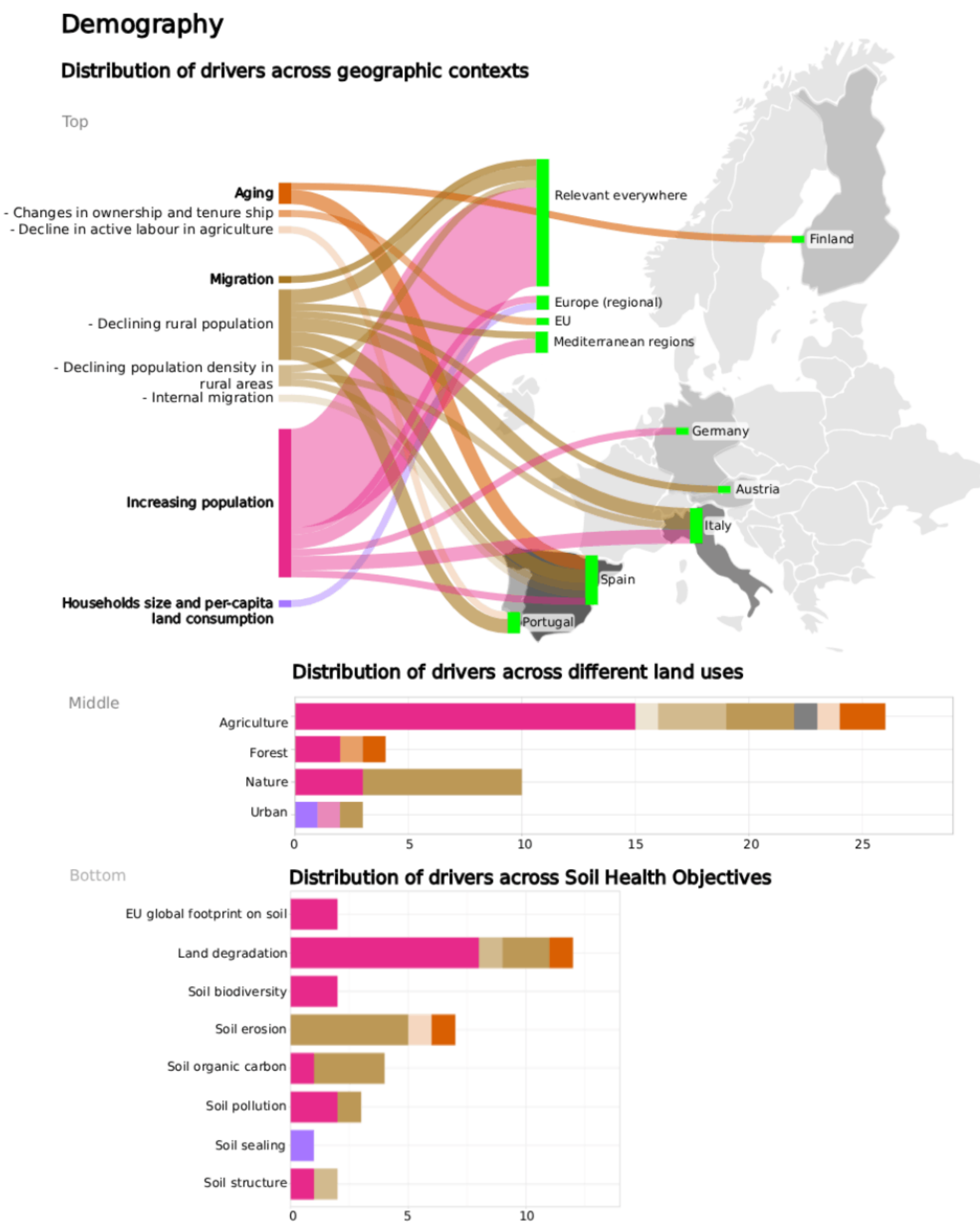

Figure 4: Distribution of demography drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Drivers are presented as generic categories with grouped specific drivers. Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

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3.4 Policy and institutional arrangements

Policy and institutional drivers encompass regulatory frameworks, governance structures, and their interactions across scales. To provide context for the numerous drivers identified in this category, generic drivers are further subdivided according to governance levels (global, EU, and national) (see Table 1 for the full list). This category (n = 94) reflects the strong influence of EU-level strategies, agreements, conventions, laws, and regulations on soil and land use in the region (Figure 5, top). Most prominently, laws and regulations regarding agriculture, particularly the Common Agricultural Policy (CAP) and the Nitrates Directive, are the most frequently cited drivers (n = 39), studied both at EU level and across Member States, especially Germany, Spain, Portugal, and Italy. In parallel, laws and regulations regarding soil and land (n = 15) and global initiatives such as the UNCCD's Land Degradation Neutrality programme (n = 3) are also identified as influential. Broader governance frameworks further emerge, including laws and regulations regarding sustainability (SDGs, n = 12; EU-level, n = 14), climate, waste and pollution (n = 13), and conservation (n = 8), all contributing to soil health outcomes across multiple scales. Several studies (n = 7) highlight interactions between global, EU, and national laws and regulations, often identifying synergies, while a smaller number (n = 2) point to conflicts between governance levels. Overall, Germany (n = 9), Italy (n = 8), and Spain (n = 6) are the most frequently examined national contexts within this driver category.

Agricultural land use dominates this category (n = 54), reflecting the central role of policy in shaping decision-making in the sector (Figure 5, middle). It is most strongly associated with laws and regulations regarding agriculture, followed by laws and regulations regarding sustainability, waste and pollution. Notably, all studies addressing conflicts between regional and national policies, as well as most studies focusing on laws and regulations regarding climate, also link these drivers to agricultural land use. Nature land use (n = 27) is also strongly influenced by conservation and sustainability policies, with relatively balanced attention across laws and regulations regarding agriculture, soil and land, and sustainable development. Urban land use (n = 13) is primarily associated with laws and regulations regarding soil, land, waste and pollution, while forest land use (n = 3) is mainly linked to laws and regulations regarding agriculture.

Policy and institutional arrangements drivers are most strongly associated with land degradation (n = 26), followed by soil pollution (n = 17) and soil biodiversity (n = 16) (Figure 5, bottom). Laws and regulations regarding agriculture are linked to all SHOs, while other drivers show more specific associations (e.g. soil and land to soil literacy and land degradation, climate to the EU global footprint on soil, conservation to soil biodiversity, and waste and pollution to soil pollution). Soil structure is the least represented (n = 3), and no driver is explicitly linked to soil sealing.

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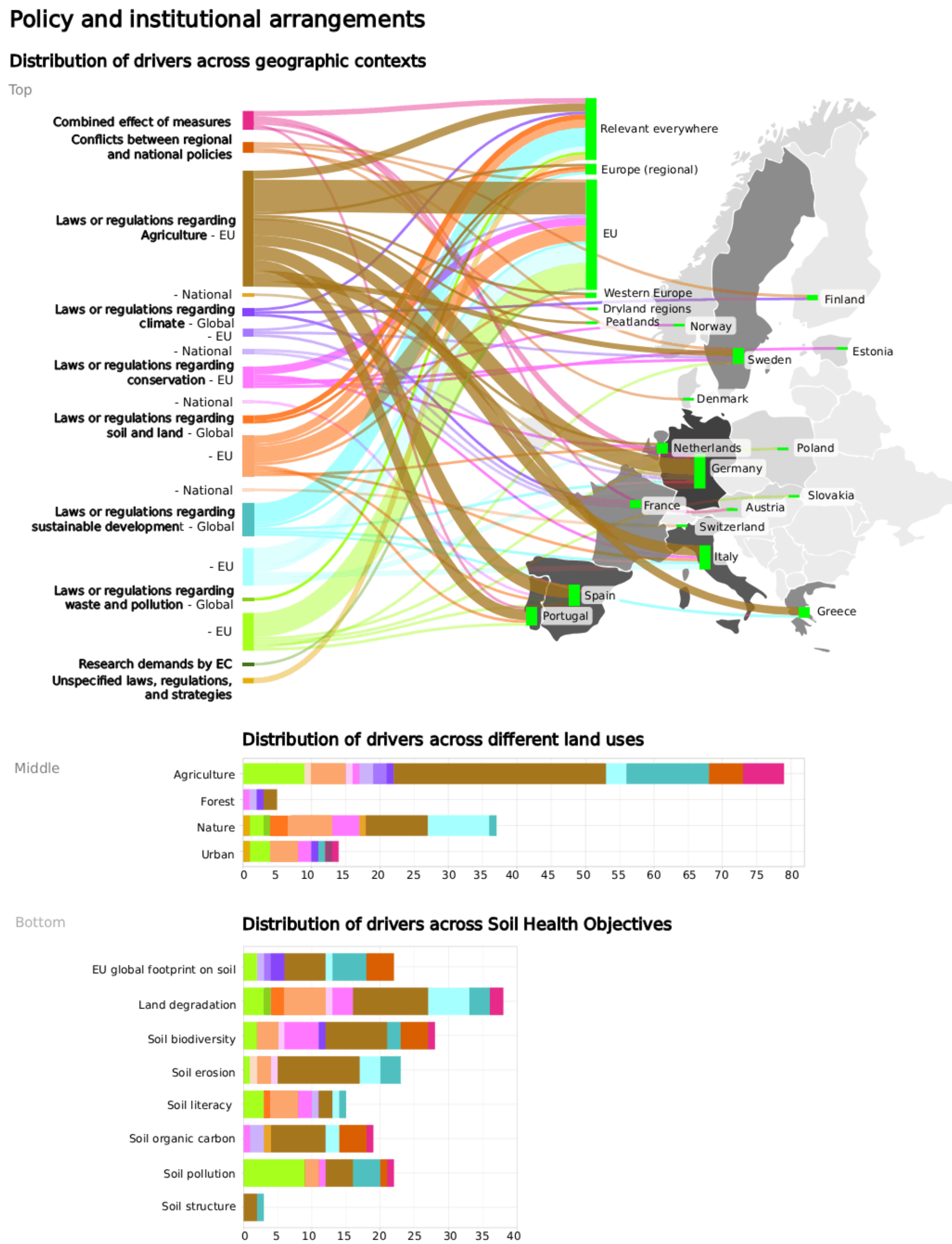

Figure 5: Distribution of Policy and institutional drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Policy and institutional drivers are classified according to governance scale (global, EU, and national). Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

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3.5 Socio-cultural contexts

The socio-cultural contexts category of drivers encompasses societal values, behaviours, and perceptions that shape land use decisions and soil management practices. This category (n = 92) highlights the growing importance of behavioural and knowledge-based influences on soil health (see Table 1 for the full list). Changes in consumption patterns and demand are the most dominant driver (n = 63), with widespread relevance across Europe and a significant influence in Spain (n = 10), followed by Germany (n = 7), France (n = 5), Italy (n = 5), and Austria (n = 3) (Figure 6, top). A small number of studies (n = 3) also highlight the increasing demand for food security. Increasing awareness and literacy of soil-based ecosystem services (n = 19) and land managers' attitudes and willingness (n = 12) further shape decision-making processes for future land use and soil management. At the same time, the lack of knowledge transfer between science and practice (n = 10) illustrates barriers to effective knowledge-based decision-making. A large share of studies link this driver to Spain (n = 4), followed by Austria (n = 3), with some studies establishing broader relevance across Europe (n = 2) and at the EU level (n = 1).

Nature land use shows the strongest association (n = 51), particularly linked to changes in consumption patterns and demand. Agriculture (n = 28) is connected to all drivers in this category, while forest (n = 7) and urban land use (n = 5) are less represented (Figure 6, middle). Urban land use is mainly associated with awareness and knowledge-related drivers. Changes in consumption patterns and demand are the most frequently referenced driver for three SHOs: land degradation (25 out of 30), soil biodiversity (12 out of 14), and soil organic carbon (SOC) (11 out of 12) (Figure 6, bottom). Soil literacy (n = 14) is primarily influenced by increasing awareness and literacy of soil-based ecosystem services and land managers' attitudes and willingness. Soil sealing, soil structure, and soil pollution are minimally represented within this category.

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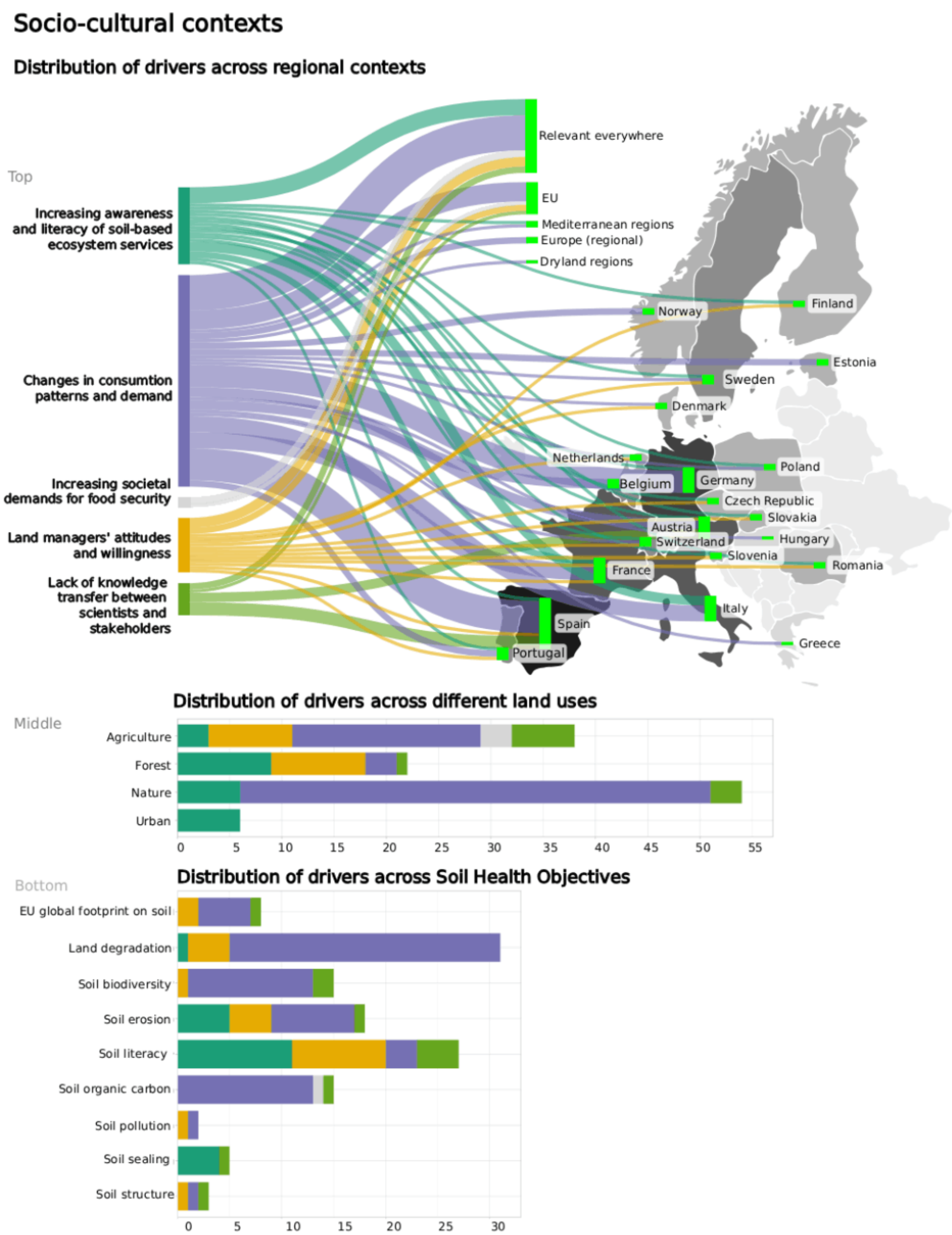

Figure 6: Distribution of socio-cultural contexts drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Drivers are presented as generic categories with grouped specific drivers. Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

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3.6 Economy

Economic drivers refer to current or changing demand, market dynamics, and growth-driven processes that influence the use of soil and land resources and, consequently, soil health (see Table 1 for the full list). This category is widely represented (n = 95) and is well distributed across EU Member States (Figure 7, top). The most prominent drivers include expansion of built-up areas (n = 28), increasing demand for food (n = 26), market pressure and volatility (n = 26), and increasing demand for renewables (n = 24). At the country level, Spain (n = 13) and Germany (n = 10) are the most frequently examined, although with different dominant drivers (market pressure and volatility in Spain; increasing demand for food in Germany). While market pressure and volatility, increasing demand for renewables, and expansion of built-up areas show broad relevance across multiple Member States, other drivers—such as historical mining and improved access to global markets—are more spatially specific, and armed conflicts are primarily associated with Ukraine and active conflict zones.

Agricultural land use is most strongly affected (n = 52), with all major economic drivers represented (Figure 7, middle). Urban land use (n = 22) is dominated by the expansion of built-up areas, while nature land use (n = 13) is more closely linked to increasing demand for food. Forest land use shows more limited (n = 10) but diverse associations, including market pressures and tourism demand.

The relationship of these drivers with soil health is highly specific to certain SHOs (Figure 7, bottom). Soil sealing (n = 12) is exclusively linked to the expansion of built-up areas, which connects to all SHOs except the EU global footprint on soil. Soil erosion, although less studied (n = 10), is linked to all economic drivers except armed conflict, while soil structure and soil literacy are associated only with market pressure, volatility and expansion of built-up areas. In contrast, land degradation (n = 23) is the most connected SHO, linked to all economic drivers, particularly increasing demand for food and increasing demand for renewables. These two drivers are also prominent across the EU global footprint on soil, soil biodiversity, soil organic carbon, and soil pollution, with soil pollution being the only SHO linked to historical mining.

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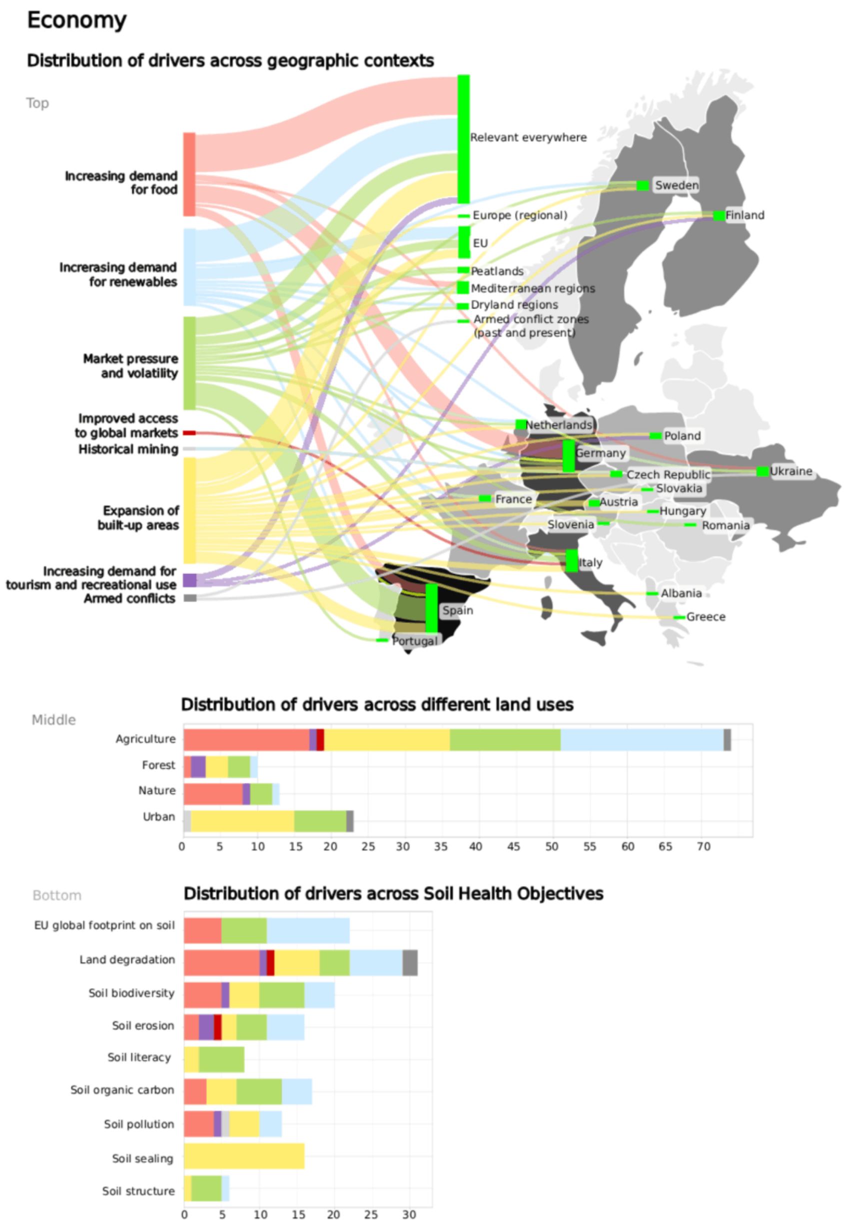

Figure 7: Distribution of economy drivers across geographic contexts, land use types, and Soil Health Objectives (SHOs). Drivers are presented as generic categories with grouped specific drivers. Sankey diagrams (top) illustrate the distribution and relative contribution of drivers across geographic contexts, including global, EU, regional, and country-level locations. The thickness of the flows is proportional to the number of studies associating each driver with the corresponding location. Bar plots (middle) show the distribution of drivers across land use types. Segment size represents the number of studies, and the x-axis indicates study counts. Bar plots (bottom) present the distribution of drivers across SHOs. Colour coding is consistent across all panels and links drivers between the Sankey diagrams and the bar plots. Individual studies may be associated with multiple drivers, locations, land-use types, and SHOs.

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4 Discussion and conclusions

4.1 Dominant soil health drivers across Europe

This study develops a standardised typology of soil health drivers by synthesising evidence from 451 studies spanning diverse geographic contexts, land uses, and SHOs. The evidence map accompanying the resulting typology of drivers provides a structured basis to compare and analyse different categories of drivers. Beyond standardising fragmented terminology, the typology enables the identification of dominant drivers, evidence gaps, and interactions among overarching driver categories influencing soil health. Several overarching patterns emerge, highlighting both well-studied domains and persistent knowledge gaps.

Technology and management drivers are the most frequently represented across the study region, indicating the importance of management practices such as the use of fertiliser and waste management, as well as technological development such as machinery and precision technologies in shaping soil conditions. The prominence of nature-based solutions for climate change mitigation (sustainable practices) reflects both increasing scientific attention to climate-related challenges and an increasing shift toward more climate-adaptive management strategies. Climate change, in this regard, is not only a driver directly influencing soil health, but can also be a trigger for other drivers, such as resilient or adaptive management (Kabato et al., 2025).

Climate change and the associated drivers in the nature and environment category, in turn, are widespread across the evidence base. Shifts in precipitation, temperature increases, and extreme weather events are consistently identified across all land uses and locations. Mediterranean region and countries within emerges as particular hotspots, aligning with the existing understanding of the climatic vulnerability of the region (Ferreira et al., 2022; Tuel & Eltahir, 2020). In contrast, processes such as prolonged growing seasons are largely confined to northern regions, demonstrating the spatial differentiation of climate change across Europe.

Economic drivers also exhibit broad relevance across the study, especially demand for food, renewables, and built-up areas exerting significant pressure across all land uses and influencing multiple SHOs. In contrast, demographic drivers display strong regional clustering. Declining rural population and ageing can influence the management capacity and might result in land abandonment. While population increase is commonly identified as a broadly relevant driver across Europe, migration, declining rural population, and ageing are concentrated in specific regional contexts, particularly in Mediterranean countries. Declining rural population, coupled with increasing population in general and migration lead to an increasing population in the urban areas, which in the EU results in contrasting demographic development (JRC, 2025). These demographic patterns contribute to divergent trajectories, which are also identified as drivers: expansion of built-up areas fuelled by urbanisation on one hand, and declining agricultural labour forces on the other. Despite the target of ´zero net land take by 2050´ of the EU soil strategy ("COM(2021) 699 final," 2021), net land take for artificial surfaces has increased by 32% in the urban and periurban areas in the EU member states in 2018-2021 compared to 2012-2018 (EEA, 2023). These conversions are coming mostly at the cost of loss of productive arable land, pastures, and forests (EEA, 2025; Naumann et al., 2019). Such contrasting trends can make the already complex assessment of soil health require integrating even further dimensions.

Socio-cultural drivers highlight the growing influence of societal values and behavioural trends on land use decisions and soil health. Changes in consumption patterns increasingly shape demand for

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agricultural products and land resources both within and beyond Europe (Plinke et al., 2026). While food consumption trends vary across the region (Biganzoli et al., 2025), the overall plant-based alternatives market grew by 21% from 2020 to 2022 (GFI, 2022). The shift towards plant-based alternatives (EC, 2025), coupled with increasing demands for renewables (EC, 2026), will likely bring forward a complex set of changes and challenges regarding soil and land management. Increasing awareness of soil-based ecosystem services also reflects a broader societal shift towards more environmentally conscious land use decisions.

At the same time, the lack of knowledge transfer between scientists and other stakeholders hints at a more challenging future to navigate for policymakers. Although there is no clear evidence of a lack of trust in science (Starkbaum et al., 2025), even a small minority of scepticism can result in wider disruption to evidence-based decision-making and adaptation (Cologna et al., 2025). This is crucial because certain institutional and policy drivers, especially CAP, play an instrumental role as frameworks for soil and land-use decisions. The regional policies regarding agriculture, sustainability, pollution, and conservation have been broadly covered by much of the literature, emphasising influence in aspects of soil health across the region. The prevalence of region-wide regulations and broad policy categories indicates a methodological tendency to analyse policy at coarse scales and supports the idea that policy issue positions are becoming increasingly similar across EU member States (Sorace, 2025). Thus, conflicts between local and regional legislation appear only in isolated cases, despite their potential significance for land management.

4.2 Evidence gaps and geographical imbalances

Taken together, the results reveal clear imbalances in research coverage. Countries in the Mediterranean region appear heavily represented across most driver categories, especially climate, demographic change, and land management practices. Central and Northern Europe are well represented in technological and institutional drivers, whereas Baltic, Balkan, and Eastern European countries show substantial data gaps, often only appearing under general labels such as “relevant everywhere” or “EU-wide.” This occurs despite these regions being identified as hotspots for land use change, including declines in the management intensity of cropland (Kuemmerle et al., 2016). Certain drivers will evidently be influential in soil and land use decision-making in the missing locations, for example, migration (Bell et al., 2010). These gaps limit the comparability of results and highlight the need for more geographically diverse research efforts. At the same time, the concentration of evidence, e.g. the Mediterranean region, likely reflects the prominence of soil challenges in the region and the corresponding focus of research and policy efforts.

The concentration of policy studies in a handful of countries suggests a broader imbalance in the representation of policy contexts across Europe. This trend is not limited to this category; the uneven geographical distribution of studies has been prevalent in most categories. Such patterns should not necessarily be interpreted solely as omissions in the literature. They may also reflect differences in monitoring capacity, policy priorities, research investment, and the perceived urgency of soil-health challenges across regions.

Similarly, certain drivers are also underrepresented in the studies despite their importance in soil health. Abiotic factors and invasive species remain comparatively under-represented in the studies. This could highlight a gap and consequent need to understand the consequences of non-climatic nature and environmental drivers on soil health. This could also potentially be because abiotic factors, for example, soil pH, are not drivers influencing the changes in the use or management of soil, but rather as indicators of soil health (Lebron et al., 2025) that are changing due to other

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drivers, for example, use of fertiliser (Bai et al., 2018; Zhang et al., 2022). Studies also point out widespread interest in advances in soil monitoring tools, precision technologies, and waste and pollution management. These findings align with the current trend in the region regarding precision agriculture and digitalisation, which are not only shaping current soil conditions but also redefining the future of soil stewardship (EC, 2025).

4.3 Methodological challenges of driver standardisation

The central challenge of this study has not been identifying the drivers, but standardising and classifying them. It was recognised from the outset that the drivers would not be found verbatim in the text, which motivated the planned standardising workshops. However, these workshops evolved beyond standardisation, and required collective discussion and agreement of what should be considered a driver and to which category individual drivers should belong. This process highlighted the need for a broader systemic understanding of soil and land as resources (Chowdhury et al., 2025) and the unique role transdisciplinary research can play as a common ground for several complex and in-depth fields of research regarding soil health (Bouma et al., 2015; Gillespie et al., 2025; Rodrigo-Comino et al., 2020). The categorisation of drivers used in this study, such as grouping climate change within the Nature and Environment category or placing armed conflicts within the Economy category, reflects the investigating researchers' understanding of the dominant mechanism through which each driver operates, rather than the full spectrum of its consequences. Through the lens of soil health, climate change manifests primarily through biophysical processes (Allen et al., 2011). In contrast, armed conflicts can be argued to be a socio-economic phenomenon (Le et al., 2022). This classification, despite not being appropriate to encompass all the varied contexts, is necessary to disentangle complex, multidimensional influences on soil health and enables clearer comparison across regions and land use types.

A second challenge was linking the drivers to SHOs. Although drivers exert positive, negative, or mixed influences on SHOs, it was simplified to an association in the analysis. While some studies would explore a driver in relation to a specific SHO with clear determiners for positive or negative influence, many more would explore several drivers, several SHOs, or several locations, with varying or unclear degrees of influence that are hard to streamline. As a result, the relationship between drivers and SHOs was often inferred indirectly from the soil processes or impacts described, rather than studied. Thus, the relationship between the drivers and SHOs is kept as a link, which also helps to harmonise with the rest of the datasets. This highlights an important study limitation and the need to reconstruct driver–SHO linkages and more soil-focused analytical frameworks.

In addition, geographic locations were recorded primarily at NUTS0 level. Consequently, the analysis reflects national patterns of driver representation and may not capture important sub-national heterogeneity in soil-health drivers and land-use dynamics. Although recurring standardisation workshops were used throughout the review process, data collection was conducted independently across four land-use groups, which may have introduced minor differences in interpretation and coding. The evidence base is also constrained by the scope of the literature review. The search was conducted using a defined database, keyword strategy, and publication period, and therefore may not capture all relevant studies, particularly those contained in additional databases or grey literature sources. While the applied protocol ensured consistency across land-use groups, alternative search strategies may have produced a different representation of drivers and associated evidence.

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4.4 Interactions among driver categories

A recurring finding across the evidence base is the overlap and interconnectedness between different drivers. Climate change leads to nature-based solutions for mitigation and sustainable practices, among other technological innovations and management shifts (Long et al., 2016; Singh, 2025) as well as laws or regulations regarding climate (e.g COP26, European Climate Law 2021/1119) ("European Climate Law," 2021). Similarly, policy drivers such as the Nitrates Directive (91/676/EEC) have been imperative in the advancement and adoption of efficient fertiliser replacement and recovery technologies (e.g. RENURE (recovered nitrogen through manure initiative)) (Vingerhoets et al., 2025). Changes in consumption patterns and climate-related policy objectives also contribute to increasing demand for renewables (Morone et al., 2026; Shivakumar et al., 2019).

The expansion of built-up areas provides another example of a cross-cutting driver. It can be linked back to increasing population, migration, and increasing demand for tourism, while directly influencing several SHO, such as soil sealing. These interdependencies suggest that future soil-health assessments and governance approaches require integrated, cross-sectoral perspectives capable of accounting for interactions across environmental, technological, socio-economic, and institutional domains.

4.5 Conclusions

The analysis points to several key opportunities for advancing soil health research and action. Standardised terminology and categorisation of drivers facilitate cross-regional and disciplinary comparison and reduce fragmentation in the literature. The study also demonstrates the value of structured expert standardisation for synthesising fragmented evidence across disciplinary and land use domains. Improved integration of socio-economic and behavioural perspectives could enrich the understanding of land use decisions. Expanded research in under-represented regions would strengthen Europe-wide assessments and help determine whether observed evidence gaps reflect true research priorities, data limitations, or currently overlooked soil-health challenges. Finally, further exploration of interactions among drivers, rather than treating them independently, may reveal new pathways for anticipating change and designing effective responses.

5 CRediT author statement

Shaswati Chowdhury: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Formal analysis, Validation, Visualisation, Project administration. **Maria von Post:** Investigation, Data curation, Validation. **Roger Roca Vallejo:** Investigation, Data curation, Validation. **Karen Naciph Mora:** Investigation, Data curation, Validation. **Jenni Hultman:** Investigation, Data curation, Validation. **Taina Pennanen:** Investigation, Data curation, Validation. **Antti-Jussi Lindroos**: Investigation, Data curation, Validation. **Davide Geneletti:** Writing – review & editing, Validation. **Chiara Cortinovis:** Investigation, Data curation, Validation. **Silvia Frezzi:** Investigation, Data curation, Validation. **Laura Zara**: Visualisation. **Katarina Hedlund:** Validation, Funding acquisition. Katharina Helming: Writing – review & editing, Validation, Funding acquisition

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7 Code and Data availability

The curated dataset underlying this study is publicly available through the BonaRes Repository (https://doi.org/10.20387/zalf-a15w-f1kh) and has been described in detail in Chowdhury et al. (2024b). No custom software was developed for this study. Scripts used for data processing and visualisation are available from the corresponding author upon reasonable request. Further information required to reproduce or reanalyse the results presented in this study is available from the corresponding author upon request.

8 Declaration of Interests

The authors declare no competing interests.

Declaration of Generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the author used AI-assisted tools for language refinement and editorial suggestions. All content was critically reviewed and edited by the author, who takes full responsibility for the content and conclusions of the publication.

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