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Assessing synergies between soil research in the Republic of Ireland and European Union policies

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ABSTRACT

Recent policies on soil in Europe are shifting towards sustainability, climate goals, and a holistic approach to soil quality. In line with these policy changes, research on Irish soils is also changing: the historical primary focus on agriculture, linked to Ireland's economic reliance on agriculture, is being supplanted by policies focussed on soil quality. Here, we perform a systematic review of recent research on Irish soils and of how this research aligns with key elements of the European Soil Strategy (ESS) for 2030. Our results show that the dominant natural setting within each county does not always determine the research focus. Instead, the research focus in each county is driven by the national emphasis on funding of major environmental research centres and by the strength of Ireland's agricultural sector. Our results also show that most publications are small in scale, typically reporting data on < 30 samples. Importantly, the most common parameters analysed vary among study settings. Publications in agricultural settings include analyses of more soil parameters than those from non-agricultural settings, but typically lack data quality indicators (e.g., standard reference materials, duplicates and/or analytical replicates). In non-agricultural settings, publications often include analyses of soil metal concentrations, but not other important parameters such as total porosity and soil nutrients. Overall, soil pH is the most common parameter assessed in all settings, while soil organic carbon, soil moisture and soil porosity are the least common. Our data also reveal a lack of a standard soil classification system, due, in part, to differences in soil classification systems used among scientific fields. Benchmarking current research on Irish soils against the ESS highlights key knowledge gaps. Resolving this issue is critical to Ireland's ability to address future challenges relating to soil protection, reuse, monitoring, restoration, remediation, and the maintenance of soils for healthy water resources.

1. Introduction

Healthy, high-quality soil is critical to life on Earth and to human society. In recognition of this, national, European and global policies now increasingly acknowledge soil and its role as a vital resource for life. At a global level, the United Nations (UN) Sustainable Development Goals (SDGs) refer to the importance of reducing soil pollution, restoring soils and safeguarding soils for the future (UN, 2022). These aspirations are articulated through SDG 3: *Good health and well-being*, SDG 6: *Clean water and sanitation*, SDG 11: *Sustainable cities and communities*, SDG 12: *Responsible consumption and production*, SDG 13: *Climate action* and SDG 15: *Life on land* (European Environment Agency, 2019). In Europe, five key policies relating to soil have been published in the past five years, including the European Green Deal (EC, 2019), the European Commission Soil Health and Food Mission (EC, 2020a), the EU Biodiversity Strategy for 2030 (EC, 2020b), the EU Soil Strategy for 2030 (Directorate-General for Environment, 2021) and the European Missions: A Soil Deal for Europe (EC, 2021a). An additional major development is the forthcoming EU Soil Health Law for 2023 (EC, 2021b).

In response, the Government of Ireland has developed several strategies, associated with published reports, that refer to soil and aim to address these new and incipient EU policies: (1) *The Climate Action Plan* 2021 and 2023 (Department of the Environment, Climate and Communications, 2023, 2021); (2) a *National Soils Strategy* under the Programme for Government: Our Shared Future Report (Department of the Taoiseach, 2020); and (3) the Environmental Protection Agency (EPA)

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Ireland State of the Environment Report 2020 (EPA Ireland, 2020).

Similar exercises to the one carried out here have been carried out in the 1990s and early 2000s and included survey data that were conducted by An Foras Talúntais (AFT) and the Irish Soil Information System (ISIS) project, both of which covered around 40 % of the land area in Ireland (Creamer et al., 2014). A land cover exercise spanning the period 1851–2000 included an analysis of soil organic carbon stocks by using historic and CORINE land cover maps (Eaton et al., 2008). Ireland also has a long history of agriculture, in particular cattle farming and fertiliser application have been the subject of much research to help maintain good quality water and soils, due to various stresses from run-off, farming practices and fertiliser applications (Jordan et al., 2005; Kurz et al., 2006; Radu and Diamond, 2009; Zhang and McGrath, 2004).

In light of recent rapid and successive policy developments through both national and EU-wide policies (National Soil Strategy, The Climate Action Plan, EU Green Deal, etc.), a comprehensive review of recent research on Irish soils is needed in order to provide context for future policy development. This is particularly important for the identification of knowledge gaps that may require a pivot in research focus, funding and/or policy. In fact, a need for recent data on Irish soil research was identified by the Environmental Protection Agency (EPA) Ireland in order to provide an evidence base for the upcoming Soil Health Law that is currently being drafted by the Government of Ireland (EC, 2021b; Teagasc, 2023).

Here, we systematically assess the nature, scope and quality of recent research on Irish soil and the extent to which this research aligns with key elements of the European Soil Strategy (ESS) for 2030 (Directorate-General for Environment, 2021). The purpose of this study is to provide new data to inform the Irish Soil Health Law (see above). A subset of the data presented in this paper has been published in report form by the EPA Ireland.

2. Methods

This review builds on preliminary findings published previously as a government report (McNamara et al., 2022). Here, we provide a deeper interrogation of the reported data to identify trends and knowledge gaps within the recent literature on Irish soil. The ultimate aim of the current review is to better signpost future research needs and serve as a useful blueprint for similar research policy alignment exercises in Ireland and other nations.

The term "Irish soil" is used herein to refer to soil in the Republic of Ireland. Northern Ireland was excluded because it falls under UK jurisdiction and thus is no longer subject to EU policy.

2.1. Inclusion criteria

The scope of this systematic review encompasses all 26 counties in the Republic of Ireland (RoI). Relevant publications were identified using three databases (*Web of Science, Scopus* and *PubMed*). A targeted strategy was used to search for public documents published by, and/or hosted on the websites of the European Commission (EC) and various government bodies in Ireland, such as the Department of the Environment, Climate and Communications (DECC), the Environmental Protection Agency (EPA) Ireland, the Geological Survey of Ireland (GSI), and the Agriculture and Food Development Authority (i.e., Teagasc). The latter three (i.e., EPA, GSI and Teagasc) operate independently, but in communication with DECC, which is the government department responsible for regulating and communicating EC guidelines and directives nationally.

The literature search was limited to publication dates between 2013 and the database search date, which was the 7th of December 2021. Database searches were performed using the *title, abstract* and *keywords* functions in *Web of Science, Scopus* and *PubMed*. Separately, the websites of the above government bodies were manually searched over several days between 07/12/2021 and 14/12/2021. The search string used in both database and website searches was as follows: *TITLE-ABS-KEY (soil) AND TITLE-ABS-KEY (Ireland OR "Republic of Ireland" OR Carlow OR Cork OR Donegal OR Dublin OR Galway OR Kerry OR Kildare OR Kilkenny OR Laois OR Leitrim OR Limerick OR Longford OR Louth OR Mayo OR Meath OR Monaghan OR Offaly OR Roscommon OR Sligo OR Tipperary OR Waterford OR Westmeath OR Wexford OR Wicklow) AND TITLE-ABS-KEY ("degradation" OR "organic carbon" OR "carbon stock*" OR "carbon loss" OR "carbon reservoir" OR "carbon sequestration" OR "carbon-rich" OR "carbon rich" OR compaction OR sealing OR reuse OR remediation OR bioremediation OR restoration OR protection OR recovery OR erosion OR structure OR literacy OR biodiversity OR "biodiversity loss" OR biomass OR ecosystem OR salinisation OR salinization OR pollution OR contamination OR contaminant OR "climate neutrality" OR climate-neutral OR "climate neutral" OR "nutrient loss" OR "climate change" OR "circular economy" OR "land take" OR recycling OR "land damage" OR quality OR nutrient OR "nutrient recovery" OR "sustainable soil management" OR ssm OR sustainable OR "soil management" OR fertility OR resilience OR drought OR fertiliser OR pesticide OR health OR "organic matter" OR "urban soil" OR "land use" OR exploitation OR climate OR regulation OR carbon OR productivity OR wetland OR densification OR monitoring OR "land cover" OR "human health") AND PUBYEAR > 2012.*

Collectively, the searches yielded 1919 publications. After removal of duplicates, 1189 publications remained in the dataset, of which 1081 are journal articles and 108 are government reports.

2.2. Exclusion criteria

Initial screening of the search results was based on title and abstract content (Table 1). Publications were excluded where the research: (1) is not based on sites in the Republic of Ireland, (2) is not conducted on soil, (3) is conducted on Cork oak (many publications on this topic were included by the search engines because the search terms included the term "Cork" (referring to County Cork)), (4) focusses exclusively on river sediment and/or hydrogeology, (5) does not include collection and/or analysis of data on Irish soil, (6) is not classified as a peer-reviewed scientific publication or government report (e.g. conference abstracts and popular science articles), (7) focusses on the use of soil as a by-product, (8) focusses on soil engineering, (9) was published prior to 2013, (10) is a duplicate of a publication (not excluded during initial duplicate removal) or (11) is not available as a full-text publication.

During this process, 739 publications were excluded from the dataset. The full text of each publication was then screened using the same exclusion criteria, which resulted in the exclusion of an additional 186 publications. The remaining 264 publications form the dataset used in this study. Note that certain publications in the dataset conducted research in more than one county, setting, etc., and thus the number of studies providing data on certain parameters may exceed 264 (Fig. 1).

2.3. Data analysis

The ESS includes four Key Themes and 13 Subthemes (see Table S1).

Table 1
Eligibility (inclusion/exclusion) criteria employed for literature screening.

Inclusion Criteria	Exclusion Criteria
Study Type: Research articles excluding reviews, Irish governmental reports, European governmental reports	Study Type: Academic reviews, reports outside of Europe, not a scientific publication, conference proceedings
Language: English	Language: non-English
Population: Natural soils in the Republic of Ireland (RoI)	Population: Laboratory-generated soils in the RoI, natural soils outside the RoI, use of soils on secondary or as a by-product, river sediment studies, methods paper that enhance STEM knowledge but produce no new data
Period: 2013 - present	Period: pre-2013

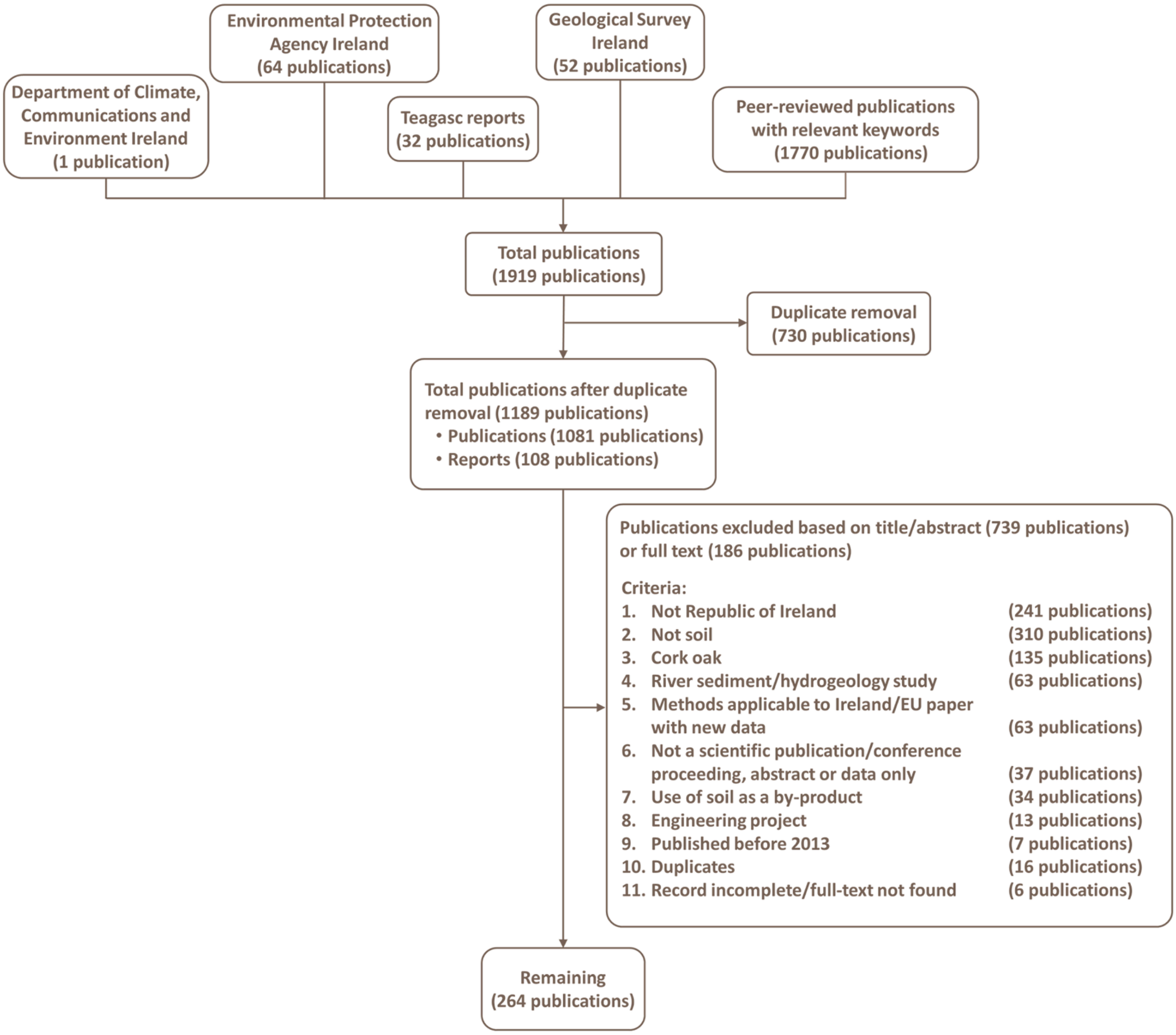

Fig. 1. Schematic overview of the screening process applied to the literature examined in this study.

Data on the following variables were extracted from each publication (where possible):

(i) alignment with ESS Key Themes (Directorate-General for Environment, 2021): We assessed whether any of the following are a focus of each publication: (a) the four Key Themes of the ESS, (b) the 13 Subthemes of the ESS and (c) 48 keywords included in the ESS (Table 1), specific to Key themes and Subthemes. These keywords were identified based on frequent use of these words, their use in headings and/or their use in highlighted parts of the ESS.

1. (ii) Geographic context: (a) county, (b) setting - i.e., agriculture, urban, forest, bog, mine, dune, and mountain.
2. (iii) Soil type: (a) soil classification system and (b) soil type (as stated in the publication).
3. (iv) Data quality: (a) number of samples analysed, (b) number of sites studied, (c) use of any of the following: analytical standards, field duplicates, analytical replicates, blind insertion of samples and standards, specific sampling protocols and/or post-processing of the data.
4. (v) Soil parameters and analytical methods: (a) soil parameters: pH, $<$ 2 mm particle-size fraction [g], soil temperature [∘C], bulk density (BD) [g], soil organic carbon (SOC) [%], depth of soil organic carbon measurement(s) (SOM) [cm], total porosity (TP) [%], soil moisture [%], greenhouse gas (GHG) emissions [kg or t], content of nitrogen (N) [mg/kg], phosphorus (P) [mg/kg], potassium (K) [mg/kg], carbon (C) [mg/kg], soil minerals [mg/kg], cation exchange capacity (CEC) [cmol/kg], (b) analytical methods: X-ray fluorescence (XRF), inductively coupled plasma-mass spectrometry (ICP-MS), inductively coupled plasma-atomic emission spectrometry (ICP-AES) and/or inductively coupled plasma optical emission spectroscopy (ICP-OES), and (c) inclusion of previously published soil data.
5. (vi) Research body that conducted the study (applies only to research conducted by a state body).
6. (vii) Key recommendations for future study or policy development.

3. Results

3.1. Geographic context

The number of publications per county is highly variable (Fig. 2) and is highest for counties Cork (19 %; $n = 49$ publications) and Wexford (16 %; $n = 42$). Collectively, almost two-thirds (63 %; $n = 48$) of the publications for these two counties focus on agricultural settings; of these, almost all (94 %; $n = 45$) are conducted by Teagasc (the Agriculture and Food Development Authority in Ireland). Counties Tipperary and Galway also represent a high proportion of the total publications (14 % and 12 %; $n = 36$ and 33, respectively), closely followed by Carlow (11 %; $n = 28$), Meath and Louth (9 %; $n = 24$ publications each), Offaly and

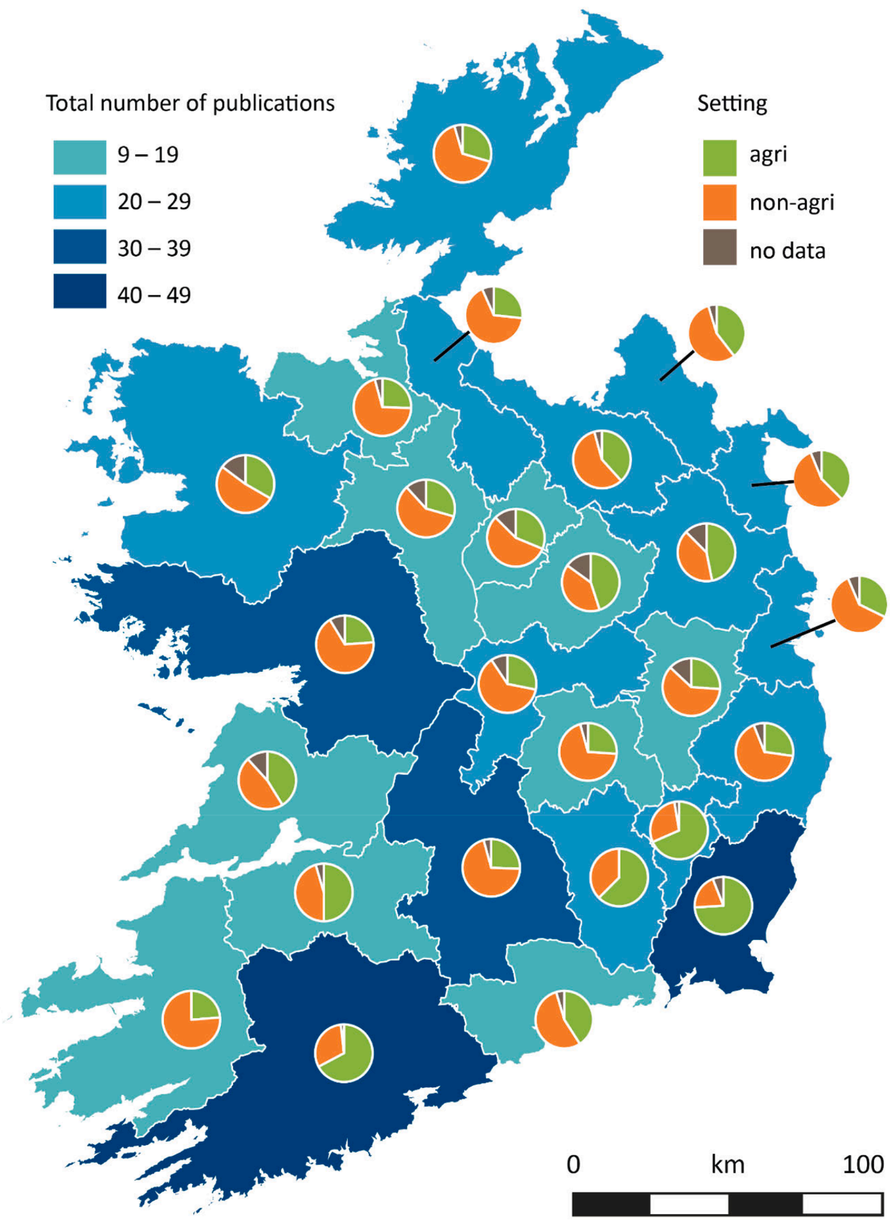

Fig. 2. Map of the Republic of Ireland showing, for each county, the total number of publications and the proportion of publications in agricultural (agri) and non-agricultural (non-agri) settings ($n = 264$).

Donegal (9 %; $n = 23$ each) and Dublin (8 %; $n = 22$). Collectively, the ten counties above represent 52 % of the dataset. Few publications focus on counties Kerry (5 %; $n = 13$), Roscommon (5 %; $n = 12$) and Longford (3 %; $n = 9$).

3.2. Environmental setting

Examination of the total dataset reveals that most of the research on Irish soils is based on agricultural settings (65 % of publications), followed by bog (27 %), forest (20 %), urban (16 %), mines (2 %), dunes (1 %) and mountain (1 %) settings. In 50 % of counties (13 of 26), agricultural settings are the most common study setting (Fig. 2), ranging from 38 % to 74 % of publications (e.g., 74 % in County Wexford, 68 % in County Carlow, 67 % in County Cork, 63 % in Kilkenny, 51 % in Tipperary, 50 % in Limerick, 47 % in Meath, 45 % in Westmeath, 41 % in Clare, 41 % in Waterford, 40 % in Monaghan, 38 % in Cavan and 38 % in Louth).

For many other counties (13 out of 26 counties), agricultural settings do not dominate, and instead diverse combinations of non-agricultural settings make up the majority of settings studied. Further exploration of these non-agricultural settings reveals county-specific trends. County Dublin, for example, has the highest proportion of publications in urban settings (39 %, $n = 12$). Counties Kildare, Laois and Offaly have the highest number of publications in bog settings (7–13 publications each). County Kerry has the highest proportion of publications in forest settings (7 publications). For each of counties Donegal, Longford, Mayo and Roscommon, agricultural and bog settings are represented by similar proportions of publications (each with 5–13 publications per setting). For each of counties Galway, Leitrim, Sligo and Wicklow, agricultural, forest and bog settings are represented by similar numbers of publications (each with 7–12 publications per setting).

3.3. Environmental setting and soil parameters

Only 58 % ($n = 152$) of studies in this dataset collected new data on soil parameters such as pH, < 2 mm particle-size fraction, C content, SOM, BD, GHG concentrations, soil moisture content, soil minerals, NPK content, total porosity or CEC.

In agricultural settings, the most common soil parameters analysed (Fig. 3) are pH, N content and BD (in 35 %, 30 % and 20 % of publications, respectively). Parameters analysed less often are (in descending order of frequency): P content, < 2 mm particle-size fraction, C content, SOM, GHG concentrations, soil moisture content, soil minerals, K content, total porosity and CEC (Fig. 3). In general, publications on soils from agricultural settings are associated with the analysis of more soil parameters than publications focusing on non-agricultural soils (Fig. 3). In non-agricultural settings, the most common soil parameters studied are pH, C and SOM content (23 %, 16 % and 16 % of publications, respectively). Further, analysis of soil metal concentrations (using XRF and/or mass spectrometry) is twice as common in non-agricultural settings ($n = 22$) than in agricultural settings ($n = 10$). Many studies do not involve the collection of new data and instead include previously published soil data (42 %; $n = 112$); of these, approximately one-third of publications include one or more mathematical simulations and/or statistical models of soil data (36 %; $n = 96$).

3.4. Number of samples

Many publications use a small number of samples: 41 % of publications ($n = 109$) are based on data from < 30 samples. Less frequently, 31 % ($n = 82$) of publications analyse > 100 samples, and 11 % ($n = 29$) of publications analyse 30–100 samples (Table 2). The remaining publications (17 %; $n = 44$) do not specify a number of samples; almost one-third of these publications, however, do not report new primary data (e.g., government reports and legislation documents) and thus number of samples does not apply.

3.5. Data quality indicators

Few publications (19 %; $n = 51$) refer to any of the data quality indicators listed in Section 3.4. For instance, field duplicates are used in only 11 % ($n = 29$) of publications, sampling protocols are defined in only 9 % ($n = 24$) of publications and analytical standards are used in only 8 % ($n = 21$) of publications.

Further interrogation of these data reveals a link between number of samples and other study parameters (Table 2). Publications with small datasets (i.e., < 30 samples) frequently analyse three or fewer soil parameters (40 %; $n = 44$), rarely refer to one or more data quality indicators (25 %; $n = 27$) and often analyse data from more than one site (68 %; $n = 74$). In contrast, publications with large datasets usually analyse more soil parameters, more frequently refer to data quality indicators, and frequently analyse samples from multiple sites. For instance, publications with datasets of 30–100 samples often analyse four to six soil parameters (31 %; $n = 9$) and usually analyse more than one site (83 %; $n = 24$); the most common data quality indicators used are field duplicates (14 % of relevant publications), analytical replicates (14 % of relevant publications) and sampling protocols (7 % of relevant publications). Publications with > 100 samples most often analyse three or fewer soil parameters (29 %; $n = 24$) but almost always (90 %; $n = 74$) analyse more than one site; the most common data quality indicators used are sampling protocols (22 % of relevant publications), field duplicates (18 % of relevant publications), analytical standards (15 % of relevant publications) and post-processing of analytical data (15 % of relevant publications).

3.6. Soil classification

More than half of publications (54 %; $n = 142$) do not use any soil classification system. For the remaining publications, a total of 18 distinct soil classification systems are used. The six systems used most frequently are: the Irish Soil Information System (ISIS; 7 % ($n = 20$)), World Reference Base (WRB; 6 % ($n = 19$); more widely known as the World Reference Base for Soil resources), U.S. Department of Agriculture (USDA; 5 % ($n = 16$); more widely known as the USDA Soil Texture Classification), National Soil Database of Ireland (NSD; 5 % ($n = 14$)), Food and Agriculture Organization of the United Nations (FAO; 4 % ($n =$

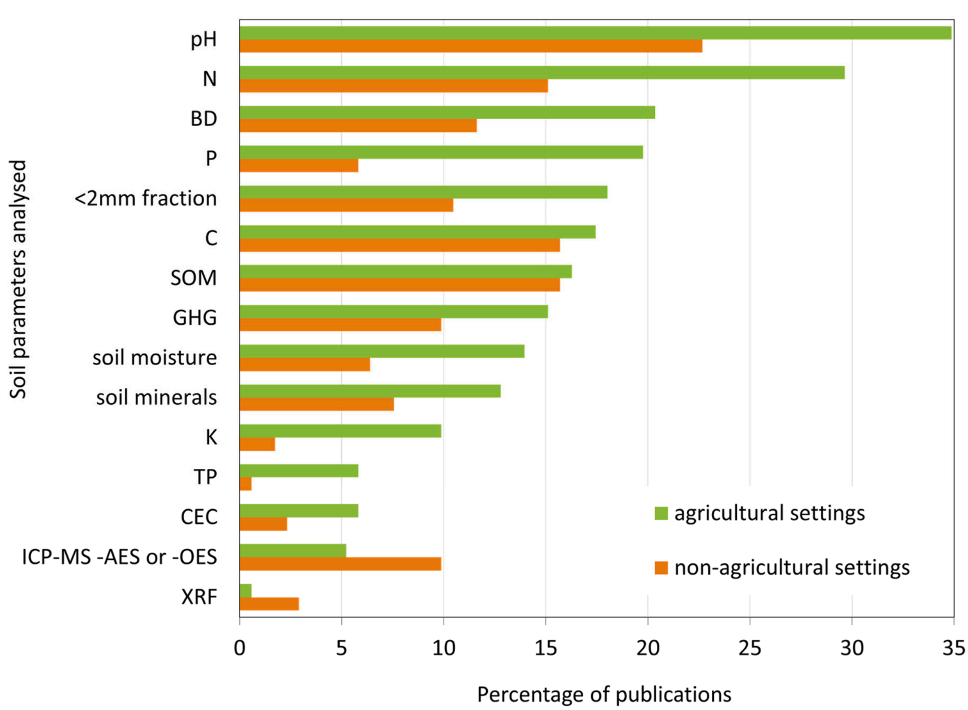

Fig. 3. Percentage of key soil parameters analysed in publications on Irish soils in agricultural and non-agricultural settings ($n = 264$). The soil parameters are pH, nitrogen (N), bulk density (BD), phosphorus (P), <2mm fraction, carbon (C), soil organic matter (SOM), greenhouse gas emissions (GHG), soil moisture, soil minerals, potassium (K), total porosity (TP), cation exchange capacity (CEC), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and X-ray fluorescence analysis (XRF).

Table 2
Summary of the key characteristics of the publications in the dataset ($n = 264$). Values indicate the percentage of publications in a particular sample size category. For instance, 41.1 % of publications used less than 30 samples. This category can be further divided according to the number of soil parameters used (i.e., 40.4 % of publications with less than 30 samples used less than three soil parameters), the number of sites used and data quality indicators used.

	Sample size category *% of each sample size category*	*< 30 samples [%]*	*30 – 100 samples [%]*	*> 100 samples [%]*	*sample size not specified [%]*	*not applicable [%]*
Sample size	-	41.1	11.0	31.1	13.6	3.0
Number of soil parameters	*≤ 3*	40.4	17.2	29.3	8.3	3.0
	4 – 6	26.6	31.0	18.3	5.6	
	≥ 7	11.9	13.8	4.9	0.0	
	not specified	21.1	37.9	47.6	86.1	
Number of sites	*1*	32.1	17.2	9.8	72.2	3.0
	> 1	67.9	82.8	90.2	27.8	
Data quality indicators	*field duplicates*	8.3	13.8	18.3	2.8	3.0
	analytical replicates	4.6	13.8	11.0	0.0	
	analytical standards	6.4	3.4	14.6	2.8	
	blind insertion of duplicates, replicates and standards	0.0	0.0	8.5	0.0	
	sampling protocols	3.7	6.9	22.0	0.0	
	post-processing of analytical data	1.8	3.4	14.6	2.8	
	not specified	75.2	58.6	11.0	91.7	

13), more widely known as the FAO Soil Groups), and the Great Soil groups of Ireland (GSG) classification system (4 %; $n = 12$).

Certain classification systems are used more frequently for soils from specific environmental settings. For example, forest soils are usually associated with the WRB, GSG and ISIS systems, in 32 % ($n = 9$), 29 % ($n = 8$) and 21 % ($n = 6$) of publications, respectively. For urban soils and bogs, ISIS and GSG are the most common systems, whereby each system is used in 31 % of publications in both urban and bog settings (i.e., $n = 4$ and 5, respectively). Finally, for agricultural settings, the USDA, ISIS, WRB and FAO systems are the most common systems used, in 23 % ($n = 15$), 21 % ($n = 14$), 18 % ($n = 12$) and 17 % ($n = 11$) of publications, respectively.

3.7. Soil type

In the total dataset, 59 % ($n = 156$) of publications reported the soil type. In total, 25 soil types are reported in the dataset, of which the most common types are loam (35 %; $n = 92$), gley (19 %; $n = 49$), brown earth (17 %; $n = 44$), peat (16 %; $n = 43$) and podzol (15 %; $n = 40$).

3.8. European Soil Strategy for 2030

In total, 98 % ($n = 259$) of publications in the dataset are aligned with one or more of the four Key Themes of the ESS (see Table S1 for a detailed breakdown of the ESS themes). These Key Themes, however, do not feature with equal frequency in Irish soil research. The most common Key Theme in Irish soil research is '*Key Theme 2: Preventing soil and land degradation and restoring healthy soils*', which relates to 77 % ($n = 202$) of publications, followed by '*Key Theme 1: Soil as a key solution for our big challenges'* (73 %; $n = 192$), '*Key Theme 3: We need to know more about soils'* (22 %; $n = 58$) and '*Key Theme 4: Enabling the transition to healthy soils'* (2 %; $n = 5$).

Each Key Theme has several Subthemes (Table S1). For Key Theme 2, the most featured Subtheme in the dataset is *'Subtheme 1: Sustainable Soil Management'*, which relates to 59 % of publications. The other Subthemes are reported less frequently: *'Subtheme 2: Preventing soil pollution'* relates to 26 % of publications, *'Subtheme 3: Restoring soils and remediating sites'* relates to 14 % of publications, and *'Subtheme 4: Preventing desertification'* relates to only 2 % of publications. For Key Theme 1, the most featured Subtheme in the dataset is '*Subtheme 2: Soil and the Circular Economy'*, which relates to 41 % of publications. The other Subthemes are featured less frequently in the dataset: '*Subtheme 3: Soil biodiversity for animal and plant health*' and '*Subtheme 1: Climate change mitigation and adaptation*' each relate to 25 % of publications and '*Subtheme 4: Soil for healthy water resources*' relates to 20 % of publications. For Key Theme 3, the most featured Subthemes in the dataset are '*Subtheme 1: Soil monitoring'* and '*Subtheme 2: Soil and the digital agenda'*, each of which relate to 14 % of publications. *'Subtheme 3: Soil research and innovation'* is featured less frequently (< 2 % of publications). For Key Theme 4, both Subthemes are featured rarely in the dataset: '*Subtheme 1: Soil literacy and societal engagement'* and '*Subtheme 2: Private finance and EU funding'* each feature in only 1 % of publications.

Our review also explored the frequency with which certain topics (represented by keywords that are linked to Key Themes and Subthemes; Table 1) are a research focus. The most common such keywords are 'soil nutrient loss / leaching' (37 %, $n = 97$), 'soil organic carbon' (33 %, $n = 86$), 'climate mitigation / GHG emissions' (26 %, $n = 68$), 'land use / land cover' (25 %, $n = 67$), and 'soil productivity / food production' (22 %, $n = 57$). Other keywords feature in the dataset less frequently. Keywords used in 11 %–15 % ($n = 29$–39) of publications are, in descending order, 'soil pollution / soil contamination', 'soil regulation', 'climate / soil resilience', 'soil restoration', 'safeguarding human health', 'reversing biodiversity loss / take stock of biodiversity', 'organic soils' and 'soil quality / health'. Keywords used in 6 %–10 % ($n = 16$–19) of publications are 'plant health' and 'soil structure'. Keywords used in 1 %–5 % ($n = 3$–15) of publications are, in descending order: 'mineral

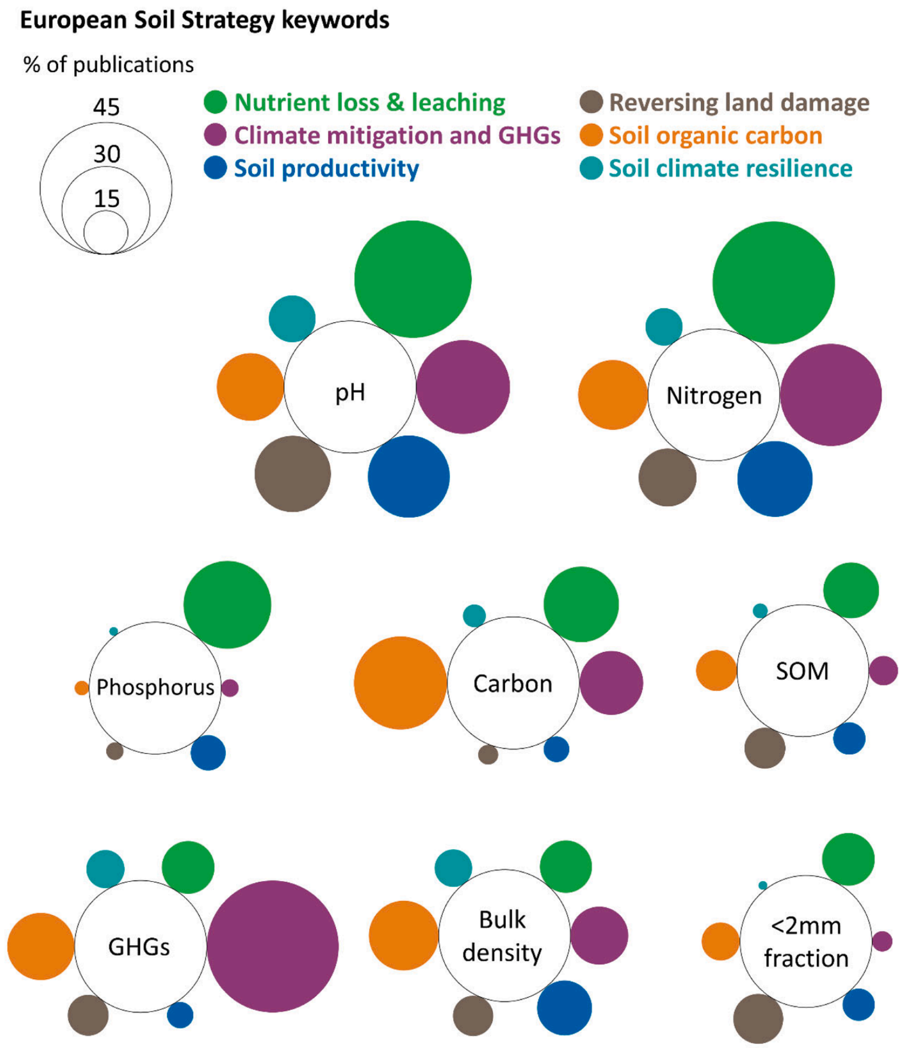

Fig. 4. European Soil Strategy 2030 keywords associated with soil parameters that are commonly referred to in publications on Irish soil. Percentage values indicate the percentage of publications in the dataset ($n = 264$) that address each keyword, e.g., 40 % of publications referring to 'nutrient loss & leaching' analysed pH data. The soil parameters are pH, nitrogen (N), phosphorus (P), carbon (C), soil organic matter (SOM), greenhouse gas emissions (GHGs), bulk density (BD) and < 2 mm fraction.

soil', 'wetlands', 'soil compaction', 'soil protection', 'soil moisture', 'minimise drought / desertification', 'minimise flooding', 'soil erosion', 'soil sealing / land take', 'climate neutrality' and 'soil reuse'. The least frequently mentioned keywords (< 1 % of publications; n < 3), in descending order, are: 'circular (bio) economy', 'excavated soil', 'soil recycling', 'soil salinisation' and 'soil capital'.

3.9. ESS keywords and soil parameters

Certain keywords are associated with analysis of specific soil parameters (Fig. 4). For example, pH analysis is most often associated with 'nutrient loss / leaching' (40 %; $n = 39$) and in descending order, less frequently with 'climate mitigation / GHG emissions' (32 %; $n = 22$), 'soil productivity' (28 %; $n = 16$), 'reversing land damage and restoring soil' (26 %; $n = 9$), 'soil organic carbon' (23 %; $n = 20$) and 'soil climate resilience' (16 %; $n = 6$). Nitrogen analysis is most often associated with 'nutrient loss / leaching' (42 %; $n = 40$) and less frequently with 'climate mitigation and GHG emissions' (35 %; $n = 24$), 'soil productivity' (26 %; $n = 15$), 'reversing land damage and restoring soil' (20 %; $n = 7$), 'soil organic carbon' (24 %; $n = 21$) and 'soil climate resilience' (13 %; $n = 5$). Phosphorus analysis is primarily associated with 'nutrient loss / leaching' (30 %; $n = 29$) and much less frequently with 'soil productivity' (12 %; $n = 7$), 'climate mitigation and GHG emissions' (6 %; $n = 4$), 'reversing land damage and restoring soil' (6 %; $n = 2$), 'soil organic carbon' (5 %; $n = 4$) and 'soil climate resilience' (3 %; $n = 1$). Carbon analysis is most often associated with 'soil organic carbon' (22 %; $n = 19$), 'nutrient loss / leaching' (21 %; $n = 20$) and 'climate mitigation and GHG emissions' (22 %; $n = 15$), and infrequently associated with 'reversing land damage and restoring soil' (14 %; $n = 5$), 'soil productivity' (12 %; $n = 7$) and 'soil climate resilience' (8 %; $n = 3$). Analysis of soil organic matter is most frequently associated with 'nutrient loss / leaching' (19 %; $n = 18$) and less frequently with 'soil organic carbon' (14 %; $n = 12$), 'reversing land damage and restoring soil' (14 %; $n = 5$), 'soil productivity' (11 %; $n = 6$), 'climate mitigation and GHG emissions' (10 %; $n = 7$) and 'soil climate resilience' (5 %; $n = 2$). Greenhouse gases are most frequently associated with 'climate mitigation and GHG emissions' (45 %; $n = 31$) and less frequently with 'soil organic carbon' (23 %; $n = 20$), 'nutrient loss / leaching' (18 %; $n = 17$), 'reversing land damage and restoring soil' (14 %; $n = 5$), 'soil climate resilience' (13 %; $n = 5$) and 'soil productivity' (9 %; $n = 5$). Bulk density is most frequently associated with 'soil organic carbon' (24 %; $n = 21$) and less frequently with 'climate mitigation and GHG emissions' (20 %; $n = 14$), 'soil productivity' (19 %; $n = 11$), 'nutrient loss / leaching' (18 %; $n = 17$), 'reversing land damage and restoring soil' (14 %; $n = 5$) and 'soil climate resilience' (13 %; $n = 5$). Analysis of the < 2 mm particle size fraction is most frequently associated with 'nutrient loss / leaching' (18 %; $n = 17$) and 'reversing land damage and restoring soil' (17 %; $n = 6$) and less frequently with 'soil organic carbon' (13 %; $n = 11$), 'soil productivity' (11 %; $n = 6$), 'climate mitigation and GHG emissions' (7 %; $n = 5$) and 'soil climate resilience' (3 %; $n = 1$).

This analysis shows that 'nutrient loss & leaching' is commonly associated with analysis of N (42 %; $n = 41$), pH (40 %; $n = 39$) and P (30 %; $n = 29$). The keyword 'climate mitigation and GHG emissions' is commonly associated with analysis of GHGs (45 %; n =31), N (35 %; $n = 24$) and pH (32 %; $n = 22$). 'Soil productivity' is commonly associated with analysis of pH (28 %; $n = 16$) and N content (26 %; $n = 15$). 'Reversing land damage and restoring soil' is commonly associated with analysis of pH (26 %; $n = 9$) and N (20 %; $n = 7$). 'Soil organic carbon' is commonly associated with analysis of C (32 %; $n = 28$), N (24 %; $n = 21$) and GHGs (23 %; $n = 20$). 'Soil climate resilience' is commonly associated with pH (16 %; n =6), N (13 %; $n = 5$) and GHGs (13 %; $n = 5$).

3.10. Recommendations

Almost half (45 %; $n = 118$) of the publications in the dataset provide explicit, specific, recommendations (Fig. S1). Recommendations for agricultural settings (10 % of publications; $n = 26$) refer to soil management and changes in application rates of nitrogen and phosphorus and to changes in sequestration of carbon. Recommendations for bog settings (7 %; $n = 18$) refer to the generation of additional maps and/or surveys and to enhancing management. Recommendations specific to grassland settings (6 %; $n = 16$) and to forest settings (3 %; $n = 8$) pertain mainly to nutrient management and reforestation, respectively.

In the total dataset, additional research is recommended in 20 % of publications; more specifically, 11 % of publications recommend extending the analysis to additional sites and/or samples ($n = 24$), of which 1 % of publications ($n = 4$) recommend extending the respective study to a national scale. Non-specific soil research expansion is recommended in 9 % of publications ($n = 25$). Specific recommendations include the measurement of GHG emissions, ground-truthing of modelled data, inclusion of data on additional soil parameters (e.g., soil temperature, peat thickness, bulk density and soil fertility), incorporation of remote data and/or on-site monitoring, consideration of ecosystem interactions, monitoring nearby land use (e.g., livestock agriculture), and providing human exposure assessments.

Further research on climate change mitigation is recommended in 14 % of publications ($n = 38$). These recommendations include the reduction of GHG emissions, management of soil carbon, and improvement of climatic models. Recommendations relating to soil management and monitoring are provided in 13 % of publications ($n = 35$), of which 61 % ($n = 21$) recommend the implementation or updating of management practices and 39 % ($n = 14$) recommend the introduction or expansion of soil monitoring systems. Recommendations for the management of soil nutrients are provided in 11 % of publications ($n = 29$) and relate specifically to applications of nitrogen, phosphorus or generic fertiliser (in 14, 10 and 2 publications, respectively). Overall, 8 % of publications ($n = 21$) include policy development recommendations, including the collection of more in-depth data to inform policy, incorporation of uncertainty modelling, and development of policy on critical N loads, soil degradation, landfill reuse, urban soil, public education and carbon trading.

4. Discussion

4.1. Context

The importance of soil health has come to the forefront of recent EU policies, but implementing the latter is associated with a number of challenges (Bouma et al., 2019; Lehmann et al., 2020; Montanarella and Panagos, 2021). Previous studies have highlighted the importance of timely soil research to achieve the SDG (Sustainable Development Goal) targets that either directly or indirectly relate to soil, such as addressing SDGs related to water quality, climate change mitigation and biodiversity preservation (Bouma et al., 2019; Ronchi et al., 2019). Closely linked to the SDGs is research on SOC stocks. Many studies have highlighted the need for data that is policy-relevant in order to achieve the goal to make Europe the first climate-neutral continent by 2050, which is proposed under the European Green Deal (Montanarella and Panagos, 2021). It is within this context that this systematic review assessed the nature and quality of recent research on Irish soil and the extent to which this research aligns with key elements of the European Soil Strategy (ESS) for 2030 (Directorate-General for Environment, 2021), in order to identify knowledge gaps and better address future challenges.

4.2. European Soil Strategy implementation in Ireland

Even though most research on Irish soils is aligned with at least one aspect of the ESS, there are pronounced gaps in the research landscape in relation to the Strategy. Key Theme 1 (Soil as a key solution for our big challenges) and Key Theme 2 (Preventing soil and land degradation and restoring healthy soils) are linked to most publications (i.e., both relate to >70 % of publications), but Key Theme 3 (We need to know more about soils) is linked to less than 22 % of publications, while Key Theme 4 (Enabling the transition to healthy soils) is linked to very few publications (2 %; $n = 264$). Compounding this, our review reveals that a number of important aspects are underrepresented in research on Irish soils. These include the development of soil monitoring programmes, restoration of soils, site remediation, links between soil and healthy water resources and the prevention of desertification. This study is not the first to mention specific soil threats for Ireland, for example Ronchi et al. (2019) highlighted the potential negative impact of a further decline in organic matter, loss of biodiversity, and the importance of targeting specifically peat, agriculture and forests. Ireland has a long history of conducting soil surveys to aid policy development, especially in monitoring land cover and land use (see Table S2 for a list of existing soil surveys in Ireland). Some of these challenges are of crucial importance to Ireland, and require timely action, such as soil restoration, soil remediation and maintaining soils for healthy water resources. Other challenges, such as managing desertification, are less relevant to Ireland due to the humid climate. Nonetheless Ireland has an indirect role in tackling desertification globally via commitments to limit the effects of climate change and to assist in the identification of solutions as mentioned in a recent IPCC report (Mirzabaev et al., 2019). In addition, challenges such as soil sealing are important for much of Europe, especially urbanised areas, but do not feature in the top 15 keywords in the current dataset; recent research has shown that the reuse of construction soils and the wider management of road and housing developments is necessary to maintain biodiversity and address flood risks in Ireland (van der Kamp et al., 2018). Many of the under-represented keywords, such as soil protection, the reuse of soil, soil recycling, soil sealing and excavated soils, are becoming increasingly important on the European Agenda (Directorate-General for Environment, 2021). This likely reflects historical factors, i.e. a persistent lack of research into urban soils; the consequences of such an approach, however, are now obvious and require immediate action, relating to issues such as high rates of soil sealing, lack of urban drainage and lack of urban green spaces (van der Kamp et al., 2018). An additional salient trend relates to the collation and reporting of data on soil remediation and soil restoration. These aspects have traditionally been perceived as largely the remit of private companies and local authorities. As such, the resulting relevant data are rarely reported in peer-reviewed publications. A greater focus for academic research into these crucial areas will have positive implications for effective remediation and restoration on Irish soils.

4.3. Geographic trends

It might be expected that the natural environment and land use patterns for each country should determine the most common settings for soil research, but this is not always the case. For example, the six largest urban centres in the Republic of Ireland (RoI) are located in counties Dublin, Cork, Wexford, Limerick, Galway, and Waterford, but soil research in four out of six of these counties is focused on agricultural settings. In addition, many counties are characterised by comparatively little research, which might relate to a high reliance on non-governmental funding for the conduct of research on non-agricultural settings. The reliance on agriculture is high throughout Ireland, which is due to the importance of agriculture to Ireland's GDP (Hynes and Hennessy, 2012) and much research to date focussed on improving agricultural systems (Higgins et al., 2019) or improving associated soil quality and health (Nag et al., 2022; Wyer et al., 2022).

4.4. Data quality

The publications included in this review differ considerably in breadth and data quality. In general, research in agricultural settings incorporates analysis of a higher number of soil parameters than publications based in other settings, but certain data quality indicators are consistently absent (i.e., use of standard reference materials and blind insertion of duplicates, replicates and standards). This could relate to the use of a consistent methodology by Teagasc, a government body that oversees much of the soil research in Cork and Wexford (where most research on soil is based). For example, we found that publications on agricultural soils often focus on soil nutrients and pH, but soil metal concentrations are more frequently reported in publications for non-agricultural settings. Furthermore, such trends may reflect the regulation of agricultural soils by the European Commission, where monitoring of certain soil parameters is required (European Soil Bureau, 2000; Pollak and Favoino, 2004). Non-agricultural soils, especially urban soils, have not been subject to such regulation and therefore research on non-agricultural soils usually incorporates a wider array of parameters, and publications tend to view parameters in isolation (O'Riordan et al., 2021). Soil monitoring is also required for specific parameters, such as soil moisture, which require measurement in sequence to understand the complex dynamics at play.

Noticeably, there is no consistency in the number of samples used in the studies in the dataset. Most studies either provide small-scale (< 30 samples) or large-scale (< 100 samples) assessments. There has been discussion on the frequency of soil sampling and the repeat sampling of the same site; many authorities have made recommendations pertaining to nutrient management (Teagasc, 2017) and forest soils (Lawrence et al., 2016), while some progress has been made for urban soil sampling (Glennon et al., 2014). A judgement call is necessary for individual sites on whether repeat sampling benefits the analysis of a site or if the sampling of additional sites is a more effective use of resources. Moreover, no single soil parameter is used widely across the analysed dataset, except for the monitoring of land cover and/or land use (see Table S2). Standard soil parameters such as soil pH are reported in only a third of publications, while other important soil parameters such as soil organic carbon, soil moisture and soil porosity are each reported in less than 20 % of publications. This supports existing findings of a lack of standardised soil quality indicators and inconsistent reporting, which in turn impacts monitoring of the SDGs and overall soil assessment (Lehmann et al., 2020; Maurya et al., 2020). The inconsistent application of soil classification systems is a clear barrier to future comparative publications. Our findings support recent calls to standardise methods and develop a minimum dataset (Batjes et al., 2017; Lehmann et al., 2020; Maurya et al., 2020), which would strongly support future research and data-sharing, not only on Irish soils, but globally.

4.5. Future challenges and policy recommendations

Lastly, the dataset reveals a striking lack of recommendations for development of government policy. Instead, the most common recommendation is for additional research. These trends are consistent with a wider disconnect between policy and producers of knowledge (Choi et al., 2005; Howarth et al., 2022; Montuschi, 2017). Furthermore, EU member states differ in their approaches to adopt legislation and there is a lack of homogeneity and coherence across EU member states (Ronchi et al., 2019). Survey data and other research conducted by consultancies is infrequently published in peer-reviewed journals and (inter-)governmental reports and are thus excluded from this review and from similar exercises. It is therefore likely that there is a large body of data on soils that is not readily accessible to academic researchers. Enhanced communication between government bodies responsible for soil monitoring and consultancies will encourage the development of new mechanisms for sharing soil data and study findings among private and public bodies. Key soil surveys for Ireland are summarised in Supplementary Table S2 and provide an overview of the available soil data across Ireland, in addition to the database reported on in this review.

There is clearly a need for additional initiatives to bridge the gap between scientists and policymakers (Berggreen, 2023). One such initiative is currently underway, i.e., EJP Soil (the European Joint Programme on Soil), but many more need to follow in order to obtain and share data that can inform science and policy. Furthermore, global initiatives are already underway, such as the Global Soil Laboratories Network (GLOSOLAN), part of the Global Soil Partnership (GSP) initiative coordinated by the Food and Agriculture Organisation of the UN (FAO). Going forwards, it is critical to develop a consistent approach to the analysis and reporting of data for soil science research to allow meaningful comparative studies and meta-analyses. A second, important, requirement is increased regulation of non-agricultural soils.

5. Conclusions

In this systematic review we outline the nature, scope and quality of recent research on Irish soil, and the extent to which this research aligns with key elements of the European Soil Strategy (ESS) for 2030 (Directorate-General for Environment, 2021). There are major knowledge gaps relating to soil monitoring, restoration, remediation, the maintenance of soils for healthy water resources, soil protection, soil sealing and soil reuse. Critically, most publications fail to provide recommendations for government policy. Our findings also highlight an urgent need for standardisation of soil analysis methodologies and reporting in order to enhance national programmes for soil monitoring and data sharing, and to better facilitate future comparative analyses among publications. Future research should target specific challenges that were highlighted in this study, namely, 'enabling the transition to healthy soils' through funding, societal engagement and soil literacy, and 'we need to know more about soils' through soil monitoring and digital data sharing. Ireland, in particular, lacks crucial data to address future challenges regarding soil protection, reuse, monitoring, restoration, remediation, and the maintenance of soils for healthy water resources, which need to be addressed to achieve Ireland's SDG targets and to implement EU policy.

CRediT authorship contribution statement

H. Binner: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Visualization, Writing – original draft. **L. Andrade:** Visualization, Writing – review & editing. **M.E. McNamara:** Funding acquisition, Supervision, Methodology, Data curation, Conceptualization, Writing – original draft, Writing – review & editing, Validation.

Declaration of competing interest

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

Data availability

The data is shared through a file added in the Appendix of the paper.

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Supplementary materials

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