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Contributions and future priorities for soil science: Comparing perspectives from scientists and stakeholders

Mihai O. Cimpoiasu[1,2] | **Emily Dowdeswell-Downey**[3] | **Daniel L. Evans**[3,4] | **Christopher S. McCloskey**[3,5] | **Lewis S. Rose**[2] | **Emma J. Sayer**[4]

[1]Shallow Geophysics, British Geological Survey, Keyworth, UK
[2]Division of Agricultural and Environmental Sciences, School of Biosciences, University of Nottingham, Sutton Bonington, UK
[3]School of Water, Energy and Environment, Cranfield University, Cranfield, UK
[4]Lancaster Environment Centre, Lancaster University, Lancaster, UK
[5]The James Hutton Institute, Aberdeen, UK

Correspondence
Christopher S. McCloskey, School of Water, Energy and Environment, Cranfield University, Cranfield, Bedford MK43 0AL, UK.
Email: c.mccloskey@cranfield.ac.uk

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Abstract
Soils are a fundamental natural resource but intensifying demands and increasing soil degradation necessitate focussed research into the sustainable use of soils. Since soil functioning is critical for the operations and performance of multiple industries, businesses and municipalities, soil scientists need to actively engage with these bodies to orientate research goals towards stakeholder needs. To achieve this, stakeholder views about the current and potential contributions of soil science to different sectors need to be taken into account when setting the future research agenda. Here, we assessed whether the current and future research priorities of soil science match the needs of four major industrial and environmental sectors: agriculture, ecosystem services and natural resources, waste management, and water management. We used an online questionnaire, distributed to 192 organisations and via social media, to compare stakeholders' and scientists' perceptions of (a) the contributions of soil science to date, (b) the areas not currently served by soil science and (c) future research needs in soil science. Stakeholders generally rated the contributions of soil science to date as 'great' or 'fundamental', but scientists rated the contributions more highly. Respondents identified numerous areas that soil research has not yet sufficiently addressed, which were mostly sector-specific and often overlapped with perceived future research needs. Importantly, stakeholders' and scientists' views of future research priorities differed strongly within sectors, with the notable exception of agriculture, where views were generally consistent. We conclude that soil science may hold unexplored potential in several industrial and environmental sectors. We call for improved research communication and greater stakeholder involvement to shape the future soils research agenda and ensure the sustainable use of soils across multiple areas of society.

Mihai O. Cimpoiasu, Emily Dowdeswell-Downey, Daniel L. Evans, Christopher S. McCloskey and Lewis S. Rose are joint first authors.

Highlights

- How soil science has served, and could further serve, four major sectors was investigated.
- Soil science contributions to agriculture, ecosystem services, waste and water sectors were assessed.
- Stakeholders' and scientists' views on future contributions of soil science frequently differed.
- Greater stakeholder engagement could greatly enhance the impact of soil science in the future.

KEYWORDS

agriculture, ecosystem services, industry-focussed research, research gaps, soil science priorities, future soil research needs, stakeholder survey, waste management, water management

1 | INTRODUCTION

Soils are fundamental for supporting food production, purifying water, storing carbon, cycling nutrients, remediating waste and providing habitats (Blum, 2005). The services provided by soils are critical for the health, productivity and longevity of a society. Delivering on societal demands in the context of climate change and unprecedented population growth places great pressure on global soil resources. Thus, there is a need for an urgent, sustained and widespread effort to protect soils worldwide. In recent decades, soil scientists have increasingly recognised the importance of working with other disciplines through the exchange of concepts, methodologies and data to sustain soils globally (Brevik et al., 2015; Bridges & Catizzone, 1996; Hartemink & McBratney, 2008; Wild, 1989). Such interdisciplinary networks are arguably essential for tackling large-scale, cross-disciplinary objectives such as the UN Sustainable Development Goals (Bouma, 2014; Bouma & Montanarella, 2016) particularly 'End poverty in all its forms everywhere', 'Zero hunger', 'Clean water and sanitation', 'Responsible consumption and production', 'Climate action' and 'Life on land' (Hou et al., 2020).

Evaluating the extent to which the contributions of soil science are addressing complex, global challenges and identifying areas requiring further work is essential. Previously, soil science impact has been quantified by assessing the number of publications and journal impact factors; for example, Hartemink and McBratney (2008) demonstrated that the number of publications increased linearly (by about 545 per year) between 1993 and 2007, while the impact factors of the major soil science journals increased over the periods 1975–2007, with a sharper increase post-2000. Similarly, there has also been a marked acceleration in the number of studies by international organisations in which the global importance of soils features prominently (Hartemink & McBratney, 2008). Such studies at the global scale reflect increasing recognition that soil science can contribute to global challenges, but we nonetheless need to identify whether the investment in, and output from, soil science are benefitting the businesses, industries and stakeholders that rely on soil resources.

Although soil scientists have successfully engaged with other disciplines to set priority areas for soil science, the research agenda to date is still largely determined by academics. Without effective stakeholder engagement, attempts to reframe soils research around policy can result in exaggerated claims of relevance or importance, while falling short in practice (Baveye, 2021a, 2021b). Achieving soil sustainability thus implies the need to reach out to stakeholders from an array of industrial and environmental domains, including agriculture, ecosystem services and natural resources (ESNR), waste management and water management (Davies, 2017; Warkentin, 1999). Reorientating soil science in this way to make it more outward-facing allows it to focus more on – and make a positive contribution to – the local and regional environmental issues faced by these sectors (Simonson, 1991). Moreover, one of the key roles of the soil scientist in interactions with stakeholders is not solely to respond to questions but to assist in defining the issues, knowledge gaps and research needs at the outset (Bouma, 2001).

The aim of this work was threefold. First, we used an online survey to collate opinions from stakeholders working in agriculture, ESNR, waste management and water management with regards to (a) how soil science has contributed to their respective sector's challenges; (b) the challenges that soil science has not currently addressed and (c) the future research needs in soil science. Second, we contrast these opinions with those of soil scientists to identify areas of agreement and disagreement. Finally, by embracing both the views of researchers and stakeholders, we provide clear recommendations for future collaborative soils research to meet the needs of these sectors (Box 1).

2 | METHODS

2.1 | Survey design

We designed a questionnaire to evaluate the impact of soil science beyond academia, how far the research priorities of soil science align with the perceived needs of each sector and to identify potential knowledge and research gaps. Agriculture, ESNR, waste management and water management were identified as major stakeholder sectors for soil science, based on international policy frameworks and in the scientific literature. The questionnaire was built and hosted using the online survey platform Qualtrics (www.qualtrics.com) and was split into five streams: one for each stakeholder sector and one for soil scientists. Respondents self-identified as belonging to one or more of the streams. Each sector-specific stream included 12 questions, while soil scientists were asked six questions regarding the sector their research related to; in addition, five metadata questions were included for all respondents (Supplementary information S1). Questions focussed on (a) the contribution and importance of soil science to the sector, (b) currently under-served soil research needs of the sector, and (c) future soils research priorities. Questions were presented to respondents based on the sector or sectors they identified as working within. The survey was built to permit respondents to navigate rounds of questions multiple times so that they could answer for multiple sectors. Hence, those who selected multiple sectors (including soil science) were given separate, comparable questions for each sector (Supplementary information S1). The soil scientists' stream was further divided into a set of questions relating to each industry, and soil scientists were asked to answer the questions for the sector(s) their research best related to. Hereafter the soil scientists' streams are referred to as $\text{soil}_{\text{agriculture}}$, $\text{soil}_{\text{ESNR}}$, $\text{soil}_{\text{waste man}}$ and $\text{soil}_{\text{water man}}$. The survey questions and flowchart outlining the survey pathways are given in Supplementary information S1 and S2. Of the 12 questions put to stakeholders, three required nominal or binary answers, four presented possible responses on a five-point Likert scale and five required open-text responses. Of the six questions soil scientists were asked, three presented options on the Likert scale and three required open-text answers. Ethical approval for the survey was granted by Cranfield University.

2.2 | Survey circulation

The survey ran for 3 months from 18 December 2019 to 18 March 2020. Two approaches were taken to distribute the survey. First, an online link to the survey was circulated via Twitter (posted 18 December 2020 and 3 February 2020). The posts achieved a combined total of 12,166 views; tweets were clicked 127 times and retweeted 43 times; the link to the survey was clicked 20 times.

Second, a contact list of stakeholders within each sector was collated from internet searches and personal knowledge using publicly available organisational email addresses. The contact list included policymakers, industrial bodies, charities and commercial enterprises. Given that it was important to target a broad range of organisations relevant to each sector, those selected spanned local to international scales. We focussed on UK institutions to keep the survey circulation manageable. In total, 192 stakeholder organisations were contacted; of these, 36 were primarily related to agriculture, including national- and regional-level bodies, unions, agribusinesses, bodies representing different farming sectors and organisations promoting particular farming practices, such as 'nature-friendly' or 'organic' farming. A total of 41 national and regional organisations connected to ESNR were contacted, including charities conserving the natural environment and promoting recreational use of the UK's natural capital, bodies responsible for natural resource management and policy and organisations working in ecosystem services markets. The 81 contacted organisations relating to waste management consisted predominantly of waste disposal and recycling businesses ranging from the local to national scale. For water management, 25 organisations were contacted, including businesses and charities involved in the conservation of river environments, as well as those working in flood risk, flood protection and water sustainability. Nine recognised learned societies and organisations affiliated with soil science were contacted (national and international in reach), such as the British Society of Soil Science and the International Union of Soil Sciences, who advertised the survey in their newsletters. To ensure respondents provided open and frank views, the surveys were completed anonymously, and we therefore cannot assign responses to a specific organisation or field. A full list of organisations contacted is included in Supplementary information S3.

2.3 | Survey analysis

Survey data were subject to initial processing in which we removed responses that were nonsensical or insufficiently complete for continued analysis ($n = 39$). Respondents that had identified a sector and sub-sector (or, for soil scientists, only identified the sectors their research relates to) but had not completed any subsequent questions were not considered for further analysis. Hereafter 'stakeholders' refers to respondents answering sector-specific questions, and 'soil scientists' refers to respondents answering soil scientist-specific questions.

Following an initial screening, stakeholders who had identified their sector as 'other' were assessed, and those with relevant, albeit tangential, connections with our four selected sectors were reassigned ($n = 15$). In instances where a single respondent working in several sectors had answered a set of questions for each sector, each set of responses was treated as independent. In some cases, respondents referred to answers previously given for another sector rather than producing a new answer, in which case, referenced answers were included in the analysis for both questions. However, it is possible that participants submitted more thorough responses for the sector they first answered for. Additionally, respondents were able to answer both as a stakeholder and as a soil scientist. Responses on behalf of a sector were classed as stakeholder responses, even if the participant was a soil scientist working within that sector. In some instances, identical answers were received for equivalent stakeholder and soil scientist-specific questions. Although we assumed that the respondents did this intentionally, it is possible that such identical answers may have reduced differences between the views of stakeholders and soil scientists.

For closed questions requiring a binary answer (e.g., 'have you ever worked with soil scientists?') percentages for each answer were calculated to allow comparison among sectors. Likewise, questions requiring the respondent to answer using a Likert scale were analysed by calculating the percentage of responses for each category on the scale. To identify keywords in open-text responses, themes emerging from each response were identified through qualitative analysis to develop an initial long-list based on the full dataset. Synonymous and interchangeable themes were then grouped to create a shortlist of higher-order keyword categories (Supplementary information S4). Finally, keywords were assigned to each open-text response and the assignments were reviewed by individual authors to ensure consistent keyword application. By assigning common higher-order keyword categories to open text-field responses, we were able to compare responses among sectors more consistently; however, this approach eroded some of the nuances of individual responses. It was further necessary to combine multiple related concepts into categories (Supplementary information S4) to keep the number of keywords manageable for analysis and presentation, but this also sacrificed some nuance. To visualise the differences in the use and frequency of keywords across questions and sectors, heat maps were created using Python 3.6 (Python Software Foundation, n.d.) in which keywords were allocated to cells, with cell colour representing the percentage of responses that had been assigned that keyword.

Two open-text questions probed potential or missing contributions of soil science to stakeholder sectors ('In what ways could soil scientists contribute to (sector)?' and 'What major challenges in (sector) are not currently served by soil science?'). To display how keywords and concepts were connected between and within answers to these two questions, network maps were created using VOSviewer 1.6.15 (van Eck et al., 2010). To explore differences in the views of stakeholders and soil scientists, two maps were created for each question; the first map combined all responses from stakeholders from all four sectors and the second map presented responses from soil scientists. The network maps displayed a node for each assigned keyword and the node size represented the number of responses that keyword was assigned to. To ensure the network maps were clear, keywords that were assigned to two or fewer responses in the sector maps, or just one response in the soil scientist maps, were omitted; this difference in cut-off threshold was due to substantially greater numbers of responses from stakeholders. Lines indicate links among keywords that co-occurred in a single response. Hence, the network maps provided a visualisation of the keywords that were more frequently cited together, allowing us to explore how far respondents overlapped in their views. The keywords with the most connections within each network map were identified and VOSviewer grouped keywords into clusters based on the frequency of inter-keyword connections. We explored whether keywords within a cluster raised similar, interlinked, points or themes, potentially highlighting different ways of viewing, or approaches to tackling, the challenges facing the four sectors. For each network map, a list of the keywords assigned to each cluster can be found in Supplementary information S5.

3 | RESULTS

3.1 | Overall survey results

A total of 199 questionnaires containing answers beyond the initial identification with a sector or as a soil scientist/stakeholder were received; of these, 160 were more than 70% complete. Of the 199 completed questionnaires, 96 were related to agriculture, 61 to ESNR, 31 to waste management and 24 to water management. Of the 34 respondents that selected 'other', 15 had their answers reassigned to another sector based on the definition they provided of their work. Of the

199 respondents, 53 identified as soil scientists and of these, 37, 26, 9 and 11 related their research to agriculture, ESNR, waste management or water management, respectively. There was some cross-over among sectors, whereby 52 respondents provided answers for more than one sector, including 30 who answered both for a sector and as a soil scientist. Over two-thirds of stakeholders had previously worked with soil scientists, and at least 90% had applied soil science in their work (Supplementary information S6).

Location information was provided by 147 respondents, with the majority based in the UK ($n = 114$; 78%). Most respondents were alerted to the questionnaire by email ($n = 121$; 82%), compared to relatively few by Twitter ($n = 4$; 3%) or by newsletters from soil science organisations ($n = 9$; 6%).

3.2 | Current contributions of soil science

Across the four sectors, 97% of stakeholders considered soils to be of 'high' importance or 'essential', which was similar to the proportion of soil scientists (98%; Figure 1a). While agriculture was the only sector in which all stakeholders considered soils to be highly important or essential, this opinion was shared by over 90% of stakeholders in all sectors other than waste management (87%). However, in contrast to the opinion of waste management stakeholders, all soil scientists working in relation to waste management felt soils were of 'high' or 'essential' importance.

Most respondents rated the contribution of soil science to each sector as highly positive (Figure 1b), but soil scientists held a more positive opinion of the contribution of soil science than stakeholders, with 93% of all soil scientists, but only 79% of stakeholders, considering the contribution of soil science to have been 'fundamental'. The opinion of stakeholders working in waste management, contrasted with those in the other sectors, with only 57% of responses considering the contribution to be 'great' or 'fundamental', compared to 89% of soil scientists in the same sector.

In response to the question 'In what ways has soil science research contributed to (your sector)?' there was some overlap in recurring topics between stakeholders and soil scientists but also several important differences, depending on sector (Figures 2–5). Within stakeholder responses the majority of keywords were referenced by

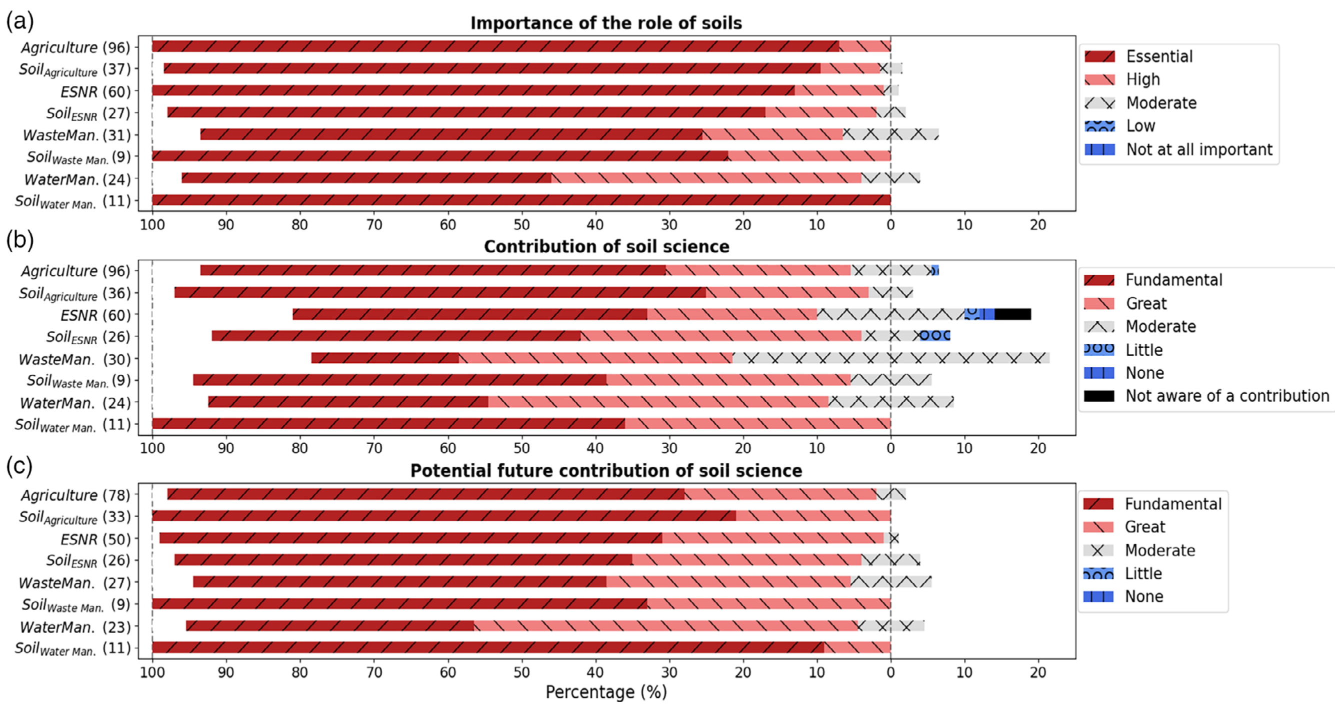

FIGURE 1 Likert scale responses regarding (a) the importance of soils, (b) the contribution of soil science to date, and (c) the potential future contribution of soil science to key stakeholder sectors; responses are grouped by sector and by soil scientists related to each sector. Likert scale responses are given as a proportion of the total number of responses for each group. Soil$_{Agriculture}$ refers to soil scientists working within agriculture; ESNR refers to ecosystem services and natural resources; Soil$_{ESNR}$ refers to soil scientists working within ESNR; WasteMan. refers to waste management; Soil$_{WasteMan.}$ refers to soil scientists working within waste management; WaterMan. Refers to water management and Soil$_{WaterMan.}$ refers to soil scientists working within water management. The number of responses for each question are presented in parentheses [Color figure can be viewed at wileyonlinelibrary.com]

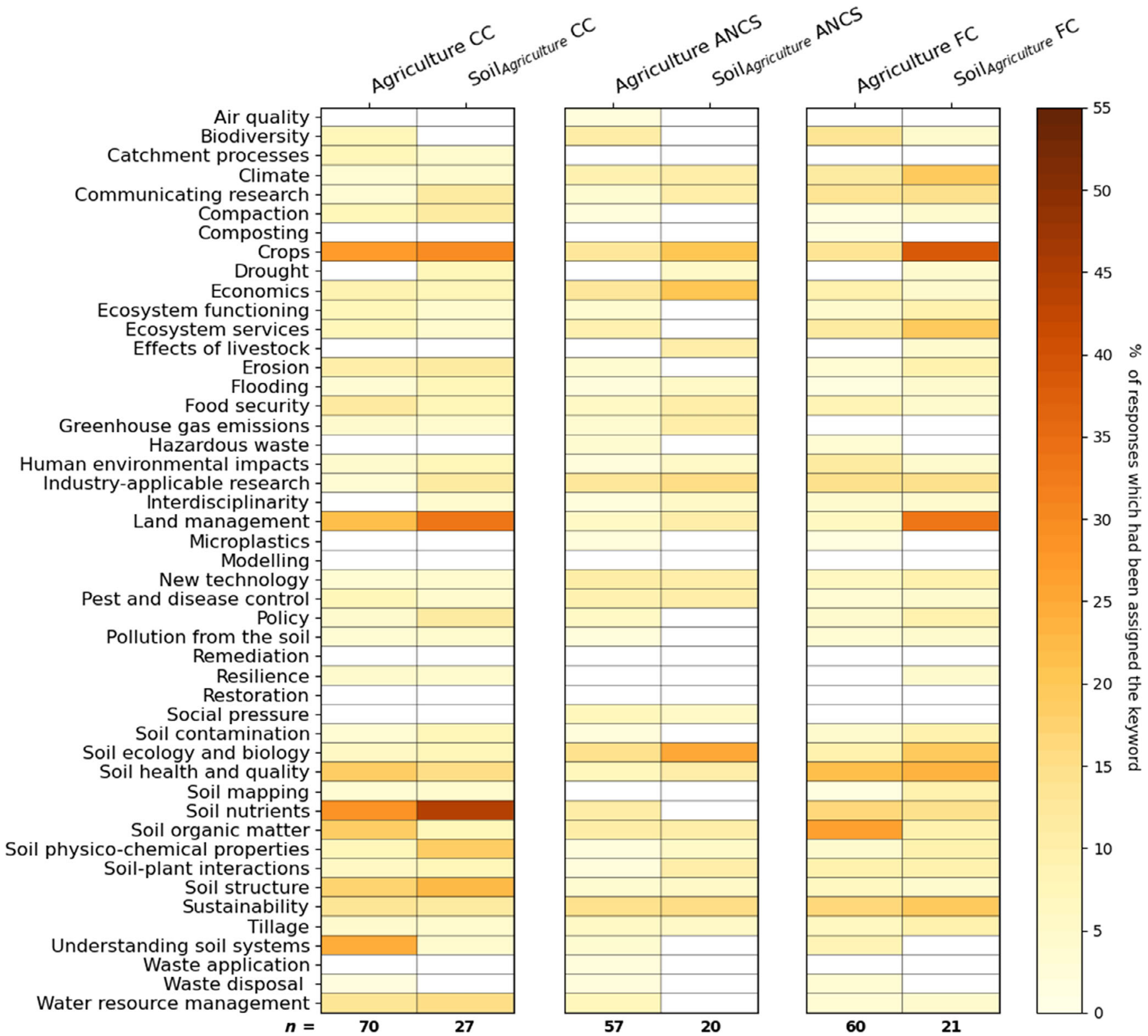

FIGURE 2 Heat map displaying keyword assignments to qualitative responses, comparing stakeholders working in agriculture and soil scientists whose research relates to agriculture, whereby CC refers to current contributions of soil science; ANCS refers to areas not currently served by soil science; FC refers to potential future contributions of soil science. Keyword assignments are given as the proportion of the total number of keywords assigned to each response, and the total number of responses (n) to each question are given at the bottom of each column [Color figure can be viewed at wileyonlinelibrary.com]

members from two or fewer sectors, suggesting that respondents' views on soil research contributions were relatively sector-specific. Two key areas of broad importance emerged: *soil nutrients* and *soil organic matter*, which were mentioned in at least 18% of the responses from three sectors (Figures 2–5). Within soil scientists' responses less than a quarter of keywords were referenced in relation to more than two sectors. However, the key areas focussed upon were less sector-specific than those referenced by stakeholders. *Pollution from the soil* and *soil nutrients* were both referenced by at least 17% of responses in three sectors, while *crops*, *erosion*, *soil health and quality* and *sustainability* were each referenced by at least 11% in three industries. Full details of keyword totals for each question are presented in Supplementary information S7.

Within agriculture, there was substantial agreement between stakeholders and soil scientists. Stakeholder responses included a broad and varied range of topics (74% of all keywords) and no one keyword was mentioned in more than 29% of responses (Figure 2). The most frequently recurring topics in stakeholder responses related to the management and productivity of the soil,

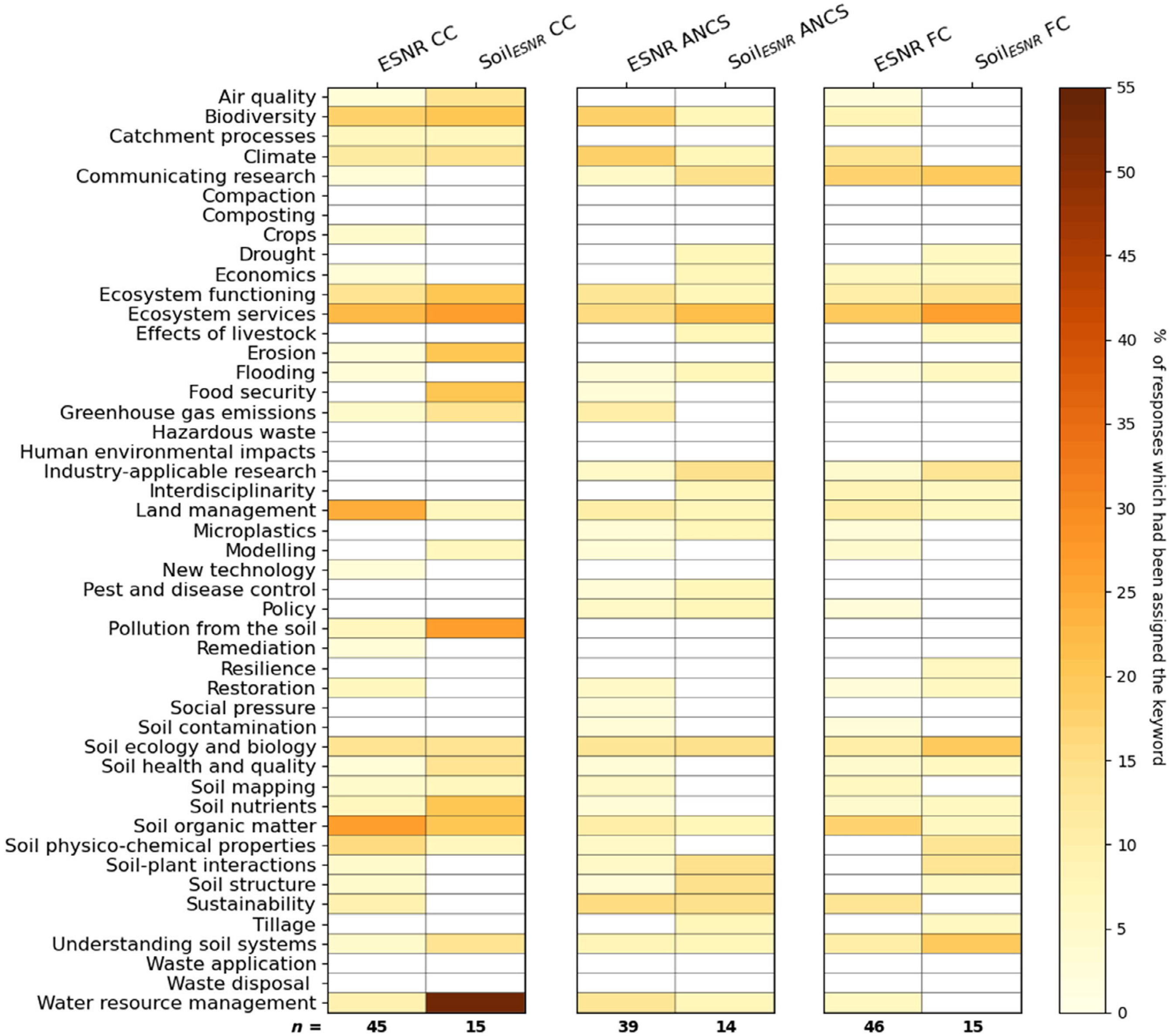

FIGURE 3 Heat map displaying keyword assignments to qualitative responses, comparing stakeholders working in ecosystem services and natural resources (ESNR) and soil scientists whose research relates to ESNR, whereby CC refers to current contributions of soil science; ANCS refers to areas not currently served by soil science; FC refers to potential future contributions of soil science. Keyword assignments are given as the proportion of the total number of keywords assigned to each response, and the total number of responses (*n*) to each question are given at the bottom of each column [Color figure can be viewed at wileyonlinelibrary.com]

principally: *soil nutrients*, *crops*, *understanding soil systems* and *land management*. The responses of soil scientists working in agriculture focussed on similar topics, although with a much greater focus on *soil nutrients* (referenced in 44% of soil scientists' responses, compared to 29% of stakeholder responses), followed by *land management*, *crops* and *soil structure*.

ESNR stakeholder views of the contribution of soil science focussed on fewer topics than those from agriculture (60% of all keywords) and highlighted *soil organic matter*, *land management* and *ecosystem services* as key areas to which soil science research has contributed (Figure 3). Soil scientists' answers showed a substantially greater focus on *water resource management* (referenced in 53% of responses, compared to 9% of ESNR stakeholders), followed by *ecosystem services* and *pollution from the soil*.

Responses from stakeholders in waste management included fewer keywords (38% of the total), with the greatest focus on *sustainability*, which was referenced in 44% of responses, more than double the occurrence compared to the responses from other sectors (Figure 4). Other frequently used keywords were *soil nutrients*, *composting* and *soil contamination*. A third of the responses by soil

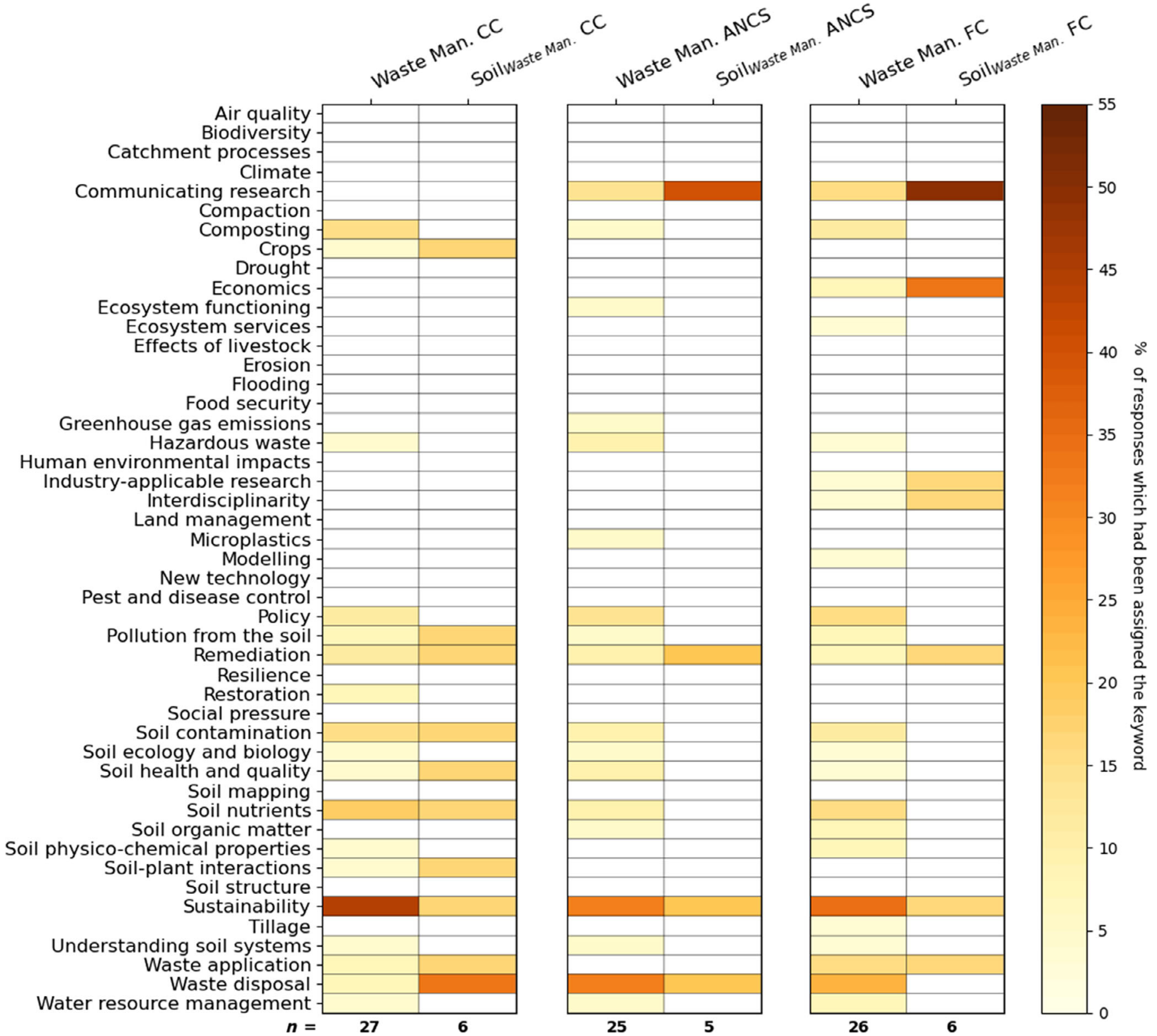

FIGURE 4 Heat map displaying keyword assignments to qualitative responses, comparing stakeholders working in waste management and soil scientists whose research relates to waste management, whereby CC refers to current contributions of soil science; ANCS refers to areas not currently served by soil science and FC refers to potential future contributions of soil science. Keyword assignments are given as the proportion of the total number of keywords assigned to each response, and the total number of responses (*n*) to each question are given at the bottom of each column [Color figure can be viewed at wileyonlinelibrary.com]

scientists considered soil science to have contributed to *waste disposal*, although only six scientists answered the question.

The views from stakeholders in the water management sector also featured fewer keywords (44%). Soil scientists strongly emphasised *water resource management* and *pollution from the soil*, and both groups also frequently mentioned *catchment processes* (Figure 5). However, stakeholders also referred to *soil nutrients*, and *soil organic matter*, whereas soil scientists highlighted *flooding* as a strong contribution of soil science to the sector to date.

3.3 | Areas not currently served by soil science

Regarding areas not currently served by soil science, the majority of keywords were referenced in responses by stakeholders from at most two sectors, although *sustainability* stood out, mentioned by at least 14% of stakeholders from three sectors. For soil scientists, the majority of keywords were again used with regard to two or fewer sectors. However, *industry-applicable research* and *communicating research* were both referenced by at

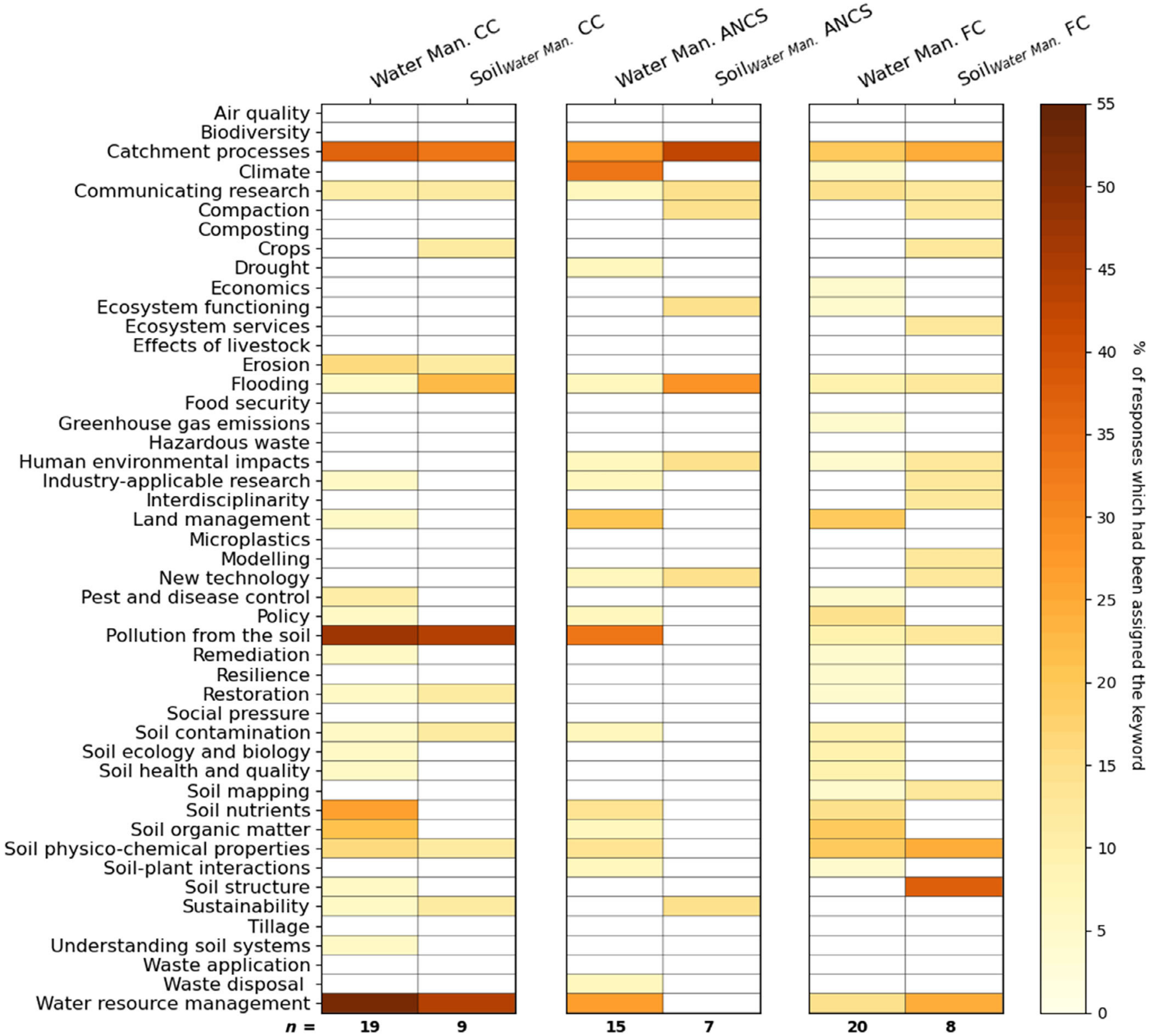

FIGURE 5 Heat map displaying keyword assignments to qualitative responses, comparing stakeholders working in water management and soil scientists whose research relates to water management, whereby CC refers to current contributions of soil science; ANCS refers to areas not currently served by soil science and FC refers to potential future contributions of soil science. Keyword assignments are given as the proportion of the total number of keywords assigned to each response, and the total number of responses (n) to each question are given at the bottom of each column [Color figure can be viewed at wileyonlinelibrary.com]

least 12% of soil scientists in relation to all four sectors, suggesting that soil scientists view these as challenges transcending individual industries (Figures 2–5).

Responses from agriculture stakeholders identified a broad range of areas not currently served by soil science (referring to 81% of all keywords) and, compared to current contributions, an overall shift away from a focus on productivity was apparent. Stakeholder responses highlighted *soil ecology and biology*, *sustainability*, *crops*, *economics* and *industry-applicable research* (Figure 2) as under-served areas, and a similar range of topics was addressed by soil scientists, although with a greater focus on *soil ecology and biology*, *crops* and *economics*.

Responses from ESNR stakeholders were more focussed (mentioning 60% of keywords), particularly referencing *biodiversity*, *climate*, *ecosystem services* and *sustainability* as areas not currently served by soil science (Figure 3). Soil scientists also primarily identified *ecosystem services* as an under-served area but mentioned many other topics such as *communicating research*, *industry-*

applicable research, *soil ecology and biology*, *soil–plant interactions*, *soil structure* and *sustainability*.

The combined waste management stakeholders' responses showed a narrower focus (referencing 38% of keywords) and focussed on *sustainability* and *waste disposal* as areas currently under-served by soil science, alongside other issues including *communicating research* and *policy* (Figure 4). The soil scientists who answered also frequently referred to *communicating research*, *sustainability* and *waste disposal*, alongside *remediation* as under-served areas.

Water management stakeholders' responses covered a similar breadth of topics to waste management (38% of keywords). A third of stakeholders referenced *climate* and *pollution from the soil* as currently under-served areas, with *catchment processes* and *water resources management* also mentioned frequently (Figure 5). Of the soil scientists who responded in relation to water management, the greatest focus was on *catchment processes* and *flooding* as areas currently under-served by soil science.

The network maps grouping keywords given in responses to the question 'What major challenges in (the sector your research relates to) are not currently served by soil science?' showed a distinct clustering in the use of terms between stakeholders and soil scientists. The keywords from stakeholder responses were grouped into four clusters (Figure 6) with a degree of thematic grouping: one cluster clearly focussed on soil science dissemination and application (Figure 6, red cluster, e.g., *communicating research*, *industry-applicable research* and *policy*), and one on soil degradation and contamination (Figure 6, blue cluster, e.g., *microplastics*, *soil contamination*, *soil health and quality* and *waste disposal*). Nevertheless, almost all keywords were linked to multiple clusters and many were highly interconnected. The most interconnected keywords were *sustainability* (connected to 27 of the 33 keywords), *soil ecology and*

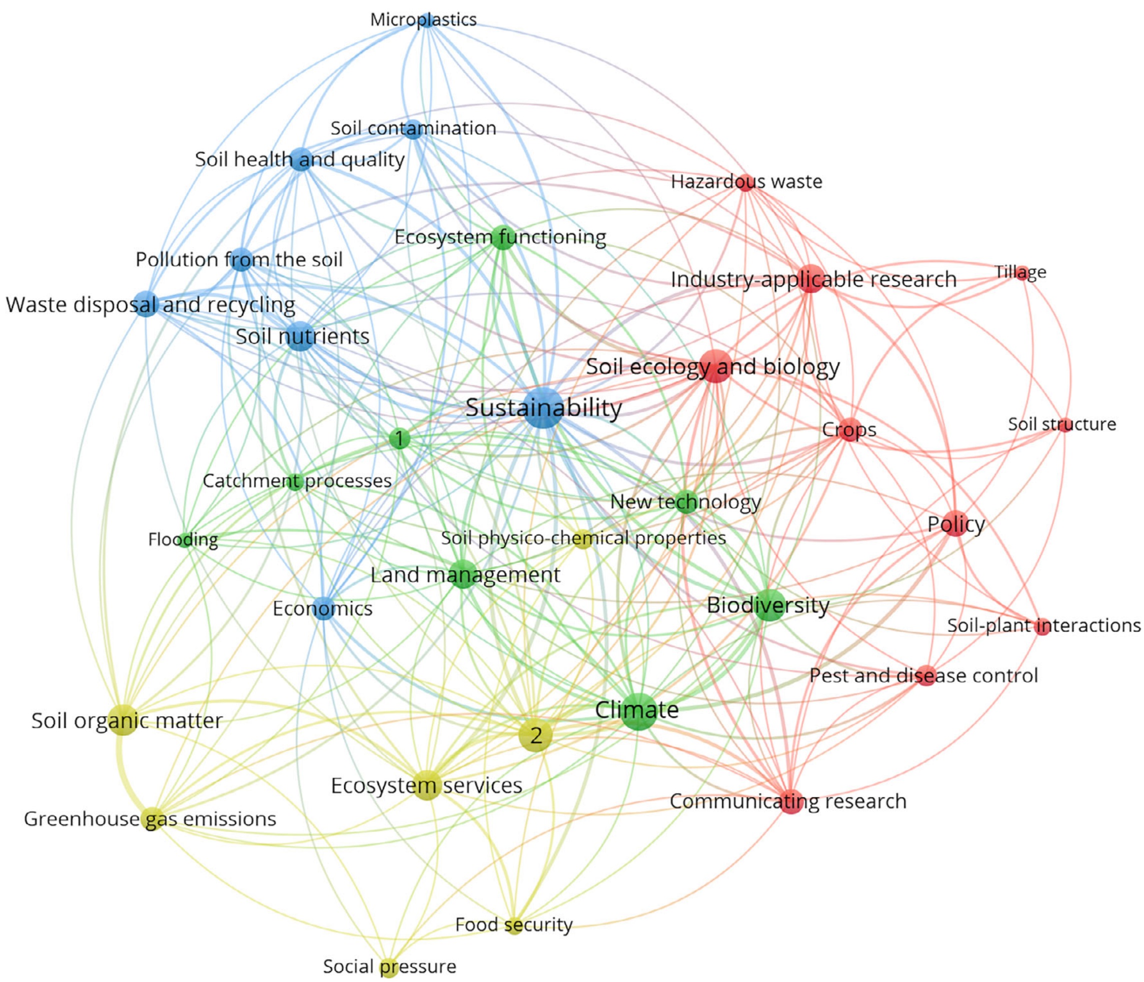

FIGURE 6 Network map showing keywords assigned to stakeholders' responses to the question 'What major challenges in (your sector) are not currently served by soil science?' Results from the four sectors are combined and keywords assigned to two or fewer answers are not shown. Colours indicate clusters of keywords based on the frequency of co-occurrence in responses. Keywords that were too long to fit on the map are represented by numbers, where 1 = *understanding soil systems* and 2 = *water resource management*. See Supplementary information S5 for lists of keywords in each cluster [Color figure can be viewed at wileyonlinelibrary.com]

biology (26 connections), *climate* (22 connections), *water resource management* (22 connections), *industry-applicable research* (19 connections) and *ecosystem services* (19 connections). By contrast, keywords from soil scientists' responses (Figure 7) are split into three clusters. Of the two largest clusters one was broadly related to soil physical processes and properties (Figure 7, green cluster; e.g., *drought*, *flooding*, *soil organic matter* and *soil structure*), and the other to broader societal issues (Figure 7, red cluster; e.g., *communicating research*, *economics*, *ecosystem services* and *human environmental impacts*). Several keywords were heavily interconnected, including *soil ecology and biology* (connected to 17 of the 25 keywords), along with *flooding*, *industry-applicable research*, *land management* and *sustainability* (each with 15 connections).

3.4 | Future soil science contributions to these sectors

Overall, respondents used a greater proportion of keywords to describe the potential future contributions of soil science to each sector, indicating a positive shift in the perception of soil science's potential to address challenges going forward across all sectors (Figure 1c), and implying that respondents from all sectors believe soil science holds an unrealised potential. Many of the areas previously identified as under-served areas were also flagged as potential future contributions of soil science (Figures 2–5). The majority of keywords used to describe the potential future contributions of soil science were referenced by two or fewer sectors, demonstrating that the future research needs are sector-specific. However, the importance of *communicating research*, which does not naturally pertain to a particular industry, was referenced in at least 13% of responses across all four sectors by both stakeholders and soil scientists. Under 20% of keywords were referenced by soil scientists in relation to three or more sectors, although *industry-applicable research* was suggested as a future contribution in 13% of soil scientists' responses across all four sectors. Whereas stakeholders frequently referenced *soil organic matter* and *sustainability*, soil scientists more often referred to *crops* and *ecosystem services*.

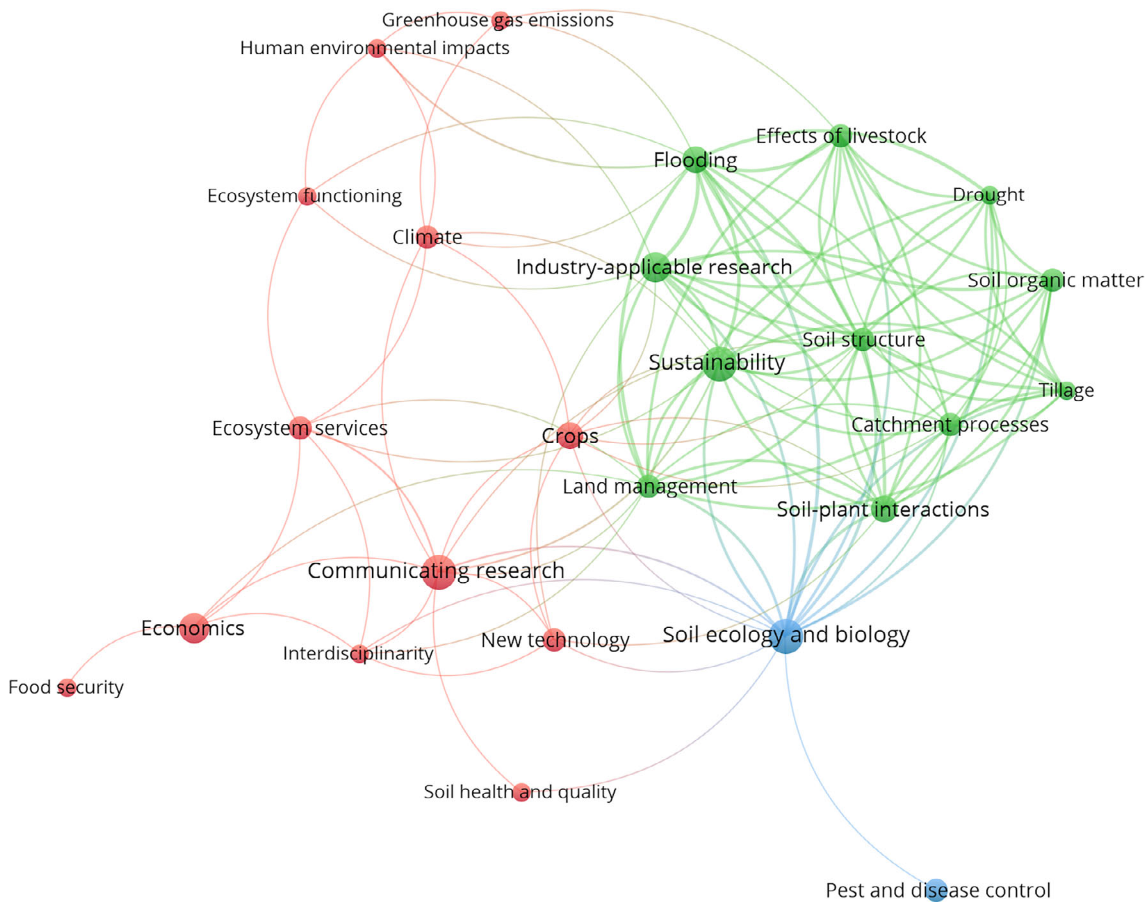

FIGURE 7 Network map showing keywords assigned to soil scientists' responses to the question 'What major challenges in (the sector your research relates to) are not currently served by soil science?' Results from the four sectors are combined. Keywords assigned to only one answer are not shown. Colours indicate clusters of keywords based on the frequency of co-occurrence in responses. See Supplementary information S5 for lists of keywords in each cluster [Color figure can be viewed at wileyonlinelibrary.com]

Responses from agriculture stakeholders referenced a broad range of potential future contributions by soil science (77% of all keywords) and demonstrated little consensus (Figure 2). The area most frequently suggested was *soil organic matter* (27%), followed by *soil health and quality* (22%), *soil nutrients* and *sustainability* (both 17%). Soil scientists also frequently cited *soil health and quality* as a future contribution to agriculture, and *crops* and *land management* were also seen as priorities for future research (38% and 33%, respectively). In particular, soil scientists emphasised sustainable production (e.g., 'More sustainable crop production' and 'Underpins drive for sustainable intensification').

The ESNR stakeholders' responses about the potential future contributions of soil science were narrower in focus but nonetheless referenced 51% of keywords. Topics most frequently considered as potential future contributions by stakeholders included *ecosystem services* followed closely by *soil organic matter* and *communicating research*, but there was little consensus, with no keyword referenced in more than 20% of responses (Figure 3). Soil scientists also considered *ecosystem services* (26%) as the main potential future contribution from soil science, followed by *communicating research*. However, in contrast to stakeholders, soil scientists also emphasised *soil ecology and biology*, and *understanding soil systems* as potential future contributions of soil science to the sector.

The greatest positive shift in the perception of soil science's potential to address challenges going forwards was recorded for waste management (Figure 4). Within stakeholder responses, roughly half of all keywords were seen as potential areas for future contributions of soil science (49%). *Sustainability* and *waste disposal* were particularly highlighted as potential future contributions, with *communicating research*, *policy*, *soil nutrients* and *waste application* also frequently referenced (Figure 4). Soil scientists referenced fewer keywords to describe the potential of soil science to address future challenges in waste management, with an emphasis on *communicating research* and *economics*.

Responses from water management stakeholders referenced 51% of keywords to describe potential future contributions of soil science. The most frequently mentioned terms were *catchment processes*, *land management*, *soil organic matter* and *soil physico-chemical properties* (Figure 5). In accordance with stakeholder responses, soil scientists also referenced *catchment processes* and *soil physico-chemical properties*, although the most frequently mentioned future contribution suggested by soil scientists was *soil structure*.

The network maps grouping keywords given in responses to the question 'In what ways could soil scientists further contribute to (the sector your research relates to)?' showed some thematic clustering in the use of terms by stakeholders, but not by soil scientists. Keywords used in stakeholders' views about the potential future contributions from soil science fell into five clusters (Figure 8). In one cluster, the prominent theme was research communication and application (Figure 8, red cluster, e.g., *communicating research*, *industry-applicable research* and *interdisciplinarity*). Another cluster referenced environmental concerns in terms of both impacts on soils and the provision of services (Figure 8, green cluster, e.g., *climate*, *ecosystem services*, *food security*, *human environmental impacts* and *sustainability*), whilst a third addressed biological aspects of soils (Figure 8, blue cluster, e.g., *biodiversity*, *ecosystem functioning*, and *soil biology and biodiversity*). However, all keywords were heavily interlinked, with none limited to linkages within a single cluster, indicating broad views of the potential future contributions of soil science. The most heavily interlinked keywords were *soil health and quality* (connected to 32 of the 37 included keywords), *soil nutrients* (31 connections), *communicating research* (29 connections) and *soil organic matter* (29 connections). By contrast, the key topics that soil scientists considered to be potential future contributions were grouped into four clusters (Figure 9), with no distinct or easily discernible themes uniting keywords within clusters. The most highly interconnected keywords differed from those in the stakeholder response map, featuring *land management* (connected to 28 of 33 keywords), *crops* (21 connections) and *industry-applicable research* (21 connections).

4 | DISCUSSION

With the notable exception of agriculture, our survey demonstrated that research priorities in soil science are not necessarily aligned with the perceived needs of key industrial and environmental sectors, indicating that improved dialogue between soil scientists and stakeholders could greatly improve the societal impact of soils research in future. The general importance of soils to each sector was recognised by all respondents but there were marked differences in the views of stakeholders and soil scientists around current knowledge gaps and the potential future contributions of soil science. It is important to note that a large proportion (>62%) of stakeholders within each sector also identified as soil scientists, but the two sectors with the largest discrepancies between stakeholders and scientists (ESNR and water management) also had the highest proportion of respondents who identified only as soil scientists. Nonetheless, the majority of respondents from both groups appreciated the potential for soil science to make major contributions to all sectors in the

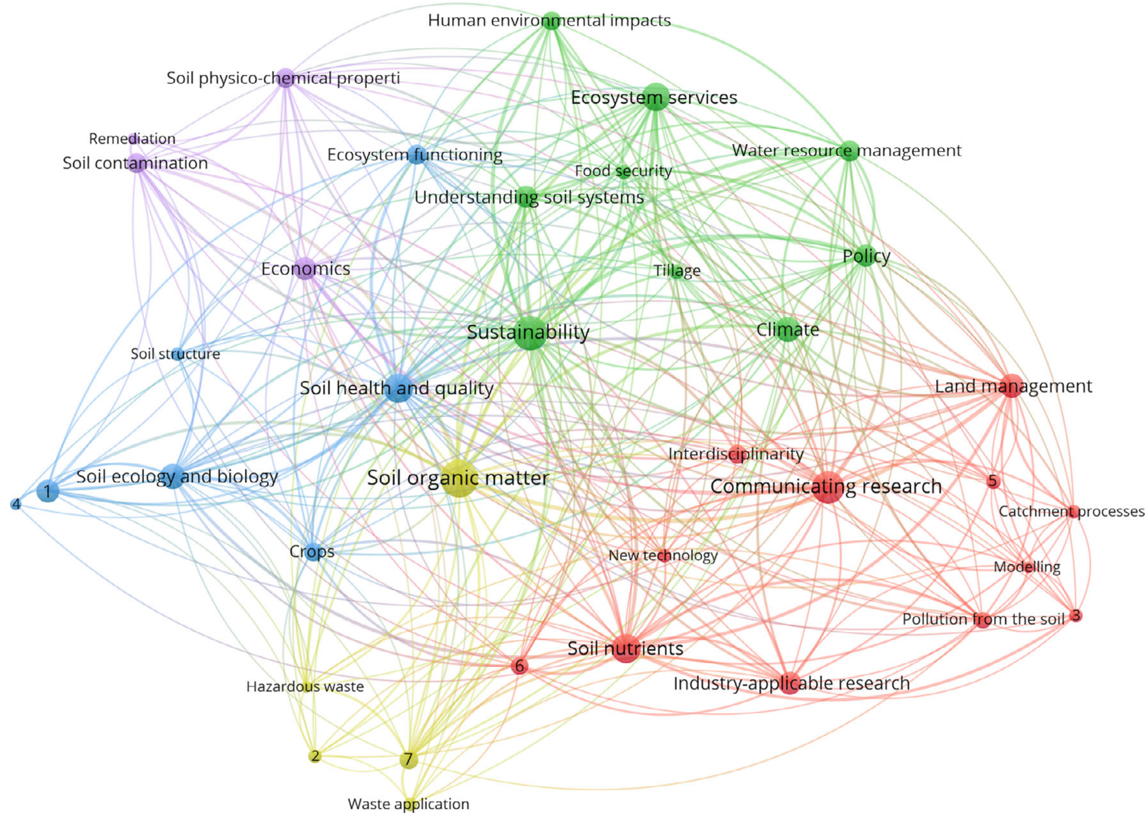

FIGURE 8 Network map showing keywords assigned to responses from those working in each sector to the question 'In what ways could soil scientists further contribute to (your sector)?' Results from the four sectors are combined. Keywords assigned to two or fewer answers are not shown. Colours indicate clusters of keywords based on the frequency of co-occurrence in responses. Keywords that were too long to fit on the map are represented by numbers, where 1 = *biodiversity*; 2 = *composting*; 3 = *flooding*; 4 = *pest and disease control*; 5 = *soil mapping*; 6 = *soil–plant interactions* and 7 = *waste disposal and recycling*. See Supplementary information S5 for lists of keywords in each cluster [Color figure can be viewed at wileyonlinelibrary.com]

future, in particular by focusing on currently under-served issues. Here, we discuss some of the discrepancies between the views of stakeholders and scientists to highlight how effective stakeholder engagement can shape the research agenda for both fundamental and applied soil science in the future.

4.1 | The status quo: Current contributions of soil science

Our survey showed that the current contribution of soil science to each sector was considered either 'fundamental' or 'great' by the majority of stakeholders (Figure 1b), but soil scientists generally rated the contributions more highly. In addition, the keywords stakeholders used to describe the current contributions of soil science were largely sector-specific, whereas soil scientists used a greater number of common keywords across sectors. The mismatch between the views of scientists and stakeholders suggests that soil scientists may overestimate the broader impact of their work, possibly because increased publication rates are regarded as a measure of increasing impact (Hartemink & McBratney, 2008), which does not necessarily reflect the practical application of soils research in industrial and environmental sectors. The difference in opinions between scientists and stakeholders regarding the current contributions of soil science differed markedly among sectors.

Of the four sectors included in our survey, it is perhaps unsurprising that the agreement between soil scientists and stakeholders regarding the current contributions of soil research was greatest in the agricultural sector. Soils have long been viewed as critical to agricultural productivity (Hou et al., 2020) and participatory research involving scientists and farmers has been used for decades to improve production (Ingram et al., 2010; Stoate et al., 2019). Most respondents in our survey placed a particular emphasis on *crops*, *soil nutrients* and *land management*, which reflects a high demand from the agricultural sector for research on topics such as nutrient management and land reclamation (Anderson, 2006). The greater emphasis of scientists on *soil physico-chemical properties* (including *soil structure*) compared to the greater

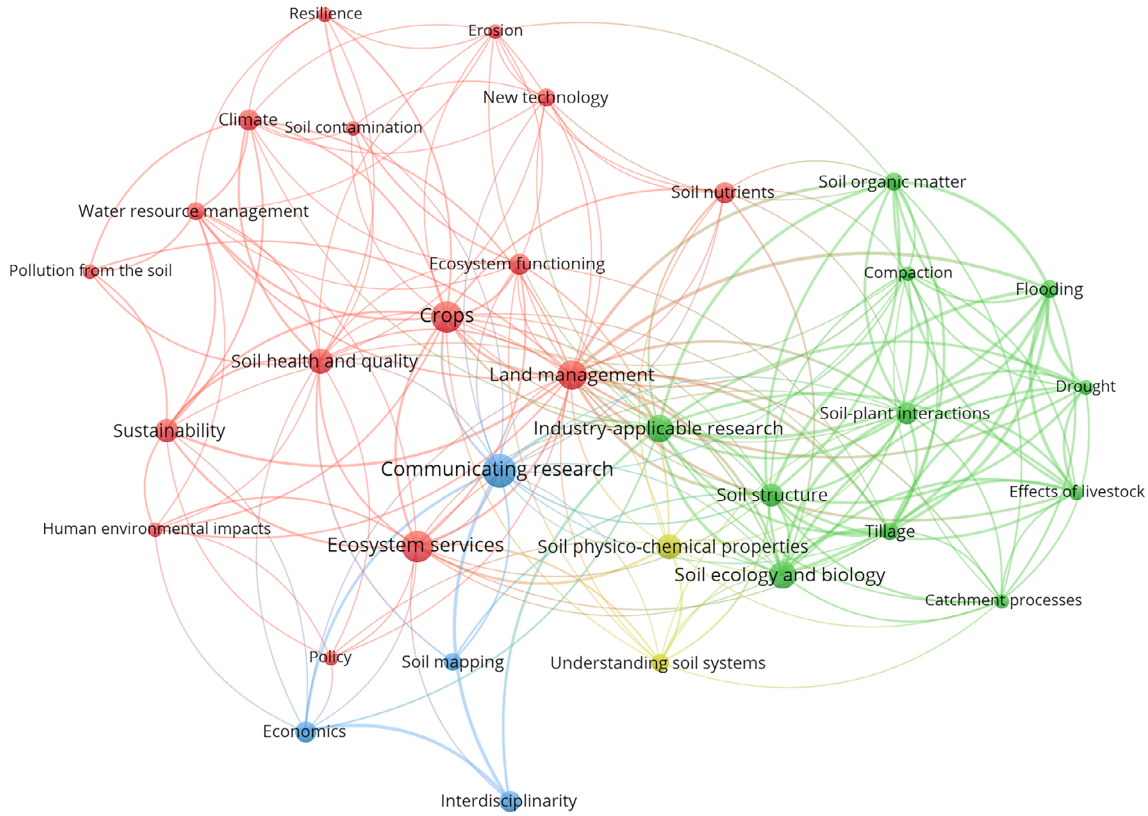

FIGURE 9 Network map showing keywords assigned to soil scientists' responses to the question 'In what ways could soil scientists further contribute to (the sector your research relates to)?' Results from the four sectors are combined. Keywords assigned to only one answer are not shown. Colours indicate clusters of keywords based on the frequency of co-occurrence in responses. See Supplementary information S5 for lists of keywords in each cluster [Color figure can be viewed at wileyonlinelibrary.com]

emphasis of stakeholders on *soil health and quality* could indicate differences in terminology, rather than perceived contributions. Scientists are likely more used to technical descriptions of the multiple physical and chemical characteristics of soils such as pH, particle size distribution, texture or mineralogy which we grouped under '*soil physico-chemical properties*' (Field et al., 2011; Hou et al., 2020). However, the use of distinct keywords may also point to a contrast between a focus on soil function (defined as the health of a soil) among stakeholders, and a focus among soil scientists on a more detailed analysis of the characteristics of a soil.

In the ESNR sector, our survey revealed several important discrepancies between stakeholders' and scientists' views of the current contributions of soil science to the sector. Commonly used keywords by both groups are largely related to the functioning of healthy ecosystems and potential threats to ecosystem function, which highlight widespread concerns about multiple threats to soils and the public benefits they provide (Mammola et al., 2019; Sanaullah et al., 2020). However, responses from ESNR stakeholders mainly considered the terrestrial environment, whereas soil scientists placed greater emphasis on aquatic ecosystems. It is possible that the cohort of scientists answering these questions collectively had a disproportionate interest in aquatic- or marine-based ecosystems, which would explain why frequent references in stakeholder responses to *land management* and *soil organic matter* were not mirrored by soil scientists, who placed greater emphasis on *water resource management* and *pollution from the soil*.

Stakeholders in waste management valued the current contributions of soil science to the sector much less than soil scientists, although few soil scientists working in this sector participated in our survey (Figure 1b). The discrepancy between stakeholders and soil scientists persisted in the choice of keywords describing the current contributions of soil science to the sector. Stakeholders' views that *sustainability* was the principal contribution of soil science to waste management to date may reflect recent calls to improve the life cycle of waste to tackle soil loss (Ruiz et al., 2020) or current discourse on circular economy and bioeconomy to enhance environmental conservation and sustainability through better waste management (Morris et al., 2017). By contrast, soil scientists did not reference *sustainability* as prevalently in their responses, which belies recent work demonstrating how effective waste management not only enhances soil quality (Bernal et al., 2017), but also contributes to soil formation (Graham et al., 2020). Instead, soil scientists' use of the keywords *waste disposal and recycling*, *waste application*, *contamination*, *pollution from the soil* and *remediation* highlight a longstanding focus of soils research into the issues of waste disposal for soil health (Cameron et al., 1997; Fuller, 1977).

In the water management sector, fewer stakeholders than soil scientists described the current contributions of soil science as 'great' or 'fundamental' but there was nonetheless broad agreement regarding the areas to which soil science has contributed. Key terms referenced by both groups as major current contributions (*catchment processes*, *pollution from the soil* and *water resource management*) demonstrate clear recognition of the importance of soils research on processes affecting water availability (Haygarth & Ritz, 2009) or the threats to water use posed by runoff and leaching from soils (Dermatas, 2017). The consensus around the contribution of soil science to resolving environmental pollution likely stems from the high public interest in the topic during the last two decades, and the demonstrable role of soil science in developing technologies to target and mitigate pollution (Mermut & Eswaran, 2001).

4.2 | Under-served areas and future directions

The similarities and dissimilarities in the responses of scientists and stakeholders to our survey questions about under-served areas and the potential contributions of soil science reveal important considerations for engaging stakeholders with soils research in the future. The keywords used to describe stakeholders' views about areas currently under-served by soil science either covered a very broad range of topics (agriculture and ESNR) or were highly sector-specific (waste and water management). However, within each sector there was substantial overlap between stakeholders' views on current knowledge gaps and the potential future contributions of soils research (Figures 2–5). The most interlinked keywords in our network maps of areas currently under-served by soil science (*industry applicable research*, *soil ecology and biology* and *sustainability*) demonstrated that these broad areas are important to respondents despite diverse viewpoints on current knowledge gaps. In particular, the links between sustainability and multiple themes in our network maps, as well as the prevalence of *sustainability* as a keyword in responses across sectors, indicate both a desire to move towards more sustainable practices and a need for sector-specific soils research to achieve this (Hou et al., 2020; Jónsson et al., 2016; Tóth et al., 2018).

In the agriculture sector, stakeholder emphasis was evenly distributed across a wide range of topics that are currently under-served by soil science (39 out of 47 keywords) of which 35 were also identified as potential future contributions. The greater focus of soil scientists on *crops* and *land management* implies that the scientific community envisions a continuity of past research to increase productivity in a sustainable manner, which is at odds with the views of stakeholders. Poor knowledge exchange might explain the discrepancy between the views of soil scientists and stakeholders, as an increasing number of scientific studies focus on modelling and do not involve much fieldwork (Bouma et al., 2012). Furthermore, mechanistic modelling studies often disregard important social or cultural considerations, which can create discrepancies between science and practice (Crane, 2010). Nonetheless, both groups agreed on *soil health and quality* as a key item on the soil science agenda in the future, as achievements in boosting crop production have also increased environmental pollution and soil degradation (Millennium Ecosystem Assessment, 2005; Palm et al., 2007). Given the need to address both global food security and sustainability, it is clear that a major future challenge will be to increase global agricultural productivity without reducing soil quality (Kopittke et al., 2019). Our results thus suggest that stakeholders may look to soil science for solutions to mitigate the damage caused by agricultural intensification.

Given the breadth of the topic, it is perhaps unsurprising that respondents from the ESNR sector consistently highlighted *ecosystem services* simultaneously as a key current contribution, under-served area and potential future contribution of soil science. Indeed, many of the keywords used to describe current gaps and future research priorities directly address the need for more information about the provision and value of soil ecosystem services (Haygarth & Ritz, 2009; Robinson et al., 2013). For example, although the focus of ESNR stakeholders on broad under-served areas such as *climate*, *biodiversity* and *sustainability*, was at odds with soil scientists' emphasis on detail-oriented topics such as *soil–plant interactions* and *soil structure*, all of these are involved in addressing the commonly perceived deficit in soils research on ecosystem services (Adhikari & Hartemink, 2016; Smith et al., 2015). Interestingly, whereas *biodiversity* was highlighted as a major current contribution by soil scientists, it was flagged as an under-served area by stakeholders, which is likely to reflect the role of soil biota in ecosystem service provision (Lavelle et al., 2006; Smith et al., 2015) and the need to assess the cost of soil diversity loss to ecosystem functioning rigorously (Delgado-Baquerizo et al., 2020). All respondents saw the potential for soil science to serve many ESNR areas in the future, but the notable disconnect between stakeholders and soil scientists around *climate* and *sustainability* is surprising. Despite the demonstrable importance of climate-focussed soils research (Amelung et al., 2020) and the widespread recognition for sustainable use of soils to address multiple environmental and development goals (Hou et al., 2020; Jónsson et al., 2016; Tóth et al., 2018), only stakeholders considered *climate* and *sustainability* as areas to which soil science could contribute to in the future in the context of ESNR. However, the common consensus around the importance of *communicating research* in the future suggests a recognised need for more effective engagement of soil scientists with the ESNR sector.

In the waste management sector, the frequent references to *sustainability* as both an under-served area and a key future contribution of soil science to the sector suggest that, despite considerable advances in sustainable waste management, there is still much work to do in this area (Dermatas, 2017). The emphasis of soil scientists and, to a lesser extent, stakeholders on *economics* as a key future contribution of soil science to the sector could reflect recent work highlighting that technological advances are imperative for developing cheaper waste remediation techniques (Amulya et al., 2016), and ensuring high economic returns from biochar production (Yu et al., 2020). Interestingly, soil scientists proposed *communicating research* as a current gap as well as an important future priority for the waste management sector, which may explain why stakeholders identified many more under-served areas and potential future contributions of soil science to the sector (Figure 4). However, the lack of responses from soil scientists associated with waste management in our survey could be either the origin or the consequence of the perceived communication issues in this sector. Nonetheless, the notable increase in the number of topics identified as future contributions by all respondents indicates that soil science has great potential to contribute to the waste management sector in the future, provided current communication barriers can be overcome.

Despite the considerable agreement between stakeholders and scientists about the current contributions of soil science to the water management sector, there was a notable mismatch between the two groups on perceived under-served areas and potential future contributions. For example, stakeholders' views that *climate*, *pollution from the soil* and *water resource management* are under-served areas in the water management sector were not shared by soil scientists. The discrepancy around climate is surprising, considering the manifest linkages between climate and water, and the role of water management in combating climate change and its impacts (Keesstra et al., 2016). However, as the climate was not frequently cited as a potential future contribution of soil science to the sector, it is possible that stakeholders do not believe that soil science can provide solutions to address the specific impacts of climate change on water management (Allan et al., 2013), or that they consider other issues more pressing. By contrast, the potential importance of soil science in closing knowledge gaps on catchment processes and water resource management were widely recognised (Sidle et al., 2017) despite the acknowledged contributions of soil science to these areas to date. Finally, although stakeholders and soil scientists generally agreed that soil science had the potential to contribute to *soil physico-chemical properties* in the future, stakeholders placed greater emphasis on *land management* and *soil organic matter*, whereas scientists focussed on *soil structure*, all of which are essential to the capacity of soils to regulate water supply (Palm et al., 2007; Smith et al., 2015; Tóth et al., 2018).

4.3 | The importance of dialogue between stakeholders and soil scientists

One of the future directions featured repeatedly across all sectors was the need for dialogue between science and industry. *Industry-applicable research* was one of the most interlinked keywords used by soil scientists (Figure 9), which demonstrates a desire to ensure that research findings have practical applications across sectors. However, *communicating research* was one of the most interlinked keywords used by stakeholders, which emphasises persisting issues in the way soil scientists communicate their work (Hartemink & McBratney, 2008; Warkentin, 1999) and the resulting underuse of scientific expertise in the industry (Bouma, 2001). The notable mismatches between stakeholder and scientist views of under-served areas and potential future contributions specifically highlight the need for stakeholder engagement during the conception and development of research projects to achieve real-world impact (Bampa et al., 2019; Reed, 2008). In addition, these mismatches could be an artefact of the common time-lag between the formulation and funding of research, and the application of the research findings in practice. Time-lags may be an even greater issue when further investment is required to translate research findings into a usable product or service. Furthermore, it is possible that addressing some of the challenges within sectors may not require new research, but rather the effective use and dissemination of existing information (Bouma et al., 2019) through greater stakeholder engagement (Bouma et al., 2012; Reed, 2008).

The benefits of effective engagement and ongoing dialogue between soil scientists and stakeholders are particularly evident in the agricultural sector, where there was the

BOX 1 Recommendations for soil scientists to engage stakeholders effectively with soils research

The four themes (communication, applicability, process and direction) and the specific recommendations under each theme emerged from a survey in which soil scientists and stakeholders were asked for their views on the current and future contributions of soils research to four major sectors (agriculture, ecosystem services and natural resources, waste management and water management).

Communication:

- Realise that engagement works both ways, proactively engage different sectors with science.
- Utilise existing research more effectively; recognise common goals to better target future work.
- Avoid jargon and find common language; clarify the contribution of technical detail to the bigger picture.

Applicability:

- Identify applicability at the start of the research process and prioritise positive impact over number of publications.
- Discuss research foci, timeframes and funding with stakeholders to maximise future applications.

Process:

- Seek stakeholder engagement during the conception and development of research, and foster dialogue throughout the research process.
- Maximise opportunities for research to be utilised by others; consider different dissemination methods to reach broad stakeholder groups.

Direction:

- Identify and determine the source of discrepancies between stakeholder and scientist research priorities.
- Find a balance between scientific advances and stakeholder aspirations to drive innovation.

highest level of agreement between stakeholders and soil scientists in our survey. Numerous initiatives over the years have fostered collaboration between soil scientists and farming communities or landowners, to ensure that stakeholders contribute to and benefit from relevant research findings (Ingram et al., 2010; Krzywoszynska, 2019). Other sectors could benefit from similar participatory or co-production approaches to translate soils research into practical applications. Finally, some of the discrepancies in the responses of soil scientists and stakeholders might be attributed to the use of subject-specific jargon, which can undermine efforts to communicate scientific results to broader audiences (Hou et al., 2020; Sharon & Baram-Tsabari, 2013).

Our survey focussed on sectors to which soil science has made demonstrable contributions, but there is great potential for soil scientists to engage with a greater number and diversity of sectors, including, for example, energy, construction, health and education (Brevik et al., 2019; Campbell et al., 2017; Field et al., 2011). Future work could thus target other industries to assess the role of soil science in serving the wider needs of society. Similarly, capturing the current and future perceived priorities of policymakers across sectors would also be a valuable extension to the findings of our survey. Although the respondents in our survey were largely UK-based, studies in other European countries have demonstrated the need for soil scientists to engage more effectively with policy (Campbell et al., 2017; Okpara et al., 2020), the general public (Bouma et al., 2012) and other stakeholders (Bampa et al., 2019; Jónsson et al., 2016), suggesting that our findings and recommendations are likely to be widely applicable.

5 | CONCLUSIONS

By comparing the responses of stakeholders and soil scientists, our survey represents one of the first multi-sectoral assessments of the potential for soil science to address societal challenges. Whereas soil scientists and stakeholders largely agreed on the contributions of soil science to each sector to date, notable differences in scientists' and stakeholder priorities for future research indicate that the academic discipline is not always well aligned with societal needs. Although mismatches in the views of scientists and stakeholders were largely sector-specific, we identified three issues that were common across all sectors: (a) soil scientists are likely to overestimate the impact of their work on a given sector, which indicates barriers for translating research into practice; (b) stakeholder perceptions more commonly centred on broad themes such as sustainability, whereas scientists' perceptions indicated a greater focus on detailed analysis of characteristics or mechanisms; and (c) Distinct use of terminology could explain some of the discrepancies in the views of scientists and stakeholders, as scientists were more likely to use technical descriptions, whereas stakeholders generally used broader terms. Collectively, these three issues suggest that improving dialogue between researchers and stakeholders could shape a high-impact research agenda for soil science by accounting for the views and specific needs of key sectors. We argue that dialogue between science and industry is not only essential in terms of the dissemination of soils research, but also in its initial conception. To that end, we make specific recommendations to help soil scientists step up their efforts to improve engagement with relevant sectors, seeking stakeholder perspectives and guidance to ensure that research aims address current challenges, and that deliverables are fit for purpose (Box 1).

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CONFLICT OF INTEREST

The authors declare no conflict of interests regarding this study.

AUTHOR CONTRIBUTIONS

Mihai Cimpoiasu: Conceptualisation (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); software (equal); validation (equal); visualisation (equal); writing – original draft (equal); writing – review and editing (equal). **Emily Dowdeswell-Downey:** Conceptualisation (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Daniel Evans:** Conceptualisation (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Christopher McCloskey:** Conceptualisation (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (lead); validation (equal); visualisation (equal); writing – original draft (equal); writing – review and editing (equal). **Lewis Rose:** Conceptualisation (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Emma Sayer:** Formal analysis (equal); writing – original draft (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article. Due to ethical restrictions the full survey dataset cannot be made available.

ORCID

Mihai O. Cimpoiasu https://orcid.org/0000-0003-2067-1701
Emily Dowdeswell-Downey https://orcid.org/0000-0002-1358-0433
Daniel L. Evans https://orcid.org/0000-0002-4484-7874
Christopher S. McCloskey https://orcid.org/0000-0002-4439-8263
Lewis S. Rose https://orcid.org/0000-0001-5014-1264
Emma J. Sayer https://orcid.org/0000-0002-3322-4487

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