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Global blind spots in soil health research overlap with environmental vulnerability hotspots

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Healthy soils are essential for sustaining ecosystem services and human well-being. However, poorly distributed global soil health research hinders the development of local solutions to promote soil security. Here, we analyzed 31,999 articles published worldwide on soil health and its relationship to major threats to soil and global crises. Our findings reveal a significant increase in soil health publications; however, this scientific production is concentrated in European countries, China, the United States, India, and Brazil. Blind spots in soil health research are found in Central and South America (excluding Brazil), Africa, Southeast Asia, and the Middle East. These regions harbor rich biodiversity but face the highest rates of deforestation, severe erosion, and significant threats from climate change. Our study highlights the urgent need for partnerships that empower underrepresented regions with scientific leadership and local tailored practices in order to restore soil health and address global crises within an achievable timeframe.

Healthy soils provide multifunctionality that underpins planetary and human health by enabling the soil to produce biomass, regulate the carbon pool, provide habitat for biodiversity, cycle nutrients, and manage water effectively[1]. These functions are critical for maintaining ecosystem balance, supporting food production, enhancing climate resilience, and ensuring long-term sustainability[2–5]. However, soil security is threatened[6,7], because one-third of the planet's soils are degraded[8], a scenario probably exacerbated by climate change. Facing this threat, healthy soils – defined as soils' capacity to function, as a living ecosystem, that supports plants, animals and humans – offer a promising way to reconcile agricultural production with environmental protection[4,9–11]. Therefore, restoring soil health is one of the foundations for reversing the trajectory of planetary boundaries (e.g., land system change, biogeochemical flows, freshwater change, biosphere integrity, novel entities) from the high-risk zones to the less critical zones for humanity[3,12–14].

Soil health has been an emerging field since the 2010s[15] with concepts still undergoing revisions, updates, and expansions[4,16]. Methodologies and frameworks are being proposed to ensure greater reliability, accessibility, applicability, and scalability[17–19]. However, since critical values (thresholds) of soil health depend on ecosystem boundaries – which range widely depending on pedoclimatic conditions and land management – refining local data interpretations is critical to avoid making inappropriate regional applications and comparisons[4,9,20,21]. Based on this premise, two enormous challenges must be addressed. First, to create large, robust, and comprehensive datasets that considers the variability of the main environmental drivers of soil health[16]. Second, to ensure the establishment and strengthening of local research leaders to appropriately harmonize and standardize these data, ensuring an adequate soil health assessment, particularly in regions that are the most vulnerable to global crises.

Historically, the large-economy countries have made significant investments in measuring, monitoring, and mapping soil properties (e.g., Soil Survey Geographic Database in USA; the European Soil Data Centre[22]; and the China Dataset of Soil Properties[23]). These initiatives, combined with the creation of specific laws (e.g., Soil Monitoring Law proposed by the European Commission[24] and China's Soil Pollution Prevention Law) allow us to identify regions that should be prioritized for soil research and restoration investments. Conversely, nations with limited capacity to invest in and produce scientific knowledge may struggle to develop solutions and implement local actions to combat soil degradation and promote soil health. Thus, identifying potential global blind spots in scientific production on soil health, especially in the most vulnerable regions, is therefore critical to developing strategies to address global crises in a timely manner. However,

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such blind spots remain unknown. Hence, we hypothesized that research on soil health is poorly distributed across the world, and that global blind spots in knowledge generation coincide with the regions most affected by the global environmental crises.

Here we conducted a scientometric study, including 31,999 papers, to evaluate the temporal and spatial distribution of global scientific effort on soil health. Additionally, the scientific cooperation network among countries and the distribution of highly productive authors and the highly cited papers were analyzed to understand how the spatial distribution of soil health research is connected to major soil threats and global crises. Finally, global priorities for soil health research are discussed.

Results and discussion

Global scientific effort and network on soil health research

Our results show that scientific research on soil health is experiencing growth globally (Fig. 1a). This highlights the fact that soil health is an emerging scientific concept, with 52% of papers being published in the last five years and 74% in the last ten. Although the sharp growth in soil health research is significant, it is unevenly distributed among countries and regions. China alone accounted for more than a quarter of the scientific publications, more than double the output of the second-highest country, the USA (Fig. 1b). Both countries also have the highest number of citations. However, the difference between them is much smaller (Fig. 2a). Still, the USA has about three times more highly cited papers (top-1% cited papers) than China (Fig. 2b). The top-5 countries with the highest scientific productivity (i.e., China, USA, India, Brazil, and Spain) accounted for 60% of the published papers. In contrast, the top-10 countries accounted for 70% of all papers, received the most citations (Fig. 2a) and produced most of the highly cited papers on soil health (Fig. 2b). Other countries, such as France, Netherlands, Poland, Switzerland, South Korea, Pakistan and New Zealand are not listed in the top-10, but contribute significantly with highly cited papers (Fig. 2b). In summary, of the highly cited papers, 33% were published by researchers from the USA, 13% from China and 28% from Europe. Our results also confirm that the most productive soil health researchers are located in the most affluent countries. Specifically, the top-5 and top-10 countries are home to 66% and 85% of the top-100 most productive soil health researchers. A complete list of these top-100 researchers, and publications by country are provided in the "Data availability" section.

From another perspective, the ranking changes considerably when the relationship between scientific production in soil health research and the population and surface area of the countries is considered. China, the USA, India, Brazil and Spain occupy the top five spots in terms of total scientific production. However, when the number of publications is related to the country's population, they rank 43rd, 22nd, 60th, 31st and 9th, respectively (Fig. 3a). When related to surface area, they rank 28th, 42nd, 23rd, 58th and 13th, respectively (Fig. 3b). Singapore's prominence (Fig. 3b) is a result of its very small surface area, as we found only 14 scientific publications in our search for the country. This approach, considering scientific production and the population and surface area significantly increased the proportion of European countries in the top positions of the ranking. The Netherlands stands out in particular, coming fourth and second when scientific production is related to population and surface area, respectively. New Zealand, Australia and Switzerland — countries that contribute a significant number of highly cited articles — improve their position in the ranking considerably when their population and surface area are considered. Furthermore, countries with greater scientific contributions to soil health research, in general, invest a higher percentage of their gross domestic product (GDP) in research and development (Fig. 3c) and tend to be more politically stable (Fig. 3d).

Breakthroughs and productive scientific collaborations are most prevalent in the northern temperate zone, which accounts for 71% of all papers and most highly cited papers. Western European countries serve as a central hub for these scientific collaborations (Fig. 1c). Conversely, there are significant global blind spots in soil health research, particularly in Africa, Central and South America (excluding Brazil), the Middle East, and Southeast Asia. In addition to the limited number of scientific publications, countries in these regions generally have lower levels of investment in research and development (Fig. 3c), as well as less political stability (Fig. 3d). Of the total number of publications on soil health, 64% were produced entirely domestically, while 36% involved international scientific collaborations (Supplementary Fig. S1). The USA leads in these bilateral scientific collaborations, interacting with 104 countries, followed by Germany with 93 countries and China with 92 countries. Furthermore, China participates in 6 of the 10 largest bilateral collaborations, and the USA in 4 of them. Conversely, Australia has the fewest bilateral collaborations (51 countries) among the top-10 countries. The strongest interaction is between China-USA, followed by Brazil-USA and China-Australia. Of the 10 strongest bilateral collaborations, only Pakistan (with China) does not appear in the list of the top-10 countries producing papers. In addition, countries in Africa and Asia that are most vulnerable to climate change and environmental stressors[25] have weak international scientific cooperation with the largest producers of soil health knowledge (Supplementary Fig. S2). Nevertheless, it is important to note that regions that are considered blind spots due to a lack of publications or leading authors in soil health research are not necessarily devoid of soil health research. Researchers affiliated with institutions in other countries may still be conducting significant field experimentation on soil health in these areas. This lack of local leadership can be offset by fostering international collaboration, thereby ensuring the production and transfer of knowledge and technology to address major challenges such as food security and climate change.

Fortunately, strategic continental and intercontinental collaborations have been established to minimize the impact of this knowledge production gap and ensure sustainable land management through soil governance. Established by the Food and Agriculture Organization of the United Nations (FAO) in 2012, the Global Soil Partnership (GSP) has strengthened collaborative mechanisms to identify and establish priorities for action. These priorities are defined by technical panels comprising representatives from all regions of the world, thereby ensuring regional equality in the development of soil governance strategies.

The 'Living Soils of the Americas' initiative, led by the Inter-American Institute for Cooperation on Agriculture (IICA) and the Carbon Management and Sequestration Centre (CMASC) at Ohio State University (USA), is an example of a successful collaboration strategy. Through IICA's regional offices, the initiative's governance is based on technical cooperation mechanisms with local universities, national agencies, research and development centers, etc. Thus, the outline of activities for the main components of the initiative, which are i) measuring and monitoring soil organic carbon, ii) soil policies and regulations, and iii) best management practices to promote soil health, is based on the main challenges faced by each country. Recently, in 2024, a partnership between IICA and the Alliance for a Green Revolution in Africa (AGRA) launched 'Living Soils in Africa', seeking to adopt the initiative's strategies on the African continent.

Collaboration between agricultural and environmental research institutions in France and African countries has also resulted in the development of strategic programmes, such as the TSARA Initiative (Transforming Food Systems and Agriculture through Research in Partnership with Africa). This initiative seeks to promote sustainable soil management and agricultural systems by ensuring local knowledge. Through initiatives such these, soil health knowledge and technologies will be not only transferred, but also co-developed. Furthermore, these technologies require research resources and infrastructure to be adapted, updated, and used. Soils4Africa, for example, funded by the European Commission's Horizon 2020 programme, has been developed procedures and tools to intensify soil sampling and laboratory analysis activities in Africa with the aim of providing an open-access soil information system. However, science-based solutions to promote soil health and soil monitoring depend on the local capacity to generate knowledge, train change agents, and encourage local communities to take transformative action.

There are many reasons why it is urgent to promote a global soil health agenda, particularly in the most vulnerable regions. Blind spots in soil health research overlap with gaps in soil biodiversity and ecosystem function

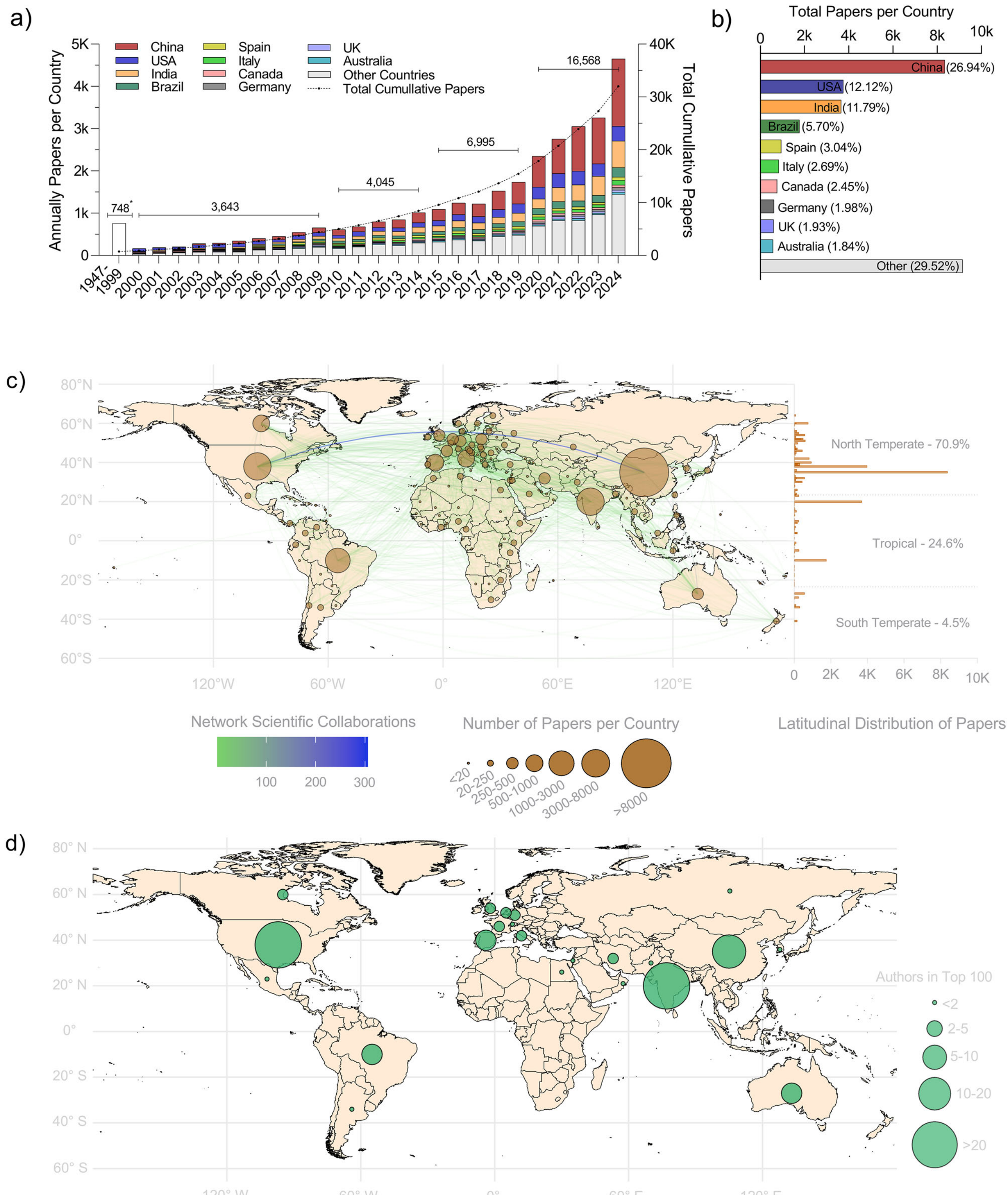

Fig. 1 | Global soil health research distribution. a Number of scientific papers (annual and cumulative) on soil health, highlighting the production of the top-10 most productive countries. **b** Total number of publications from the top-10 countries from 1947 to 2024; **c** Global soil health scientific collaboration network, number of publications by country and latitudinal distribution; **d** Location of the top-100 most productive researchers (authors), grouped by country.

research[26] and are located in regions with the highest risk of species extinction[27,28]. These areas support some of the most unique soil community assemblies[29]. Additionally, these regions are heavily impacted by land use change (LUC) pressures, particularly deforestation[30–32]. This significantly impacts soil properties and functions, including losses of soil carbon[33] and biodiversity[34,35]. In South America, sub-Saharan Africa, and Southeast Asia - where the blind spots of soil health research are concentrated - there is the strongest pressure from LUC, which is the main driver of greenhouse gas (GHG) emissions[36,37]. Furthermore, these tropical regions are the most vulnerable and affected by erosion[38], nutrient depletion[39–41], land degradation and abandonment, and, thus, threats to food security[42,43]. At the same time, the global and regional agricultural market is driving cropland

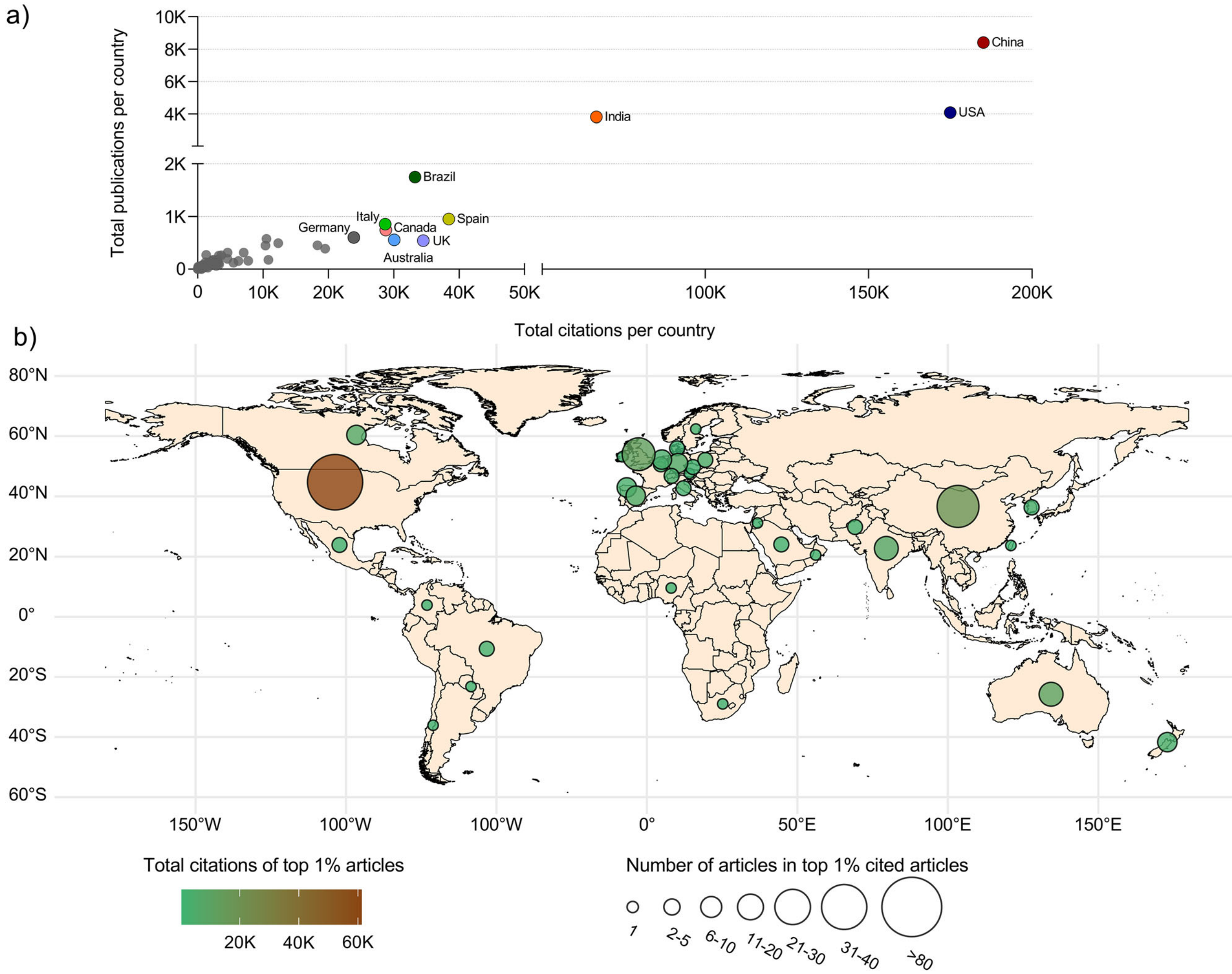

Fig. 2 | Global scientific influence of soil health research. a Number of scientific papers (cumulative from 1947 to 2024) on soil health *vs* number of citations per country; **b** Global distribution (per country) of the top-1% cited papers on soil health.

expansion, particularly in the tropics[44], increasing GHG emissions from LUC, thereby exacerbating climate change[45]. This, in turn, diminishes the capacity to deliver ecosystem services in the face of increased environmental stressors[46].

In fact, the primary function of agricultural soils – the production of food, feed, and fiber – inevitably generates trade-offs in other ecosystem services. However, in order to provide adequate quantitative comparisons, the reference healthy soils must consider the wide variability of pedoclimatic zones and all the possible land-use types and intensities. This recent approach called soil health benchmarking seeks to optimize soil multifunctionality[16]. Therefore, appropriate land use and management that considers the soil health benchmarking approach can ensure agricultural soils' primary function (i.e., food, feed, and fiber production) while preventing the expansion of croplands, enhance carbon sequestration in naturally restored areas, and reduce habitat loss in biodiversity hotspots[47]. Despite having the highest emissions related to LUC, these vulnerable regions (especially Africa and Asia) exhibit the lowest per capita food-related carbon footprints[28]. In addition, developing countries in Asia, Africa, and Latin America, which comprise 75% of the world's population, were responsible for only 8.0% of the emissions that exceeded the planetary boundary of 350 ppm of atmospheric CO_2 concentration[48]. However, these countries are the most vulnerable to climate change[25].

Higher frequency and severity of extreme climate events[49,50] increase crop yield variability, being one of the greatest threats to global food security[51]. Furthermore, the greatest reduction in crop yield with rising global temperatures is expected to occur predominantly in the blind spots of soil health research (i.e., Africa, Southeast Asia, and Central and South America[52]). A further impact related to climate change is the reduction in precipitation and increase in evapotranspiration rates, which causes aridity and threatens the provision of ecosystem services in drylands[53]. Such aridification is expected to result in a global expansion of drylands by up to 6.9%[54] predominantly in the developing regions[55], exacerbating its socioeconomic vulnerability. In addition, aridification leads to losses of biodiversity and soil multifunctionality[56], intensifying the risks of desertification and increasing human water demand, and water scarcity in these regions[57].

Ecosystem restoration plays a pivotal role in protecting and recovering biodiversity and mitigating climate change. However, the global priority areas for restoration are concentrated in Central and South America, Africa, and Asia[58], which are also the largest blind spots on soil health research. These regions experience significant cropland abandonment due to several socioeconomic factors, such as the migration of rural population and a reduction in the agricultural labor force[59,60] as well as land degradation[43] caused by soil erosion, nutrient depletion, and soil carbon loss resulting from poor land management[60–63]. Mitigating the negative impacts of cropland abandonment requires, as a first step, identifying regional hotspots and their main local drivers, in order to direct integrated planning and support the design of government programs[64,65]. Such initiatives combined with the adoption of sustainable management practices can lead to more productive and climate-resilient farming systems[66–70]. Adopting sustainable land management has tremendous potential for recovering abandoned

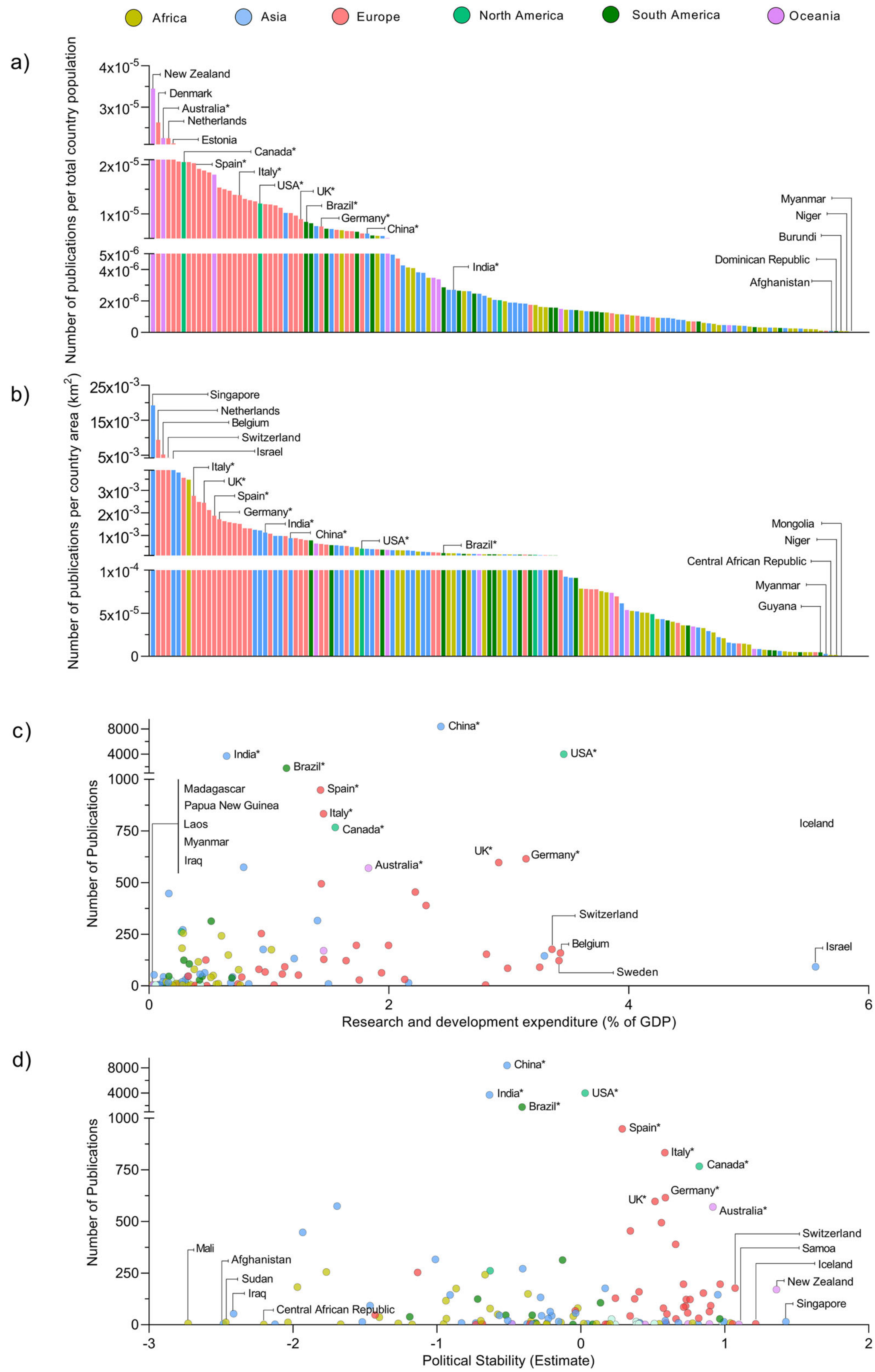

Fig. 3 | Soil health research and its relationship with geographical and economic indices. Relationship between the number of publications on soil health and **a** population, **b** surface area, **c** percentage of gross domestic product (GDP) expended in research and development, and **d** estimate political stability per country. The top-10 countries by number of publications, and the top-5 countries on the X and Y axis were identified by name.

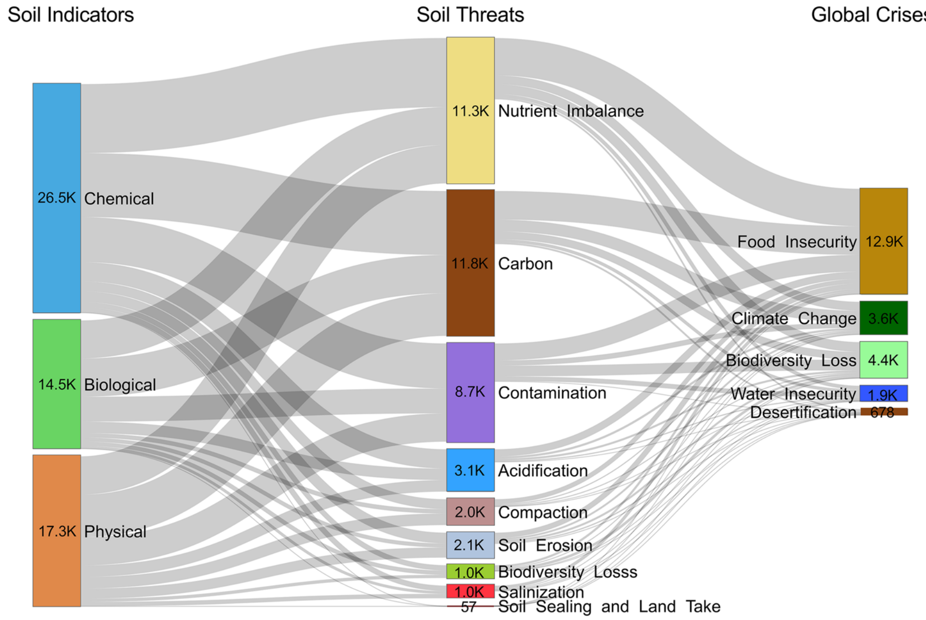

Fig. 4 | Sankey diagram showing the interconnections between soil health indicators, soil threats, and global crises. The size of the boxes and the thickness of the gray lines are proportional to the number of papers that addressed these topics.

croplands, ensuring increased food production, economic multifunctionality, and mitigating climate change[43,71]. In the face of this scenario, integrated farming systems (e.g., crop-livestock, crop-livestock-forestry) have been identified as a promising way to achieving sustainable food production along with other environmental benefits[72–75]. However, such integrated agricultural systems require substantial initial investment, a robust extension services and an extensive farmer training in integrated management, which is particularly challenging in African and Asian countries[73,76–78].

Global priorities for soil health research: insights and challenges

Promoting healthy soils is pivotal to achieving the Sustainable Development Goals (SDGs) by tackling global challenges such as food and water insecurity, climate change, biodiversity loss, and desertification[1,2,79]. However, the extensive body of soil health publications (Fig. 1a) is not necessarily fully aligned with these global challenges. An analysis using a Sankey diagram (Fig. 4), revealed that out of the total of 31,999 publications, most evaluated chemical (26,563), followed by physical (17,283) and biological (14,510) indicators. In total, soil health indicators were cited 58,356 times in publications. However, the correlation of these indicators with major soil threats decreased to 41,454 citations (71%) and an even smaller proportion (40%) established an association with major global crises. Surprisingly, this proportion between the soil health indicators cited and soil threats and global crises has not changed significantly over time (Supplementary Table S1). Although our search, limited title-abstract-keywords, does not allow us to conclude that there is no link between soil threats and global crises, it does provide an important insight: researchers from multidisciplinary fields (e.g., non-soil scientists) may not have access to many articles in their searches. The strongest interactions were observed between the chemical indicators, with nutrient imbalance and carbon losses, and between these soil threats and food insecurity. Only a few studies have explored soil's multiple functions and services[7,79]. Most soil health studies have focused on agronomic goals (crop production) rather than environmental goals (climate, water quality, biodiversity)[4]. Currently, 1600 million hectares are used for crops and 3200 million hectares for grassland and pasture, while other soil functions receive significantly less attention globally. Future research must therefore strengthen the links between soil health and global challenges. Raising public awareness and political interest will be critical to advancing this agenda on a global scale[7].

Global priorities on soil health research need to be closely related to the SDGs but there is a huge knowledge gap between countries, although soil health can have different prioritization depending on the country-specific context. Some countries are likely to be more aware of the vital role that healthy soils play in ecosystems and may have mechanisms in place to prioritize soil health research and its implementation. Conversely, countries experiencing serious soil degradation and environmental issues due to unsustainable land use may be pressured to invest in research to develop solutions to mitigate and reverse these problems. Nevertheless, in a global perspective, working towards the targets of SDG 17 - "Partnership for the Goals" is urgently needed to reduce global disparities in soil health research and support the implementation of actions to reverse soil degradation and sustain soil health in productive lands. The first step is to strengthen and increase the number of existing bi- and multilateral cooperation funding programs (e.g., United Nations Development Programme; Horizon Europe through Mission Soil Platform; Foundation for Food and Agriculture Research; Soil Initiative for Africa) and soil health-oriented partnerships (e.g., Coalition of Action 4 Soil Health; Soil Health Institute; Living Soils of America and Africa; Brazilian Soil Health Partnership). In addition, new mechanisms of research funding and collaboration should be promoted to link well-established research groups, located in most productive and influential countries, with emerging ones located in regions with limited soil health research. Such a strategy will empower soil health researchers to lead their own research in underserved regions to generate local knowledge, build infrastructure, and build human resources to implement interventions in these vulnerable regions.

The European Commission's actions through Horizon Europe have boosted intercontinental collaboration to promote soil health. The programme recently opened a funding call called 'Broadening the living labs approach for soil health in Africa and Latin America and the Caribbean (LAC)' with a budget of €12 million. To reduce the gap between the production of scientific knowledge and the application of site-specific practices, funded research should be based on three main components: i) the co-creation of solutions with a large group of stakeholders; ii) research carried out in real-life settings; and iii) the involvement of end users. This approach aims to accelerate and expand the adoption of context-specific solutions for protecting and restoring soil health in Africa and LAC, by combining research, development, education and extension activities.

Mobilizing the public and private sectors for funding to support developing countries through regenerative agriculture, carbon farming and forest restoration programs is also pivotal to boost soil health agenda. However, it is crucial that these programs adopt the soil health benchmarking approach, which considers variations in land use, climate, and soil properties when assessing the benefits and trade-offs of ecosystem services in agricultural, forest, urban, and wetland soils, as well as in mining and other natural or semi-natural areas[16]. This approach is also an effective way to develop soil health measurement tools tailored to local conditions and to enable the scaling up of sustainable management practices[80]. Nevertheless, properly applying this approach requires significant long-term investments due to the challenges of creating databases that cover the wide variability of pedoclimate zones and land-use types, resulting in delays in developing rapidly scalable soil health assessment tools. Thus, simple, low-cost tools are a viable alternative for assessing soil health, particularly on a local scale. The Open Soil Index framework, developed in the Netherlands, is a successful example of a digital tool that has made soil health assessments scalable. This tool, developed in collaboration with farmers, soil experts, researchers and financial institutions, calculates the soil health index based on easy-to-obtain input data low cost, and also provides practical recommendations for farmers[11]. Similarly, the Soil Bioanalysis technology launched by the Brazilian Agricultural Research Corporation (Embrapa) in 2020[81,82], gives farmers access to soil health assessments carried out in routine laboratories across the country. Furthermore, the Soil Health and Management Assessment Kit (SOHMA KIT®), developed at University of São Paulo – Brazil, a portable, low-cost and scalable technology that allows on-farm assessment of seven sensitive soil health indicators[83]. These two powerful technologies allow Brazilian farmers, consultants and extensionists to assess soil health and use this information to improve soil management.

Thus, to address disparities in soil health research and assessment, providing more specific recommendations could help create more equitable and inclusive research practices and field applications. By highlighting the factors contributing to these discrepancies, the discussion can offer actionable insights for policymakers, researchers, and stakeholders aiming to promote greater collaboration and knowledge exchange in this field. When linked to scientific organizations, these strategies can further promote engagement in favor of a soil health agenda, such as the 2025–2034 Decade of Soil Sciences for Sustainable Development recently declared by the International Union of Soil Sciences (IUSS) under the theme 'Healthy Soils for Humanity'.

The slow progress toward achieving the SDGs necessitates an extension of the United Nations 2030 Agenda, particularly due to the low scores of the Global South, with a more severe situation on the African continent[84–87]. Restoring and enhancing soil health is essential for ensuring soil security and providing climate resilience, as soil carbon accounts for one-fourth of the potential for nature-based solutions to mitigate climate change and soils support over half of global biodiversity. However, to effectively address major global crises such as climate change, biodiversity conservation, and sustainable development, it is crucial to translate global goals into science-based local actions[88].

In summary, soil health has become a pressing global research agenda over the last decade. However, the knowledge produced in this field is unevenly distributed worldwide. The top-10 countries account for 70% of all publications, and the strongest bilateral collaborations occur between these same countries. Significant blind spots in soil health research exist in Central and South America (excluding Brazil), Africa, Southeast Asia, and the Middle East. Deforestation and poor land management in these regions pose serious threats to soils, including nutrient imbalances, carbon loss, erosion, and the risk of species extinction. These regions are also the most vulnerable to climate change and have the largest gap in achieving the UN-SDGs. Therefore, we propose prioritizing soil health on national and global agendas, creating and strengthening soil health research groups, and promoting international scientific funding and partnerships. Well-trained researchers and financial resources are essential to shed light on the blind spots of soil health research and help developing countries implement regionally adapted climate-smart solutions that reconcile soil security, food production and environment protection.

Limitations

Our study reveals valuable insights, showing that global blind spots in soil health research coincide with regions most vulnerable to food insecurity, climate change and other environmental treats. However, the study also has some limitations that must be taken into account, as follows: (i) Our search was performed exclusively in English, considering the title, abstract and keywords in the Scopus database. Including other languages and databases in the search would retrieve a larger number of papers, although we believe that the main message of our study would remain similar, since most of the indexed papers are published in English (or at least have an English abstract). (ii) Our analysis considered only papers that explicitly addressed the terms "soil quality" or "soil health"; however, these concepts are still evolving and are sometimes are intertwined with other related terms, such as soil fertility, land quality, soil capability and soil security[4,89]. Therefore, valuable publications that addressed soil health principles using different terminologies, such as classic handbooks used for basic soil management recommendations, would not be properly considered in this study. Our data showing recent growth in publications can also be associated with the decision to consider only "soil quality and soil health" terms, which were defined more recently than others such as "soil fertility". Our aim was to characterize the global research on specific "soil quality" and "soil health" terms rather than considering the evolution and transition of all related concepts in a broader scope. (iii) Due to a lack of publications or leading authors in soil health research, our study only allows us to establish blind spots, not the exact location where soil health research was performed. Undoubtedly, a significant proportion of the research has been conducted outside the home countries of the leading researchers. Nevertheless, the main blind spot reported here lacks studies on soil health, as was recently reported specifically for the Brazilian territory[90]. This insightful topic needs to be further addressed in a future study. (iv) The practical applications of soil health knowledge generated by publications was not evaluated. Therefore, the assumption that countries with a larger number of publications are more advanced in terms of soil health conservation lacks stronger support from data on the implementation of management practices.

Methods

Literature selection

A search of the peer-reviewed literature was conducted to systematically review publications related to soil health using Scopus database, considering scientific articles and reviews published between 1947 and 2024. The scope of this review was limited to the terms "soil health" or "soil quality", which were considered synonymous, although conceptual differences are still being debated[4]. Soil quality emerged in the 1990's based on three pillars, biological productivity, environmental quality, and plant, animal and human health[91]. Over the last decade, the concept of soil quality concept has been replaced by that of soil health, due to advances in our understanding of soil as a living ecosystem that supports multiple functions and critical ecosystem services[92]. Therefore, we considered both concepts, since "soil quality" is the former concept of "soil health" and both are still in use. The search yielded a total of 31,999 documents, with the full dataset provided in the "Data availability" section. Notably, search terms in languages other than English were not included. For each document, comprehensive citation data was collected, covering authors, titles, publication years, electronic identifiers (EID), source titles, volumes, issues, pages, citation counts, publication stages, and DOIs. In addition, detailed bibliographic information was retrieved, including author affiliations, serial identifiers, correspondence addresses, abstracts, and keywords (both author-assigned and database-indexed). Among the 31,999 documents, 3652 and 264 did not provide correspondence address information and details on the authors' affiliations, respectively.

Data processing

To define the geographic coordinates of each author's affiliations, a custom function was developed in the software R[93]. The function was designed to systematically parse author affiliation strings retrieved from the Scopus database. To achieve this, the script leveraged the R package *maps* as a reference database. The process iterated through each author's affiliation string to identify and match city and country names against the package's standardized geospatial data. Since 11% of the documents lacked correspondence address details, the affiliation address of the first author was used as the primary location to classify the country of origin for all documents. The global network of scientific collaboration in soil health was established by analyzing only documents that had at least one author affiliated with a country, other than the first author's country. The georeferenced coordinates were then projected using the WGS84 coordinate system, resulting in a comprehensive dataset that mapped the country of origin for each study, as well as the countries of co-authors involved in international collaborations. Additionally, the coordinates of the first author's country were used to classify the studies based on their latitudinal position relative to the Tropic of Cancer and the Tropic of Capricorn. Citation data were also analyzed to assess the correlation between the total number of documents per country and their total citations. The top 1% of the most cited documents (higher than 320 citations) were identified by country, and the total number of citations and documents within this top 1% were displayed on a world map to visualize the geographic distribution of influential research.

From the 31,999 papers found in our initial search, we identified the association between specific soil health indicators, soil threats and global crises through specific terms used in the title, abstract, and keywords of the documents, as described below. Soil indicators were categorized into biological, chemical and physical groups by searching each paper for specific terms: *biological* - "biology*", "enzym*", "microorgan*", "fung*", "bacte*", "archaea*", "biot*", "microb*"); *chemical* - "chemic*", "fertil*", "nutri*", "cation*", "phosphor*", "potass*", "nitrogen*", "acid*", "alkal*"), and *physical* - "physic*", "aggregat*", "penetration", "bulk", "density", "water", "porosity", "particle*"). Global crises included multiple terms related to Climate Change (e.g., "climate change", "global warming", "greenhouse"), Water Issues (e.g., "water use", "water supply", "water quality"), Desertification (e.g., "desert*", "arid*", "dryland"), Biodiversity Concerns (e.g., "biodiver*"), and Food Insecurity (e.g., "food", "yield", "productivity", "supply"). Soil threats were identified by keywords related to Soil Erosion ("erosion"), Nutrient Imbalance ("fertility", "nutrient"), Salinization ("salinization", "saline*", "sodifi*"), Soil Sealing and Land Take ("sealing", "land take"), Biodiversity Loss ("biodiversity loss", "species richness", "species diversity", "invasive species"), Contamination ("contamination", "pesticide", "pollut*", "toxi*"), Acidification ("acidification", "acidity", "alkal*"), Compaction ("compaction", "poros*"), and Carbon Loss ("carbon"). A full list of soil indicators, threats, and global crises correlation is available in the "Data availability" section.

To establish the relationship between the number of soil health publications per country and its i) population; ii) surface area; (iii) research and development expenditure (as percentage of GDP); and estimated political stability we used data from the World Bank Development Indicators. A complete list of these indicators for each country is provided in the "Data availability" section. All data processing, including cleaning, transformation, and integration of datasets, was conducted using R software[93]. Geographic maps were produced to visually represent the spatial distribution of soil health publications. Additionally, graphs illustrating the relationships between soil degradation drivers - deforestation, erosion, biodiversity, and climate change vulnerability - and the total number of publications by country were generated using Prism GraphPad®.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data supporting this study's finding are openly available in Zenodo at https://doi.org/10.5281/zenodo.16533452[94].

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Author contributions
M.R.C. conceptualized and coordinated the research, and was responsible for drafting and revising the manuscript. C.R.P.J. contributed to the results interpretation and the writing of the draft and revision. L.F. N.S and L.P.C. performed data processing and visualization, and the writing of the draft and revision. T.O.F, C.E.P.C, B.M. and P.S. developed the final concept, wrote and edited the manuscript. All authors contributed equally to the final review and approval of the manuscript.

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