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ORIGINAL ARTICLE

The future of soil science education at the university level to meet societal demands at the global level

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Abstract

The number of soil science university programs has decreased in many countries around the world. There is an ongoing need for more effective ways to attract students to the discipline, train soil specialists, and support instructors to challenge the future format of soil science education. The objective of this paper was to explore possible future directions of soil science education at the university level over the next decade. We discussed the content of undergraduate soil science courses and programs, considering how soil scientists who teach at universities can improve soil science education while ensuring high-quality educational programs. Soil science education, which traditionally included classroom-based lectures and field trips, needs to be updated through the inclusion of more engaging learning activities, multimedia, and potentially even generative artificial intelligence, but with careful considerations regarding data privacy, accessibility, and equity. Soil science education should train soil scientists who can meet societal grand challenges by focusing soil science education on soil health and the diverse soil functions. Keeping and/or

Abbreviations: AI, artificial intelligence; IUSS, International Union of Soil Sciences; LLM, large language model; MOOC, massive open online course; SDGs, sustainable development goals; YECS, Young and Early Career Scientists Working Group.

reviving traditional subdisciplines such as pedology is also important, as soil management is highly dependent on the spatial distribution of soil properties. Soil science educational reforms need to be carefully promoted while ensuring quality assurance systems for both soil scientists working in the discipline and soil educational systems. We hope that this paper provides points for informed discussion and guidance for soil science educators as we seek to improve education in our discipline going forward.

Plain Language Summary

Soils are essential for growing food, storing water, reducing climate change, and supporting plants and animals. Yet university soil science programs are declining in many countries, raising concerns about training enough experts to manage this vital resource. This paper examines how universities can strengthen soil science education to meet global challenges. We recommend emphasizing soil health (how well soil functions), the benefits soils provide, and practical field skills while maintaining core knowledge of how soils form and vary across landscapes. Modern approaches such as digital tools, virtual field trips, and problem-based learning can engage students, especially those from urban backgrounds. Collaboration across disciplines and strong quality standards are also important. Revitalizing soil science education is essential to prepare professionals who can address environmental and food-related challenges.

1 | INTRODUCTION

The importance of soil is beginning to be recognized worldwide (Pereira et al., 2023). The public is becoming increasingly aware that soil is not just a medium for producing food but also has diverse roles to play (regulating water and nutrient cycles, maintaining biodiversity, storing carbon, mitigating climate change, filtering contaminants, and supporting a wide range of ecosystem services (Bouma, 2014; Keesstra et al., 2016), and there are various global-scale events and activities to raise awareness regarding the importance of soil. Thus, there is now a need for soil professionals to not only have a good understanding of soil science concepts about agriculture or agronomy but also to raise awareness about the importance of soils in other land-related disciplines and—ultimately—with the general public (Brevik, Hannam, et al., 2022). On the other hand, the question remains whether university education has been able to adapt to this shift in global interest in soil.

The discipline of soil science has been attenuated at many universities. Universities have undergone significant changes since the onset of the Green Revolution, which occurred between the 1960s and 1980s (Brevik, Krzic, et al., 2022; Hartemink & McBratney, 2008). Those changes included pressures to provide more cost-effective teaching methods (e.g., online classes, larger classes, and less field activities) while establishing and supporting programs that recruit relatively large numbers of students. The commercialization of universities in some jurisdictions has mainly been due to declining public support for higher education relative to the cost of provision (Brevik, Krzic, et al., 2022; Hartemink & McBratney, 2008). While online education has been making substantial progress in degree delivery, even in traditionally hands-on fields like environmental sciences (Kennepohl & Moore, 2016), the rate of change increased dramatically with the COVID-19 pandemic. This further pushed the development of virtual and online courses and has profoundly altered the university classroom (Clary et al., 2022; Hews et al., 2022; Mahler et al., 2021).

These pandemic-induced changes have impacted soil science education, which has also experienced several other important changes. Previous studies have discussed how university courses with low enrollment (i.e., lower potential as an income source for universities), including soil science, have declined in many countries around the world (Diochon et al., 2017; Havlin et al., 2010). As a result, soil science training has become part of broader programs such as biological science, environmental and natural resources sciences, and geosciences, where soils are often taught as one part of a more general curriculum (Baveye et al., 2006; Brevik, Krzic, et al., 2022; Diochon et al., 2017). For example, a recent study by Brevik et al. (2020) suggested that of the approximately

3266 regionally accredited colleges and universities in the United States, only about 86 offer bachelor's degree programs that prepare students to work as a soil scientist, although courses that provide some soil science training are much more widespread (Brevik, 2009). Similar situations exist in other countries around the world. This dynamic is only valid for countries where tuition makes up a relatively large portion of the higher education budget, such as Australia, Canada, Japan, New Zealand, South Korea, the United Kingdom, and the United States (Diochon et al., 2017; Garritzmann, 2023; Jongbloed, 2023). In countries such as Denmark, Estonia, Norway, Poland, Belgium, the Slovak Republic, Sweden, and Turkey, which charge little to no tuition at their universities (Garritzmann, 2023; Jongbloed, 2023), and where tuition does not make up a relatively large share of the university budget, the pressure to eliminate smaller programs that do not bring in as much revenue is not as intense.

While it is beneficial that soil science is being covered in various courses offered within broader university programs, it is also essential that comprehensive soil science programs continue to exist. The protection of the soil resource and the ecosystem services it provides requires a solid understanding of soil science concepts. In other words, specialists who "know" soil are needed (Field, 2019). Soil-related management work is not limited to professional soil scientists but is also undertaken by geologists, ecologists, professional engineers, and crop advisors, among other groups, who often lack more nuanced soil training and experience (Walter et al., 2024). Additionally, more soil scientists should be involved in the policy-making process, informing decision-makers.

The types of students entering soil science and/or natural resources programs at universities have also changed considerably since the onset of the Green Revolution (Hansen et al., 2007; McKenna & Brann, 1992). Only a few decades ago, growing crops or gardening for subsistence was common in many countries, and most students had informal knowledge about soils before enrolling in university soil science courses. Hence, as most people had a basic understanding of growing their own food, soil science also typically was not covered in primary or secondary education. The increasing global urbanization and specialization of the food sector have reduced such informal soil knowledge (Muggler et al., 2023). Thus, there is an urgent need to engage urban students with urban soil issues, from basic "hands-on" experiences to using modern technology and community engagement (Paltseva, 2025). Thus, to address this need, future soil science courses and programs might have to cover different basics of soils. Furthermore, the learning behaviors of university students have also changed as the present generations have grown up with information communication technology (Bates, 2022). Current university students handle digital information daily (including artificial intelligence [AI]) are connected via mobile technologies, work interactively, and often perform several tasks simultaneously. While this had the effect of making more people aware of soil, there are cases where complex concepts, such as soil health (the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and humans, Doran & Zeiss, 2000), are excessively simplified and conveyed as misinformation through social media and multiple AI tools (Stroud, 2019). It has become necessary to consider how soil education should be provided for these types of students and how to ensure the quality of the human resources produced by such education (Brevik, Krzic, et al., 2022).

Core Ideas

- Soil science education must evolve to address societal grand challenges by emphasizing soil health, soil functions, and planetary boundary processes.
- Future curricula must integrate both fundamental soil science skills—such as pedology, field description, and laboratory analysis—and emerging digital and artificial intelligence (AI)-based tools.
- Strengthening experiential learning (fieldwork, labs, and community engagement) is essential to support informed soil management and professional competency.
- Quality assurance systems for soil scientists and soil science programs are increasingly necessary in a world of misinformation, digital education, and interdisciplinary degree structures.
- A globally informed, forward-looking roadmap can guide universities as they modernize soil science education for the next decade.

This paper considers possible future directions of soil science education at the university level over the next decade. We discuss the content of undergraduate soil science courses and programs, considering how soil scientists who teach at universities can improve soil science education while ensuring high-quality educational programs. The overall goal of this paper is to provide points for informed discussion and guidance for soil science educators as we seek to improve education in our field going forward. This manuscript extends previous work by offering an integrated, global framework that brings together soil health, pedology (the branch of soil science that studies the origin, formation, classification, and spatial distribution of soils as natural bodies in landscapes; Basher, 1997), planetary boundaries (a set of Earth system processes that regulate the stability and resilience of the planet; Kopittke et al., 2021), digital and AI tools, and quality assurance. As illustrated in Figure 1, this framework links global environmental pressures, institutional change,

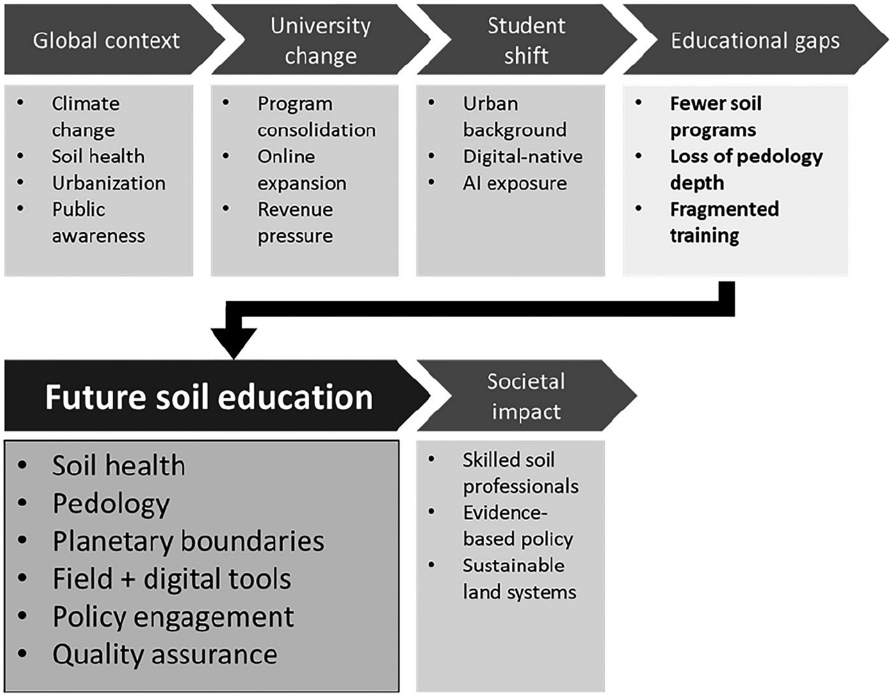

FIGURE 1 Simplified conceptual framework showing how global pressures, institutional change, and evolving student characteristics create gaps in soil science education and how an integrated educational model can strengthen societal outcomes.

and shifting student characteristics to emerging educational gaps and outlines key components of a revitalized soil science curriculum designed to generate meaningful societal impact. In doing so, it provides a forward-looking roadmap that links soil science education directly with emerging societal challenges.

2 | SOIL SCIENCE EDUCATION TO MEET SOCIETAL GRAND CHALLENGES

The contribution of soil to the planetary boundary processes (Richardson et al., 2023) as well as the United Nations Sustainable Development Goals (SDGs) (United Nations, 2024) has been widely recognized (Keesstra et al., 2016; Lal et al., 2021). However, one issue is whether our current educational structure adequately prepares students to make soil-based contributions to these grand challenges, since students may only take a limited number of soil science courses. The global grand challenges such as food, energy, soil, and water security, climate mitigation, reversing biodiversity loss, and habitat restoration have become problems facing humanity and are reflected in the SDGs. The soil science community needs to more actively contribute to reaching the SDGs and ensure that soil science (and related) courses and programs are addressing the SDGs (Bouma et al., 2019).

Figure 2 illustrates the conceptual shift we propose for soil science education. Traditionally, introductory soil science

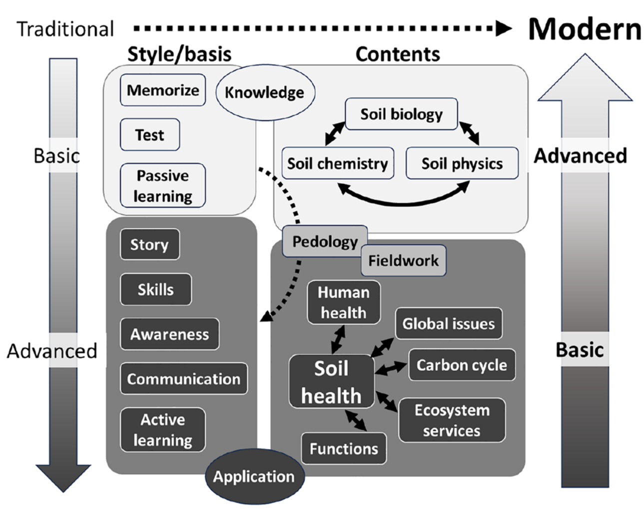

FIGURE 2 Conceptual representation of the proposed evolution of university soil science education. Traditional soil science subdisciplines (light gray)—including soil biology, chemistry, physics, and pedology—form the foundational disciplinary core of soil science education. The proposed additions (dark gray) highlight the integration of soil health, soil functions, planetary boundary processes, societal grand challenges, and policy relevance into introductory and advanced courses. Rather than replacing disciplinary depth, this framework embeds traditional soil science knowledge within a broader societal and sustainability context, enabling students to connect fundamental soil processes with global challenges such as food security, climate mitigation, and biodiversity conservation.

courses have been structured around the core subdisciplines of soil biology, chemistry, physics, and pedology, with increasing specialization in upper level courses. While this disciplinary structure remains essential, the figure highlights the need to reposition soil health and soil functions as an overarching framework that connects these subdisciplines to societal grand challenges. In this model, foundational knowledge in soil processes remains central (light gray components), but is explicitly linked to broader societal applications (dark gray components), including food security, climate mitigation, biodiversity conservation, and policy engagement. The figure therefore emphasizes integration rather than replacement: traditional disciplinary depth is maintained but embedded within a wider systems perspective aligned with planetary boundaries and the SDGs. Such an approach is important because it would demonstrate the importance of soil knowledge to society, and many students are looking to pursue fields of study that make impact and contributions to society (Ecklund et al., 2012). Furthermore, covering these topics in the introductory soil science courses may stimulate students becoming interested in further studies in soil science (Miller, 2011).

Since 95% of our food comes from plants whose growth is supported by the soil, soil health is directly related to food security, human health, and well-being (FAO, 2022). To ensure food security, soil degradation should be minimized, and increased support for soil care practices is necessary through sustainable management, regenerative agriculture, precision agriculture, and circularity in the agricultural and food systems (Pozza & Field, 2020). Furthermore, more awareness of soils in natural areas is necessary: in the face of climate change, pollution, and anthropological atmospheric depositions, soil degradation also threatens forests and protected ecosystems, and restoration strategies should acknowledge the soil not just as an abiotic substrate but as a living component of the ecosystem (Musielok et al., 2024; Vinduskova et al., 2025). This will ultimately assist in fulfilling the SDGs of ending poverty (SDG1), zero hunger (SDG2), good health and well-being (SDG3), clean water and sanitation (SDG6), climate action (SDG13), and life on land (SDG15), among other possible SDGs (Brevik et al., 2021; Lal et al., 2021).

As an example of the services provided by soils, climate change mitigation through soil carbon storage is another pressing topic (Amelung et al., 2020). The level of carbon sequestration potential varies due to inherent soil properties, land management practices, political and social will, and associated incentives and support systems. Increasing soil carbon has a significant impact on adaptation to climate change as it builds resilience to extreme weather events, enhances water storage, increases fertility through enhanced biochemical cycles, and reduces soil erosion.

Soil can also be central to reversing biodiversity loss. A recent analysis estimated that 59 ± 15% of global species live in soil (Anthony et al., 2023), demonstrating the importance of soil as a habitat in its own right and as a reservoir for biodiversity. Biodiversity loss in soil affects ecosystem services, including nutrient cycling, agricultural production, and soil carbon storage (Kopittke et al., 2021). Land use change and land degradation are critical drivers in habitat and biodiversity loss, and ecosystem restoration requires rebuilding from the soil up.

One key aspect of soil science education is to explore the trade-offs required to address these concurrent challenges, emphasizing the need to incorporate such topics into soil science courses. Table 1 demonstrates that the evolution of soil science education should be additive and integrative rather than reductive. Fundamental disciplinary depth remains essential but must be explicitly connected to global challenges, policy contexts, and modern analytical tools to ensure relevance and professional competence. For example, in introductory soil science courses, students could be provided with a range of examples of soil functions that play an important role in the societal grand challenges, such as food security, climate change, and loss of soil biodiversity. This could be followed by the inclusion of problem-based learning activities in upper level courses where students can discuss how food security could be ensured through agricultural production without compromising soil biodiversity and soil carbon sequestration. As Evangelista et al. (2023) have highlighted, these questions require transdisciplinary approaches to soil science, integrating cultural, social, ethical, economic, and technical expertise.

Interdisciplinary capstone models that focus on real-world problems foster cognitive advancement (Tripp & Shortlidge, 2019). Assessment as a measure of student achievement will rely on a balance between appropriately weighted projects across disciplines, peer evaluations, reflective journals, and discipline-specific preparatory tasks such as literature reviews (Boix Mansilla & Duraising, 2007; DeZure, 2017; Kulcsar et al., 2016; Spelt et al., 2017; Watson et al., 2018). This will rely on overcoming structural barriers with institutional leadership and centralized governance and may require the formation of committees with cross-faculty representation to implement such programs. We do recognize that the lack of experience and confidence in teaching interdisciplinary courses will need to be addressed through professional development, as suggested by Ross et al. (2022), and building a consensus on curriculum design (e.g., agreeing on a minimum 50% interdisciplinary content) to support successful implementation.

In line with the teaching environment and institutional support required for a truly deep transdisciplinary experience, we propose several specific topics that should be included in soil science programs and/or courses (Table 1). Finally, as illustrated in Figure 2, instructors must move beyond purely disciplinary delivery and facilitate integrative learn-

TABLE 1 Proposed topics that should be included in university soil science programs and/or courses in the next decade.

Topic	Delivery style	Description	Reason to be included	Approach
Pedology	Lecture and field activities	Students need to understand how soils are classified into different categories (definitions and concepts) and how they change due to environmental variables.	• Soil health or condition relates to soil types/classification. • Site-specific knowledge is crucial for informed management practices and soil sustainably.	Philosophy/Knowledge ↓
The contribution of soil to the planetary boundaries/SDGs	Lecture and problem-based learning activities	The diverse soil functions in relation to societal grand challenges should be covered.	• The maintenance of multifunctionalities of soils, not just food production, are critical to address societal grand challenges.	
Soil health, food security, and policy-making	Problem-based learning activities	Students can explore soil management practices that provide food security without negative effects on soil biodiversity, carbon contents, climate change, etc.	• The majority of current food production systems negatively impact soil health; thus, societal changes are needed.	Application ↓
Fieldwork for soil evaluation	Field activities,	Students can be coached on how soils can be evaluated and classified in the field. Also, students may be involved in activities such as local community garden projects and soil judging to understand the basics of soil properties and use.	• The skills of visual soil assessment in the field are essential for land managers to ensure soil sustainably. • The world's increasingly urban population is not fully aware of soil's roles and importance.	Practice/Tactic

Abbreviation: SDGs, sustainable development goals of the United Nations.

ing experiences—using case studies, problem-based learning, and storytelling approaches—that connect foundational soil science knowledge to real-world societal challenges rather than focusing solely on terminology (Figure 2).

3 | THINGS TO CONSIDER IN FUTURE SOIL SCIENCE EDUCATION

3.1 | Must-keep topics in future soil science education

Although future soil science programs should incorporate some new "must-have" topics, as stated above, they should not become overly general or superficial. Hence, it is still essential that fundamental concepts of the soil science discipline are included (Table 1). For example, pedology, the study of the processes, formation, evolution, classification, and distribution of soils, is essential for understanding the regional characteristics and history of soils. Pedology includes (but is not limited to) the classification of individual soil pedons into categories or soil types, comparable to how biologists group individual plants or animals into species or how geologists subdivide rocks into different groups and categories based on their composition and properties. Adequately naming and defining the object of study is essential to any science and to university-level education (Ibáñez & Brevik, 2019); yet, currently, there is a worldwide shortage of scientists who can teach pedology (Basher, 1997; Brevik, Krzic, et al., 2022; Havlin et al., 2010).

Pedology findings have implications for soil management and ecosystem dynamics that allow generalization and advancement of soil knowledge at a global level. Pedology determines the inherent capacity of a specific location for different soil functions and sustainable uses and management options of that soil (Evangelista et al., 2023). Furthermore, soil health is directly related to soil type, as what is considered healthy or optimal functioning will depend on the intrinsic properties of the soil profile. In soil security, the soil type is an important part of the "capability," or inherent ability of a certain body of soil to produce a certain ecosystem service, as opposed to its "condition" or the state of management or degradation it is in (McBratney et al., 2014).

In general, field- and laboratory-based learning remain indispensable in soil science because core competencies—such as pedology (as discussed above), soil profile description, and basic analytical skills—cannot be fully developed through classroom or digital instruction alone. Experiential approaches, including soil classification field schools, soil judging activities, and community-based urban soil investigations, have been shown to significantly improve students' conceptual understanding and confidence in applying soil science principles (Smith et al., 2020; Brevik, Hannam, et al., 2022; Brevik, Krzic, et al., 2022). In addition, low-cost laboratory modules, such as bulk density, aggregate stability, or basic fertility analyses, can be incorporated even into interdisciplinary or resource-limited programs to strengthen practical skills. Embedding these components ensures that students acquire the observational and hands-on competencies that are fundamental to professional soil science practice.

As a Canadian study by Krzic et al. (2024) has shown, course instructors find the soil health concept to be useful in teaching since it requires integration of a range of basic soil disciplinary concepts as well as implementation of active learning strategies. Costantini and McBratney (2025) see opportunities to improve soil health while simultaneously raising public awareness and soil literacy by engaging the public in citizen science initiatives. Finally, representing soils in their proper form, rather than as generalized "brown blobs" with relatively uniform properties, aids in soil communication and awareness raising.

As soil science courses have become integrated into other disciplines (e.g., biology, environmental science, and geography), the teaching of fundamental soil science skills such as soil description and classification has become a low priority or has been completely omitted (Masse et al., 2019). Considering this, let us suppose that soil science education in the decade only then covers simplified versions of soil science concepts with no training in field skills needed for soil description and classification. In that case, there will be a shortage of land managers with an adequate understanding of how to develop appropriate, spatially explicit management practices, tailored according to soil type and their spatial distribution (Brown & Krzic, 2021; Koriem et al., 2022).

Soil specialists who work with farmers must be able to describe soil properties such as texture, structure, drainage, and organic matter content by visually assessing them in the field. This is an important skill developed through fieldwork and years of experience. These features are not always interpretable from a satellite image or multispectral analysis, which have been attracting considerable attention as new soil assessment tools. These technologies are tools that soil scientists should engage with but should not replace onsite investigation. Indeed, many Geographic Information System-based analyses of soils have a digital signature (i.e., sampling grid) that cannot accurately capture field-specific (1:3000 scale) variances. Often, these variances are potential causes for declining soil health. Ground-truthing of our ever-improving spatial models still requires detailed understanding and localized field sampling.

3.2 | Use of advanced technologies and digital tools in future soil science education

Soil science education could benefit from the incorporation of various types of multimedia such as videos, computer animations, simulations, 3D imaging, augmented or virtual reality, and tablet or cellphone-based platforms (Amargedon-Madison et al., 2018; King et al., 2014; Ulery et al., 2020). For example, global soil-related issues, such as soil degradation in various parts of the world, can be vividly illustrated to students using videos and/or virtual reality. This can be augmented with associated information and knowledge sources through generative AI technologies. Such an approach holds immense promise for providing students with a platform for deeper investigation and the development of critical thinking skills.

Given the current situation where soil science is integrated into broader university programs, and with the present generation of students who have grown up with information technology, it is important first to spark students' interest in soil science and to avoid the perception that it is an outdated and unengaging discipline. These trends in digital engagement are expected to continue and even expand in the years to come, creating various opportunities and challenges for post-secondary soil science education. Using resources such as movies (Barnett & Kafka, 2007; Rose, 2003) and animations (Ulery et al., 2020) in the classroom may help spark students' interest in soils and maybe even better explain the relevance of soil science concepts across various land uses and ecosystems. Audiovisual tools can also support the integration of case studies or virtual field visits into indoor classes. Although such tools cannot replace actual field experience, they allow students to explore soil systems—such as arid landscapes, tropical forests, or highly degraded lands—that they would otherwise not have access to. Massive open online courses (MOOCs), for example, can combine video lectures, interactive quizzes, global case studies, and discussion forums to expose students to diverse soil environments and management challenges beyond their local context. In this way, MOOCs and similar online platforms can expand access to soil science education and increase global engagement with soil-related issues.

Since the release of ChatGPT 3.5 in November 2022, AI tools (e.g., ChatGPT, Gemini, formerly known as Bard, and MS Co-pilot) have been increasingly integrated into various aspects of education. Generative AI is a type of AI technology that can generate content (e.g., text, video, audio, and music) at the user's request, based on the data on which it has been trained. This technology offers opportunities for personalizing learning experiences, developing and designing teaching and learning materials, including assessments, improving teaching effectiveness, and enhancing learning outcomes (Chan & Colloton, 2024). Since the release of ChatGPT

3.5, university instructors have been exploring the numerous possibilities of generative AI while also addressing the significant risks it poses to current education systems. Khanifar (2025) tested five large language models (LLMs) against the Iranian soil science PhD entrance exam and found that, at best, the LLMs were only able to answer the questions correctly about 65% of the time, so LLMs have a long way to go before they are ready to replace soil scientists. This is an issue that will continue to present itself in the years to come, and soil science educators need to determine the best ways to work with it in the educational environment. Universities around the world have embraced the use of generative AI as part of their educational strategies, but with caution, considering issues such as data privacy, bias in algorithms, accessibility, and equity. Striking the right balance between AI and human interaction is crucial, and this requires ongoing assessments.

Although the use of AI in soil science is still emerging, broader research in higher education demonstrates that AI-supported learning environments can enhance personalization, streamline feedback, and support adaptive instruction in ways that benefit both students and instructors (Zawacki-Richter et al., 2019). In soil science education, students often enter programs with highly variable backgrounds in biology, chemistry, geography, or environmental science. AI tools can assist in identifying knowledge gaps, offering tailored practice questions, and providing formative feedback, thereby allowing instructors to focus more on higher level discussion, laboratory interpretation, and field-based mentoring. At the same time, responsible implementation requires careful attention to data privacy, algorithmic transparency, academic integrity, and digital equity—areas that have been emphasized as central pillars of ethical AI governance (Floridi & Cowls, 2021). Because of these pedagogical and ethical considerations, AI should be treated not as a replacement for soil expertise but as a complementary tool that supports critical thinking, laboratory learning, and field-based observation. Ensuring the effective use of AI will require continuous evaluation and meaningful faculty development aligned with emerging best practices in AI-enhanced education (Holmes et al., 2022).

4 | HOW TO ENGAGE NEW LEARNERS

4.1 | Improve the visibility of the discipline of soil science for younger generations

Soil science is losing its presence in universities, and one of the primary ways to address this issue is to increase the number of people interested in learning about soil and its importance. To achieve this, ongoing outreach efforts are needed, particularly aimed at elementary, middle school, and high school students (Charzynski et al., 2022; Hirai & Mori, 2020; Krzic et al., 2019; Margenot et al., 2016; Martin et al., 2008; Sandén et al., 2020; Tseng & Lai, 2025). By giving young children opportunities to learn about soil in a fun way that includes playing with and touching the soil, followed by the inclusion of soil-related topics in the curricula in elementary school and beyond, they may put soil science on their radar as a career pathway. A recent study by Charzynski et al. (2022) that compared the level of soil education in high and/or secondary schools in 43 countries showed that overall, soil science education is underrepresented worldwide. Charzynski et al. (2022) suggested the following approaches to overcome the widespread lack of soil science inclusion in the high and/or secondary school curricula (i) promoting collaborations and agreements between high schools and universities, (ii) encouraging workshops and practical (field) exercises and activities, and (iii) implementing technology tools.

A major barrier to increasing soil science exposure in elementary to high schools is that teachers often face limited time, prescribed curricula, and standardized assessment requirements, leaving little room to add new content. Furthermore, the lack of curriculum-aligned teaching modules and accessible instructional materials makes it difficult to integrate soil science systematically. Consequently, many students encounter soil science primarily through outreach activities led by universities. While such outreach is essential, it often depends on voluntary effort and receives limited institutional recognition. Addressing this gap will require both improved teaching resources and stronger support for outreach engagement.

It is also essential to inform the younger generation not only about soil science but also about the work of soil scientists and why that work is necessary in our daily lives. The goals of plant/crop biologists and zoologists, such as the discovery of new species, conservation of existing species, and research aimed at faster and more efficient crop growth, are obvious to many, including young children (Lindbo et al., 2012). However, the roles and goals of soil science, as well as their connections to global sustainability, need to be better communicated. As soil scientists, we need to demonstrate more clearly how recent state-of-the-art technology can be applied to soil science and potentially lead to solutions for global problems. We need to be aware of this when interacting with primary and secondary school students and conveying to the younger generation the significance of soil science and the work of soil scientists.

4.2 | Future introductory soil science classes/courses need to be flexible

Currently, many university students around the world are exposed to soil science concepts as part of broader courses offered in a variety of programs that include agricultural sciences, biological sciences, crop and plant sciences, environmental sciences, geosciences, and natural resource sciences, among others (Brevik, Krzic, et al., 2022; Brevik et al., 2020; Diochon et al., 2017). The introductory soils course is a perfunctory nod to a broad overview of soil science (Amador & Görres, 2004). It may or may not be integrated into a particular major (Krzic et al., 2018).

In addition, China has experienced significant growth in soil-science-related educational programs over the past decade. This expansion has been driven in part by increased national attention to soil and environmental issues, as soil and water contamination has become a major public concern in China (Lu et al., 2015). As comprehensive and agricultural universities respond to these concerns, new undergraduate and graduate programs focusing on soil science, soil ecology, and land resources have been progressively established to train specialists capable of addressing soil-related risks. These educational developments are closely aligned with China's broader environmental governance and sustainable-development strategies, which emphasize ecological protection and long-term environmental planning (Zhang & Wen, 2008).

With this background, we propose constructing the content of introductory soil science courses to be flexible and aligned with a particular program or major, as well as the future profession graduating from that program/major (Field et al., 2017). For example, a field-level understanding of the biological, chemical, and physical properties of soils, along with practical suggestions to improve soil properties in relation to the crops being produced, is often an essential skill for many agricultural consultants and could be emphasized in an agricultural curriculum. The same biological, chemical, and physical properties may also be covered in an introductory soil science course for environmental science majors, but with an emphasis on the skills needed to address pollution and related issues. In this area, future soil science courses that cater to the needs of a diverse range of students could be developed by creating classes that utilize the most up-to-date technology to personalize the student experience.

Besides covering soil science concepts, university course instructors need to help students understand the applicability of those concepts and how they can be relevant to future professional careers. This broader applicability should also motivate individual instructors to make the required effort to make the content of basic soil science classes flexible. Universities need to increase the value placed on teaching, rewarding those instructors who excel in teaching and educational innovations. Improvement in this area may encourage establishment of national and international networks focused on soil science education that would in turn lead to improvements of the soil science courses and programs globally.

5 | QUALITY ASSURANCE OF FUTURE SOIL SCIENCE EDUCATION

5.1 | Why is quality assurance needed?

To further support the establishment of a new style of soil science education, it is desirable to have a system in place to evaluate whether soil education is producing high-quality soil specialists. While some countries have national examinations for career fields (e.g., medical doctors, engineers, and veterinarians), where only those who pass these examinations can practice the discipline, this is often not the case for soil science professionals. As various studies have shown, the number of professionals worldwide with undergraduate or graduate degrees in soil science is decreasing (e.g., Baveye et al., 2006; Brevik, Krzic, et al., 2022; Diochon et al., 2017), and professionals dealing with soil-related issues may have a limited understanding of soil science concepts (Hartemink et al., 2001). Many instructors who are teaching soil science at universities in the United States do not hold degrees specifically in soil science (Brevik & Vaughan, 2020). Therefore, it remains questionable whether they have a holistic view of soil science, as opposed to simply being able to work on narrow, specialized topics that include soils.

Cross-disciplinary programs focused on food security, climate change, biodiversity, and other global-scale issues have become increasingly prominent at universities worldwide. Whether the importance of soil science is recognized in such programs needs to be carefully evaluated in the future, as soil is of critical importance for many global issues. Examples of cross-disciplinary programs in Japan that have been established in recent years include the Global Gastronomy Management Courses (Ritsumeikan University), the Graduate School of Global Food Sciences (Hokkaido University), and the International Joint Degree Master's Program in Agro-Biomedical Science in Food and Health (Tsukuba University). Still, soil is not often included in these programs. In Zambia, examples of new programs include the Master's in Sustainable Land and Environmental Management (University of Zambia) and the Master of Climate Change and Sustainable Development (Mulungushi University). These programs claim to deal with global food resource issues in general, but whether detailed soil science is included in these programs depends on the expertise of the course instructors. In contrast, there are currently 27 universities in Indonesia that offer soil science as an individual study program, at both undergraduate and postgraduate levels (Fiantis et al., 2022). The data showed students' enrollment in the Soil Science Study Programs generally increased over time, which hopefully will lead to them becoming soil science specialists soon.

Widespread access to the Internet and social media enables every individual, as well as many AI tools, to produce and publish false data and interpretations (Hopf et al., 2019). Social media has also transformed what the general public considers to be trustworthy information (Shareef et al., 2019). Scientists must speak out against false information, and educators must be diligent in ensuring the scientific literacy not just of their students but the general public as well.

It is also necessary to ensure the quality of knowledge provided by individuals involved in soil-related work, as well as the quality of services they provide. For example, in Zambia, consulting services for smallholder farmers are becoming more widespread. Some of these services prioritize economic gain and do not necessarily consider what is beneficial for the soil or the local community that relies on it. For example, some consultants recommend and sell soil amendments, claiming that they will diversify and activate soil microorganisms and increase agricultural productivity. Yet, such amendments have not been scientifically proven to be effective, and in some cases, they are not even genuine fertilizers (Ariga et al., 2019; Mdee et al., 2021). As these examples show, there is a global need for more professionals capable of giving accurate advice related to soil.

5.2 | Quality assurance of soil scientists and others working on soil-related issues

To ensure high professional standards in the soil science discipline, a system needs to be established to ensure that soil specialists have a solid understanding of the fundamental concepts. In Japan, for example, there is an examination called the Soil Doctor Certification Examination (https://www.doiken.or.jp/). Currently, university education has little to do with this certification test, as it is typically taken by employees of fertilizer companies who design fertilizer application rates based on soil analysis.

As another example, there are two primary approaches in the United States for ensuring the quality of soil science professionals. One is gaining recognition as a Certified Professional Soil Scientist. This is a voluntary certification that can be earned by someone who meets the appropriate educational standards, has at least 3 (with a graduate degree) to 5 (with a bachelor's degree) years of work experience, and passes a fundamentals of soil science exam (Soil Science Society of America, 2023). The second approach is state licensure. Sixteen states in the United States currently require licensure for the professional practice of soil science within their jurisdiction (Wikipedia, 2025). In these cases, each state establishes its own guidelines for what is needed to be licensed and what types of work require that licensure.

Contrastingly, in Zambia, the legal requirement for accreditation of soil scientists is relatively new, and it is not specific but rather grouped together with other agricultural professionals (Agricultural Institute of Zambia Act, 2017).

The quality of the professional accreditation itself needs to be ensured, and there are still some operational issues to be addressed, such as cooperation with universities that teach soil science and the ability to address issues concerning local problems. In the future, universities offering soil science courses and programs may need to be involved in providing these credentials. This could produce results that benefit both parties. Universities may improve the quality of their education through a better understanding of the information required to gain certification. At the same time, accreditation organizations may maintain or improve the quality of the certification systems based on the knowledge of and feedback from the soil scientists employed at the universities.

5.3 | Quality improvement and assurance of soil science programs and courses at university levels

5.3.1 | Recognition of teachers for the advancement of soil science education

Currently, many university faculty members are expected to focus primarily on research, often relegating teaching to a secondary role. Yet, some universities have created faculty positions that place a high priority on teaching. In parts of Australia, university faculty members who excel in teaching are promoted based on their efforts to make their classes more effective and their membership in an international organization that assesses education. Some universities in the United States and Canada also have positions dedicated to teaching; however, these faculty are often paid less than research-focused faculty. In other cases, some universities in the United States have variable appointments, where one faculty member might devote, for example, 75% of their time to research and much less to teaching. In contrast, another devotes 75% of their time to teaching and much less to research. However, time spent on research and publishing positively correlates to faculty pay in the United States, while time spent in the classroom is negatively correlated to faculty pay (Fairweather, 2005). This experience is not universal. For example, in Australia, salaries do not vary based on the proportion of time allocated to teaching versus research. In other countries, such as Japan, teaching emphasis is rarely recognized or treated differently. Abundant research shows that student learning benefits from a shift from a traditional, lecture-based teaching style to other styles more focused on student engagement, including field activities (Brevik, 2020; Field et al., 2017; Muggler et al., 2023; Rees & Johnson, 2020; Smith et al., 2020; Ulery et al., 2020; Vasiliadou, 2020). It is worth considering a future where soil science instructors, who actively reform and innovate teaching activities, receive recognition on par with their more research-focused peers.

5.3.2 | Review systems for the university soil science courses

University soil science programs and courses should be quality-assured and revised to tackle global soil-related issues. Some examples of the existing quality assurance approaches for university soil science programs and courses are outlined below, together with suggestions on how to improve the quality of soil science education in the future.

In Canada, existing university programs are subject to periodic reviews (typically done every 10 years) by two to four external reviewers from other national and/or international universities. Similar reviews are conducted in some US universities. In addition to the review of courses, reviewers also interview students, faculty members, administrators, and staff. For programs such as soil science, which are relevant for various professional designations (e.g., professional forester or wetland scientist), reviewers also check course offerings in the particular program to determine if they are well-aligned with the requirements of those professional designations. In such cases, the reviewers must understand the importance of soil science education. With the ongoing disappearance of soil science degree-granting programs and the integration of soil science into other interdisciplinary programs, there is likely a further dilution of soils knowledge held by the reviewers. This is a global concern that emphasizes the need for international discussion among soil scientists regarding what constitutes an adequate soil science curriculum at the university level and how to successfully implement it into academic programs that partly rely on soil science concepts.

Soil science educators need to engage in collaboration in educational pedagogy (Charzynski et al., 2022; Jelinski et al., 2019). This provides a clear route to encourage more unified content on key soil concepts and a broader geographical exposure to soil diversity, all the while allowing for regional-specific content. Here are a couple of recent examples of such initiatives from around the world. In 2022, the International Union of Soil Sciences (IUSS) established the Young and Early Career Scientists Working Group (YECS) with a mission to support early career scientists and to expand soil science education to children and youth while promoting diversity and inclusion within the IUSS (Cerón-González et al., 2025). Since its establishment, YECS has initiated specific key actions to promote international partnerships and culturally inclusive soil education. In addition, many professional soil science societies maintain dedicated education and outreach divisions, including K-12 education committees that have developed teaching modules, outreach materials, and teacher-support resources to strengthen soil literacy at multiple educational levels. Another example is the open-access introductory soil science textbook that was prepared by the Canadian Society of Soil Science (Krzic et al., 2021). Preparing this text required that the 41 contributors reach an agreement on the important aspects to be covered in an introductory soil science course. These educational approaches may have the potential to increase student engagement in soil science and ignite a desire to explore the field more deeply. However, student engagement depends on the quality of the open-access textbooks and the teaching content derived from them (Trust et al., 2023).

While this paper proposes a forward-looking framework for soil science education, several limitations must be acknowledged. First, the feasibility of integrating new topics—such as soil health, pedology, and interdisciplinary capstone models—varies widely across national curricula. Many universities already face crowded programs or limited flexibility for adding specialized content. Second, the availability of instructors trained in pedology, field description, and soil taxonomy is uneven worldwide, and shortages may constrain the implementation of field-intensive models. Third, resource limitations, including access to field sites, laboratory infrastructure, and digital tools, pose challenges for institutions in low-income or remote regions. Fourth, although AI offers opportunities for personalized learning, reliance on these tools may exacerbate inequalities if robust governance frameworks and training are still not in place. Finally, the conceptual nature of this synthesis highlights the need for future comparative research to systematically evaluate the outcomes of proposed educational models across countries and institutional contexts.

6 | CONCLUSIONS

This study contributes to a concise, globally oriented roadmap that integrates soil health, pedology, planetary boundaries, digital technologies, and quality assurance. It advances beyond earlier national or topic-specific studies by aligning soil science education with broader societal needs. As soil returns to being an important keyword in relation to global issues, this should be reflected in changes to soil education at universities. Fewer students are majoring in soil science at universities in many parts of the world, while the knowledge of soil specialists is becoming more widely sought by society. Here, we propose new “must have” topics in soil science programs, essentially starting from the role of soil in tackling grand challenges by highlighting the services and functions soil provides to society and the planet. Building on these concepts in subsequent courses offers the learner greater depth in soil science through the fundamentals of soil biology, chemistry, and physics. This should be underpinned by more field-based skills and knowledge of pedology, supported by technologies including AI and weaving soil science across transdisciplinary programs.

The issues addressed by soil science are changing; this needs to be accounted for in soil science education programs so that we reach out to new prospective soil scientists. Good examples of this are the increasing importance of urban soil knowledge, integrating digital tools and technology, and highlighting how soil science can address many pressing global challenges. Quality assurance for soil scientists and the programs offering soil science is necessary and has to be performed by people with the knowledge base to do so. Soil science is indispensable for solving many global issues, but the collaboration of the various sectors discussed in this paper will be essential for building a society in which this knowledge can be effectively utilized.

AUTHOR CONTRIBUTIONS

Yoshitaka Uchida: Investigation; methodology; visualization; writing—original draft; writing—review and editing. **Maja Krzic**: Data curation; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Jacqueline Hannam**: Methodology; supervision; writing—original draft; writing—review and editing. **Eric C. Brevik**: Methodology; project administration; supervision; writing—original draft; writing—review and editing. **Damien J. Field**: Investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Karen Vancampenhout**: Conceptualization; methodology; writing—original draft; writing—review and editing. **Feng Zhu**: Methodology; writing—original draft; writing—review and editing. **Ron Reuter**: Methodology; writing—original draft; writing—review and editing. **Sri R. Utami**: Investigation; methodology; writing—original draft; writing—review and editing. **Ikabongo Mukumbuta**: Investigation; methodology; writing—original draft; writing—review and editing. **Hassan El-Ramady**: Methodology; writing—original draft; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Agriculture Institute of Zambia Act. (2017). *Government of the Republic of Zambia*. https://www.parliament.gov.zm/sites/default/files/documents/acts/The%20Agricultural%20Institute%20of%20Zambia%20Act%20No%202%20of%202017.pdf

Amador, J. A., & Görres, J. H. (2004). A problem-based learning approach to teaching introductory soil science. *Journal of Natural Resources and Life Science Education*, *33*, 21–27. https://doi.org/10.2134/jnrlse.2004.0021

Amargedon-Madison, J., Krzic, M., Simard, S., Adderly, C., & Khan, S. (2018). Shroomroot: An action-based digital game to enhance post-secondary teaching and learning about mycorrhiza. *The American Biology Teacher*, *80*(1), 11–20. https://doi.org/10.1525/abt.2018.80.1.11

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*, Article 5427. https://doi.org/10.1038/s41467-020-18887-7

Anthony, M. A., Bender, S. F., & van der Heijden, M. G. A. (2023). Enumerating soil biodiversity. *Proceedings of the National Academy of Science of the USA*, *120*, e2304663120. https://doi.org/10.1073/pnas.2304663120

Ariga, J., Mabaya, E., Waithaka, M., & Wanzala-Mlobela, M. (2019). Can improved agricultural technologies spur a green revolution in Africa? A multicountry analysis of seed and fertilizer delivery systems. *Agricultural Economics*, *50*, 63–74. https://doi.org/10.1111/agec.12533

Barnett, M., & Kafka, A. (2007). Using science fiction movie scenes to support critical analysis of science. *Journal of College Science Teaching*, *36*, 31–35.

Basher, L. R. (1997). Is pedology dead and buried? *Australian Journal of Soil Research*, *35*(5), 979–994. https://doi.org/10.1071/S96110

Bates, A. W. (2022). *Teaching in a digital age: Guidelines for designing teaching and learning* (3rd ed.). BC Campus. https://pressbooks.bccampus.ca/teachinginadigitalagev3m/

Baveye, P., Jacobson, A. R., Allaire, S. E., Tandarich, J. P., & Bryant, R. B. (2006). Whither goes soil science in the United States and Canada? *Soil Science*, *171*, 501–518. https://doi.org/10.1097/01.ss.0000228032.26905.a9

Boix Mansilla, V., & Duraisingh, E. D. (2007). Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposal. *The Journal of Higher Education*, *78*(2), 215–237. https://doi.org/10.1353/jhe.2007.0008

Bouma, J., Montanarella, L., & Evanylo, G. (2019). The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use and Management*, *35*(4), 538–546. https://doi.org/10.1111/sum.12518

Bouma, J. (2014). Soil science contributions towards Sustainable Development Goals and their implementation: Linking soil functions with

ecosystem services. *Journal of Plant Nutrition and Soil Science*, *177*(2), 111–120. https://doi.org/10.1002/jpln.201300646
Brevik, E. C. (2009). The teaching of soil science in geology, geography, environmental science, and agricultural programs. *Soil Survey Horizons*, *50*, 120–123. https://doi.org/10.2136/sh2009.4.0120
Brevik, E. C. (2020). The effect of adding online homework assignments to a small introductory physical geology class. *Natural Sciences Education*, *49*, e20020. https://doi.org/10.1002/nse2.20020
Brevik, E. C., Dolliver, H., Edinger-Marshall, S., Itkin, D., Johnson-Maynard, J., Liles, G., Mbila, M., Moorberg, C., Sanchez-De Leon, Y., Steffan, J. J., Ulery, A., & Vaughan, K. (2020). Undergraduate degrees that train students for soil science careers at universities in the USA and its territories. *Soil Science Society of America Journal*, *84*, 1797–1807. https://doi.org/10.1002/saj2.20140
Brevik, E. C., Hannam, J., Krzic, M., Muggler, C., & Uchida, Y. (2022). The importance of soil education to connectivity as a dimension of soil security. *Soil Security*, *7*, 100066. https://doi.org/10.1016/j.soisec.2022.100066
Brevik, E. C., Khaledian, Y., & El-Ramady, H. (2021). Assessing the complex links between soils and human health: An area of pressing need. *Frontiers in Soil Science*, *1*, 731085. https://doi.org/10.3389/fsoil.2021.731085
Brevik, E. C., Krzic, M., Muggler, C., Field, D., Hannam, J., & Uchida, Y. (2022). Soil science education—A multi-national look at current perspectives. *Natural Sciences Education*, *51*, e20077. https://doi.org/10.1002/nse2.20077
Brevik, E. C., & Vaughan, K. (2020). Degrees earned by faculty teaching in soil science preparatory programs at universities in the USA. *Natural Sciences Education*, *49*, e20033. https://doi.org/10.1002/nse2.20033
Brown, S., & Krzic, M. (2021). Lessons learned teaching during the COVID-19 pandemic: Incorporating change for future large science courses. *Natural Sciences Education*, *50*, e20047. https://doi.org/10.1002/nse2.20047
Cerón-González, A., Ng, H., Ivelic-Saez, J., Vega-Aguilar, A., Agbor, D. T., Pacci, S., & Glina, B. (2025). Securing the future of soil science: Addressing global demographic barriers to engage youth and accelerate early careers. *Geoderma*, *455*, 117220. https://doi.org/10.1016/j.geoderma.2025.117220
Chan, C. K. Y., & Colloton, T. (2024). *Generative AI in higher education: The ChatGPT effect*. Taylor & Francis eBooks. https://doi.org/10.4324/9781003459026
Charzyński, P., Urbańska, M., Franco Capra, G., Ganga, A., Holmes, P., Szulczewski, M., Baatar, U.-O., Boularbah, A., Bresilla, B., Cacovean, H., Datta, A., Gadsby, H., Gargouri, K., Gebrehiwot Gebregeorgis, E., Giani, L., Grover, S., Juliev, M., Kasparinskis, R., Kawahigashi, M., … Zhang, S. (2022). A global perspective on soil science education at third educational level; knowledge, practice, skills and challenges. *Geoderma*, *425*, 116053. https://doi.org/10.1016/j.geoderma.2022.116053
Clary, G., Dick, G., Yagmur Akbulut, A., & Van Slyke, C. (2022). The after times: College students' desire to continue with distance learning post pandemic. *Communications of the Association for Information Systems*, *50*(1), 122–142. https://doi.org/10.17705/1CAIS.05003
Costantini, E. A. C., & McBratney, A. B. (2025). Recent developments in global soil health protection policies. *Soil Security*, *19*, 100191. https://doi.org/10.1016/j.soisec.2025.100191
DeZure, D. (2017). Interdisciplinary pedagogies in higher education. In R. Frodeman (Ed.), *The Oxford handbook of interdisciplinarity* (2nd ed., pp. 558–572). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198733522.013.45
Diochon, A., Basiliko, N., Krzic, M., Yates, T. T., Olson, E., Masse, J., Amiro, B., & Kumaragamage, D. (2017). Profiling undergraduate soil science education in Canada: Status and projected trends. *Canadian Journal of Soil Science*, *97*, 122–132. https://doi.org/10.1139/cjss-2016-0058
Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6
Ecklund, E. H., Lincoln, A. E., & Tansey, C. (2012). Gender segregation in elite academic science. *Gender & Society*, *26*(5), 693–717. https://doi.org/10.1177/0891243212451904
Evangelista, S. J., Field, D. J., Mcbratney, A. B., Minasny, B., Ng, W., Padarian, J., Román Dobarco, M., & Wadoux, A. M. J.-C. (2023). A proposal for the assessment of soil security: Soil functions, soil services and threats to soil. *Soil Security*, *10*, 100086. https://doi.org/10.1016/j.soisec.2023.100086
Fairweather, J. S. (2005). Beyond the rhetoric: Trends in the relative value of teaching and research in faculty salaries. *The Journal of Higher Education*, *76*, 401–422. https://doi.org/10.1080/00221546.2005.11772290
FAO. (2022). *Healthy soils for a healthy people and planet: FAO calls for reversal of soil degradation*. https://www.fao.org/newsroom/detail/agriculture-soils-degradation-FAO-GFFA-2022/
Fiantis, D., Utami, S. R., Niswati, A., Nurbaity, A., Utami, S. N. H., Husnain, Taberima, S., Setiawati, T. C., Sabrina, T., Hairiah, K., Lanya, I., Rampisela, A., Ginting, F. I., Mukhlis, Mastur, S., Nurcholis, M., Anda, M., Sukarman, Mulyanto, B., … Minasny, B. (2022). The increasing role of Indonesian women in soil scince: Current and future challenges. *Soil Security*, *6*, 100050. https://doi.org/10.1016/j.soisec.2022.100050
Field, D. J. (2019). Soil security and connectivity: The what, so what and now what. In A. C. Richer-de-Forges, F. Carre, A. B. McBratney, J. Bouma, & D. Arrouays (Eds.), *Global soil security: Towards more science-society interfaces* (pp. 91–98). CRC Press.
Field, D. J., Yates, D., Koppi, A. J., McBratney, A. B., & Jarrett, L. (2017). Framing a modern context of soil science learning and teaching. *Geoderma*, *289*, 117–123. https://doi.org/10.1016/j.geoderma.2016.11.034
Floridi, L., & Cowls, J. (2021). A unified framework of five principles for AI in society. *Harvard Data Science Review*, *3*(1), 8–9.
Garritzmann, J. L. (2023). Politics of higher education funding in (Western) Europe—And beyond. In J. Jungblut, M. Maltais, E. C. Ness, & D. Rexe (Eds.), *Comparative higher education politics: Policymaking in North America and Western Europe* (pp. 121–155). Springer. https://doi.org/10.1007/978-3-031-25867-1_6
Hansen, N., Ward, S., Khosla, R., Fenwick, J., & Moore, B. (2007). What does undergraduate enrollment in soil and crop sciences mean for the future of agronomy? *Agronomy Journal*, *99*, 1169–1174. https://doi.org/10.2134/agronj2006.0318
Hartemink, A. E., & McBratney, A. (2008). A soil science renaissance. *Geoderma*, *148*, 123–129. https://doi.org/10.1016/j.geoderma.2008.10.006
Hartemink, A. E., McBratney, A. B., & Cattle, J. A. (2001). Developments and trends in soil science: 100 volumes of Geoderma (1967–2001). *Geoderma*, *100*, 217–268. https://doi.org/10.1016/S0016-7061(01)00024-6

Havlin, J., Balster, N., Chapman, S., Ferris, D., Thompson, T., & Smith, T. (2010). Trends in soil science education and employment. *Soil Science Society of America Journal*, *74*(7), 1429–1432. https://doi.org/10.2136/sssaj2010.0143

Hews, R., McNamara, J., & Nay, Z. (2022). Prioritising lifeload over learning load: Understanding post-pandemic student engagement. *Journal of University Teaching and Learning Practice*, *19*(2), 128–146. https://doi.org/10.53761/1.19.2.9

Hirai, H., & Mori, K. (2020). Development of a field-based soil education program "Where and how does your food grow?" based on the results of a student questionnaire survey on soil and rice. In T. Kosaki, R. Lal, & L. B. Reyes-Sanchez (Eds.), *Soil sciences education: Global concepts and teaching* (pp. 77–85). Schweizerbart Science Publishers.

Holmes, W., Bialik, M., & Fadel, C. (2022). *Artificial intelligence in education: Promises and implications for teaching and learning*. Center for Curriculum Redesign.

Hopf, H., Krief, A., Mehta, G., & Matlin, S. A. (2019). Fake science and the knowledge crisis: Ignorance can be fatal. *Royal Society Open Science*, *6*, 190161. https://doi.org/10.1098/rsos.190161

Ibáñez, J.-J., & Brevik, E. C. (2019). Divergence in natural diversity studies: The need to standardize methods and goals. *Catena*, *182*, 104110. https://doi.org/10.1016/j.catena.2019.104110

Jelinski, N. A., Moorberg, C. J., Ransom, M. D., & Bell, J. C. (2019). A survey of introductory soil science courses and curricula in the United States. *Natural Sciences Education*, *48*, 180019. https://doi.org/10.4195/nse2018.11.0019

Jongbloed, B. (2023). Higher education funding in Canada, the U.S. and Western Europe—A comparison. In J. Jungblut, M. Maltais, E. C. Ness, & D. Rexe (Eds.), *Comparative higher education politics: Policymaking in North America and Western Europe* (pp. 211–228) Springer. https://doi.org/10.1007/978-3-031-25867-1_9

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., Van Der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B., & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *SOIL*, *2*, 111–128. https://doi.org/10.5194/soil-2-111-2016

Kennepohl, D., & Moore, M. G. (2016). *Teaching science online: Practical guidance for effective instruction and lab work* (1st ed.). Routledge. https://doi.org/10.4324/9781003447405

Khanifar, J. (2025). Evaluating AI-generated responses from different chatbots to soil science-related questions. *Soil Advances*, *3*, 100034. https://doi.org/10.1016/j.soilad.2025.100034

King, C., Dordel, J., Krzic, M., & Simard, S. W. (2014). Integrating a mobile-based gaming application into a postsecondary forest ecology course. *Natural Sciences Education*, *43*, 1173–1125. https://doi.org/10.4195/nse2014.02.0004

Kopittke, P. M., Menzies, N. W., Dalal, R. C., Mckenna, B. A., Husted, S., Wang, P., & Lombi, E. (2021). The role of soil in defining planetary boundaries and the safe operating space for humanity. *Environment International*, *146*, 106245. https://doi.org/10.1016/j.envint.2020.106245

Koriem, M., Gaheen, S., El-Ramady, H., Prokisch, J., & Brevik, E. (2022). Global soil science education to address the soil–water–climate change nexus. *Environment, Biodiversity and Soil Security*, *6*(2022), 27–39. https://doi.org/10.21608/jenvbs.2022.117119.1160

Krzic, M., Walley, F. L., Diochon, A., Paré, M. C., & Farrell, R. E. (2021). *Digging into Canadian soils: An introduction to soil science*. Canadian Society of Soil Science. https://openpress.usask.ca/soilscience/

Krzic, M., Wilson, J., Hazlett, P., & Diochon, A. (2019). Soil science education practices used in Canadian K–12, postsecondary, and informal settings. *Natural Sciences Education*, *48*, 1–6. https://doi.org/10.4195/nse2019.09.0015

Krzic, M., Yates, T., Diochon, A., Van Eerd, L., & MacKenzie, D. (2024). Assessing the incorporation of the soil health concept in postsecondary education in Canada. *Canadian Journal of Soil Science*, *104*(2), 227–236. https://doi.org/10.1139/cjss-2024-0002

Krzic, M., Yates, T. T., Basiliko, N., Pare, M. C., Diochon, A., & Swallow, M. (2018). Introductory soil courses: A frontier of soil science education in Canada. *Canadian Journal of Soil Science*, *98*, 343–356. https://doi.org/10.1139/cjss-2018-0006

Kulcsar, L. J., Aistrup, J. A., Bulatewicz, T., Peterson, J. M., Welch, S. M., & Steward, D. R. (2016). Water and society: Interdisciplinary education in natural resources. *Journal of Contemporary Water Research & Education*, *158*(1), 120–131. https://doi.org/10.1111/j.1936-704x.2016.03223.x

Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D. J., Glaser, B., Hatano, R., Hartemink, A., Kosaki, T., Lascelles, B., Monger, C., Muggler, C., Ndzana, G. M., Norra, S., Pan, X., Paradelo, R., Reyes-Sánchez, L. B., Sandén, T., Singh, B. R., … Zhang, J. (2021). Soils and sustainable development goals of the United Nations: An IUSS perspective. *Geoderma Regional*, *25*, e00398. https://doi.org/10.1016/j.geodrs.2021.e00398

Lindbo, D. L., Kozlowski, D. A., & Robinson, C. (2012). *Know soil, know life*. Soil Science Society of America.

Lu, Y., Song, S., Wang, R., Liu, Z., Meng, J., Sweetman, A. J., Jenkins, A., Ferrier, R. C., Li, H., Luo, W., & Wang, T. (2015). Impacts of soil and water pollution on food safety and health risks in China: A review. *Environment International*, *77*, 5–18. https://doi.org/10.1016/j.envint.2014.12.010

Mahler, R. L., Krzic, M., Garramon Merkle, B., Moorberg, C., & Brevik, E. C. (2021). Natural sciences education in a COVID-19 world. *Natural Sciences Education*, *50*, e20067. https://doi.org/10.1002/nse2.20067

Margenot, A. J., Alldritt, K., Southard, S., & O'Geen, A. (2016). Integrating soil science into primary school curricula: Students promote soil science education with *Dig It! The Secrets of Soil*. *Soil Science Society of America Journal*, *80*, 831–838. https://doi.org/10.2136/sssaj2016.03.0056

Martin, D., Egan, T. M., McWilliams, A. S., Wilson, E. E., Holt, M. L., & Reaves, W. E. (2008). Meeting teacher demand, increasing teacher performance: Five years of school-university partnerships. *Scholarlypartnershipsedu*, *3*(2), Article 2. https://core.ac.uk/download/pdf/47213008.pdf

Masse, J., Yates, T., Krzic, M., Unc, A., Chen, Z. C., Quideau, S., Hodgson, K., & Warren, C. J. (2019). Identifying learning outcomes for a Canadian pedology field school: Addressing the gap between new graduates' skills and the needs of the current job market. *Canadian Journal of Soil Science*, *98*, 343–356. https://doi.org/10.1139/CJSS-2019-0040

McBratney, A., Field, D. J., & Koch, A. (2014). The dimensions of soil security. *Geoderma*, *213*, 203–213. https://doi.org/10.1016/j.geoderma.2013.08.013

McKenna, J. R., & Brann, D. E. (1992). Enhancement of recruiting activities to attract rural youth to careers in agronomy. *Journal of Natural*

Resources and Life Sciences Education, *21*, 84–92. https://doi.org/10.2134/jnrlse.1992.0084
Mdee, A., Ofori, A., Chasukwa, M., & Manda, S. (2021). Neither sustainable nor inclusive: A political economy of agricultural policy and livelihoods in Malawi, Tanzania and Zambia. *The Journal of Peasant Studies*, *48*(6), 1260–1283. https://doi.org/10.1080/03066150.2019.1708724
Miller, B. A. (2011). Marketing and branding the agronomy major at Iowa State University. *Journal of Natural Resources and Life Sciences Education*, *40*, 1–9. https://doi.org/10.4195/jnrlse.2009.0037u
Muggler, C. C., Gasparini, A. S., & Santos, D. C. L. (2023). Roots of soil perceptions by university and secondary school students in Minas Gerais, Brazil. In N. Patzel, S. Grunwald, E. C. Brevik, & C. Feller (Eds.), *Cultural understanding of soils: The importance of cultural diversity and of the inner world* (pp. 467–482). Springer. https://doi.org/10.1007/978-3-031-13169-1_23
Musielok, Ł., Vancampenhout, K., Muys, B., Gus-Stolarczyk, M., Grabska-Szwagrzyk, E., Stolarczyk, M., Bartos, A., Gołąb, A., & Buczek, K. (2024). Dynamic linkages between human pressure and stability of soil organic matter in mid-latitude mountains—A perspective review. *Geoderma Regional*, *39*, e00859. https://doi.org/10.1016/j.geodrs.2024.e00859
Paltseva, A. (2025). Participatory science in urban soil research: A framework for overcoming challenges and expanding public engagement. *iScience*, *28*(5), 112361. https://doi.org/10.1016/j.isci.2025.112361
Pereira, P., Inacio, M., Bogunovic, I., Symochko, L., Barcelo, D., & Zhao, W. (2023). Agricultural soil degradation in Estonia, Latvia and Lithuania. In P. Pereira, M. Muñoz-Rojas, I. Bogunovic, & W. Zhao (Eds.), *Impact of agriculture on soil degradation II. The handbook of environmental chemistry* (Vol. 121, pp. 59–86). Springer. https://doi.org/10.1007/698_2023_967
Pozza, L. E., & Field, D. J. (2020). The science of soil security and food security. *Soil Security*, *1*, 100002. https://doi.org/10.1016/j.soisec.2020.100002
Rees, G. L., & Johnson, D. K. (2020). Impact of a national collegiate soil judging competition on student learning and attitudes. *Natural Sciences Education*, *49*, e20007. https://doi.org/10.1002/nse2.20007
Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*, eadh2458. https://doi.org/10.1126/sciadv.adh2458
Rose, C. (2003). How to teach biology using the movie science of cloning people, resurrecting the dead, and combining flies and humans. *Public Understanding of Science*, *12*, 289–296. https://doi.org/10.1177/0963662503123007
Ross, P. M., Mercer-Mapstone, L., Pozza, L. E., Poronnik, P., Hinton, T., & Field, D. J. (2022). An idea to explore: Interdisciplinary capstone courses in biomedical and life science education. *Biochemical and Molecular Biology Education*, *50*, 649–660. https://doi.org/10.1002/bmb.21673
Sandén, T., Spiegel, H., Wenng, H., Schwarz, M., & Sarneel, J. M. (2020). Learning science during teatime: Using a citizen science approach to collect data on litter decomposition in Sweden and Austria. *Sustainability*, *12*, 7745. https://doi.org/10.3390/su12187745
Shareef, M. A., Mukerji, B., Dwivedi, Y. K., Rana, N. P., & Islam, R. (2019). Social media marketing: Comparative effect of advertisement sources. *Journal of Retail Consumer Services*, *46*, 58–69. https://doi.org/10.1016/j.jretconser.2017.11.001
Smith, C. M. S., Chau, H. W., Carrick, S., van Dijk, J. L., Balks, M. R., & O'Neill, T. A. (2020). Learning by doing is more memorable: The practice of pedagogically aligned learning in university level soil science in New Zealand. In T. Kosaki, R. Lal, & L. B. Reyes-Sanchez (Eds.), *Soil sciences education: Global concepts and teaching* (pp. 183–190). Schweizerbart Science Publishers.
Soil Science Society of America. (2023). *Become certified*. https://www.soils.org/certifications/become-certified/
Spelt, E. J. H., Luning, P. A., van Boekel, M. A. J. S., & Mulder, M. (2017). A multidimensional approach to examine student interdisciplinary learning in science and engineering in higher education. *European Journal of Engineering Education*, *42*(6), 761–774. https://doi.org/10.1080/03043797.2016.1224228
Stroud, J. L. (2019). Tackling misinformation in agriculture. *bioRxiv*. https://doi.org/10.1101/2019.12.27.889279
Tripp, B., & Shortlidge, E. E. (2019). A framework to guide undergraduate education in interdisciplinary science. *CBE—Life Sciences Education*, *18*(2), 18–11. https://doi.org/10.1187/cbe.18-11-0226
Trust, T., Maloy, R. W., & Edwards, S. (2023). College student engagement in OER design projects: Impacts on attitudes, motivation, and learning. *Active Learning in Higher Education*, *24*, 353–371. https://doi.org/10.1177/14697874221081454
Tseng, W. Y., & Lai, H. Y. (2025). The feasibility of implementing a soil education framework in compulsory schools: A case study in Taiwan. *Soil Security*, *20*, 100195. https://doi.org/10.1016/j.soisec.2025.100195
Ulery, A., Smith Muise, A., Carroll, K. C., Chamberlin, B., White, L., Martinez, P., Spears, L., & Gleason, J. (2020). Impact of multimedia learning tools in agricultural science classes. *Natural Sciences Education*, *49*, e20011. https://doi.org/10.1002/nse2.20011
United Nations. (2024). *The 17 goals*. https://sdgs.un.org/goals
Vancampenhout, K., Agnelli, A., van Groenigen, J. W., Laird, D., Minasny, B., & Kögel-Knabner, I. (2023). Should soil classification be mandatory for manuscripts aiming to publish in Geoderma and Geoderma Regional? *Geoderma*, *438*, 116642. https://doi.org/10.1016/j.geoderma.2023.116642
Vasiliadou, R. (2020). Virtual laboratories during coronavirus (COVID-19) pandemic. *Biochemistry and Molecular Biology Education*, *48*, 482–483. https://doi.org/10.1002/bmb.21407
Vindušková, O., Deckmyn, G., Reynaert, S., Vancampenhout, K., Schlüter, S., Frouz, J., De Boeck, H., Portillo-Estrada, M., Verbruggen, E., Asard, H., Beemster, G. T. S., & Nijs, I. (2025). More persistent precipitation regimes induce soil degradation. *Geoderma*, *455*, e117230. https://doi.org/10.1016/j.geoderma.2025.117230
Walter, C., Veenstra, J., Melot, R., & Coquet, Y. (2024). Identification of soil-related professional profiles for the future from a survey of European stakeholders. *European Journal of Soil Science*, *75*, e13469. https://doi.org/10.1111/ejss.13469
Watson, R. M., Willford, J. D., & Pfeifer, M. A. (2018). A cultured learning, environment: Implementing a problem- and service-based microbiology capstone course to assess process- and skill-based learning objectives. *Interdisciplinary Journal of Problem-Based Learning*, *12*(1), Article 8. https://doi.org/10.7771/1541-5015.1694

Wikipedia. (2025). *List of state soil science licensing boards*. https://en.wikipedia.org/wiki/List_of_state_soil_science_licensing_boards

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education. *International Journal of Educational Technology in Higher Education*, *16*, 1–27.

Zhang, K., & Wen, Z. (2008). Review and challenges of policies of environmental protection and sustainable development in China. *Journal of Environmental Management*, *88*(4), 1249–1261. https://doi.org/10.1016/j.jenvman.2007.06.019

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