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Natural Sciences Education

INVITED REVIEW

Soil science education: A multinational look at current perspectives

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Abstract

Soil knowledge is essential to address modern global challenges. Soil science education began with soil survey and agricultural activities, with a focus on the traditional subdisciplines of soil chemistry, soil physics, pedology, soil mineralogy, and soil biology. Soil education has evolved to address the needs of an increasing variety of fields and increasingly complex issues, as seen through the move to teach soil content in programs such as biological and ecological sciences, environmental science, and geosciences. A wide range of approaches have been used to teach soil topics in the modern classroom, including not only traditional lecture and laboratory techniques but also soil judging, online tools, computer graphics, animations, and game-based learning, mobile apps, industry partners, open-access materials, and flipped classrooms. The modern soil curriculum needs to acknowledge the multifunctionality of soils and provide a suite of conduits that connect its traditional subdisciplines with other cognate areas. One way to accomplish this may be to shift from the traditional subdiscipline-based approach to soil science education to a soil functions approach. Strategies to engage the public include incorporating soil topics into primary and secondary school curricula, engaging the public through museums and citizen science projects, and explaining the significance of soil to humanity. Soil education has many challenges and opportunities in the years ahead.

1 | SOIL SCIENCE AND ITS IMPORTANCE FOR FINDING SOLUTIONS FOR CURRENT GLOBAL ISSUES

There are several global challenges that affect the sustainability of human and planetary health. These include food and water security to support the world's population, having the ability to mitigate and adapt to the effects of climate change, and protecting global biodiversity (Bagnall et al., 2021; Godfray et al., 2010; Janzen et al., 2011; McBratney & Field, 2015). These challenges are complex, difficult to solve, and interrelated (McBratney et al., 2014). Analysis of these global challenges reveals that they are influenced by soil and its degradation (Bouma & McBratney, 2013), and soil and its management can contribute to mitigating the effect of these challenges (Bennett et al., 2019).

The role of soil is recognized through a suite of functions relevant to humanity and ecosystems (McBratney et al., 2019). The functions soil provides focus on biomass production, cycling, and buffering and transforming nutrients, water, and contaminants (Larson & Pearson, 1994; Lehmann

Abbreviations: MS, Master of Science; PhD, Doctor of Philosophy; TRIL, Teaching-Research-Industry-Learning; UNSDGs, United Nations Sustainable Development Goals.

& Stahr, 2010), as well as its ability to store C and ensure soil biodiversity (Lal et al., 2020). Simultaneously, there are up to eight significant threats to soil (McBratney et al., 2019) that compromise soil's ability to function and subsequently help address the global challenges. This recognition of the multifunctionality of soil and its threats needs to be elucidated in a contemporary soil science curriculum. Such curriculum design should still retain a focus on developing a deep knowledge of soil, including the science of soil, but would also need to include socioeconomic content (Baveye et al., 2016; Bouma, 2019; Field, 2019; Havlin et al., 2010), providing a framework where connections between modern lifestyles and soil challenges are addressed.

Generally, a comprehensive soil science curriculum is based on an understanding and characterizing of soil and its formation and evolution. This approach is supported by theoretical frameworks recognizing we know something about soil and why it occurs where it does. Since the proposal of Dokuchaev's thesis on the Russian Chernozem, and even before (Feller et al., 2006), the study of soil has been widely referred to as pedology (Simonson, 1999). The study of soil has also historically been identified through its application, using terms such as agricultural geology or edaphology (Boulaine, 1989). From its origin, soil science has developed in the established subdisciplines of soil physics, soil chemistry, soil geography and geology, and the emerging field of soil biology. While these subdisciplines share concepts, theories and knowledge common across the disciplines of physics (principles of porous media), chemistry (colloids sciences), geography and geology (distribution of soil types and properties across landscapes), and biology (biodiversity), Churchman (2010) established four aspects that are unique to soil science. These are (a) the formation and properties of horizons, (b) the occurrence and properties of soil aggregates, (c) the occurrence and behavior of colloids, and (d) soil mineral–organic complexes, soil biology, and biodiversity. These unique aspects demonstrate or moderate soil processes and are used to characterize soil change (Tugel et al., 2005) (Table 1). They transcend the subdisciplines commonly accepted in soil science and have been used as the rationale for soil science to be recognized as a natural science in its own right (Field et al., 2011), requiring a holistic approach to characterizing, knowing, and interpreting soil.

At the fundamental level, soil science's four unique aspects, processes, and ongoing change result from the soil forming factors—climate, organisms, relief, parent material, and time (Jenny, 1941). The interactions between these factors is why each soil occurs where it does, along its own evolving path. Usually, soil changes occur over a long period of time, yet recent increases in direct major disturbances due to land change and intensive land use, biological invasions, pollution, and climate change have increased the pace of change and the spatial extent of several soil threats (Field, 2019; McBratney et al., 2014). Changing global demographics, the shift to a globalized economy, technological advances, educating about relevant issues, and lack of awareness can be significant drivers of soil change (Berhe, 2019). The importance of soils to human and planetary health and the potential negative effects of rapid soil change have been recognized in a list of seven soil functions (Keesstra et al., 2016), which are strongly aligned with the four unique aspects of soil (Table 1).

Core Ideas

- Soils knowledge is essential to address modern global challenges.
- Soils education has evolved to address an increasing variety of knowledge needs.
- A wide variety of teaching techniques are used in the modern classroom.
- A focus on soil functions may emphasize the multifunctionality of soils.
- Engaging the public is an important part of soil science education.

A curriculum that acknowledges this multifunctionality provides a suite of pathways connecting its "traditional" subdisciplines with other cognate areas as illustrated in Figure 1. The assessment of and monitoring and mapping changes in the soil's capability and capacity is crucial to understanding effects of land use change and its intensification, including overuse of external inputs. This assessment can be used to analyze and compare the relative effect and performance of the soil functions in an area of concern. Since the 1990s, the rise of evaluating natural capital and ecosystem services has expanded the value provided by soil from just its ability to produce food and fiber to include accounting for other functions such as supporting biodiversity, providing resources, water purification, and cultural and economic benefits (Brevik, Pereg, et al., 2019; Costanza et al., 1997; Davies, 2017; Doran & Parkin, 1994; McBratney & Field, 2015). Where the value of these soil functions is not recognized there is the need to develop soil security through policy and raising the awareness of the community, strengthening their connections to soils (Richardson, 2021). These dimensions of capability and condition, combined with socioeconomic dimensions of capital, connectivity, and codification (Figure 1), form the evaluation strategy of soil security (McBratney et al., 2014). To achieve soil multifunctionality within a framework that tackles present challenges to soils and the environment, it is necessary to take a closer look at ways students become interested in and learn about soil. This can be achieved through a curriculum built on the different ways of knowing (Table 2; Figure 2).

TABLE 1 Relationship of the unique aspects of soil science with soil processes (Bockheim & Gennadiyev, 2000) and soil change (Tugel et al., 2005) and the seven soil functions of (i) biomass production, (ii) cycling of nutrients, (iii) cycling of water, (iv) storing carbon, (v) building materials, (vi) biodiversity, and (vii) culture and storing history

Unique aspects	Soil processes and change	Relationship with soil functions
		i–vii
Formation and properties of soil mineral-organic complexes, soil biology and biodiversity horizons	Process: main processes include argiluviation, argillization, melanization, podzolization, leaching, gleization, paludization Change: used extensively in soil classification	Partitioning of soil profiles (iv, vii) Moderating the cycling of water (iii) Nutrients and contaminants (ii, vi)
Occurrence and properties of soil aggregates	Process: main processes include ferrallitization, vertization, base cation leaching, salinization, salinization Change: strongly affected by anthropomorphic force	Provides anchor and surface area for plant for roots (i) Moderates water cycling and water holding (iii) Provides habitat for biodiversity (vi) Protection of organo-mineral complexes (iv)
Occurrence and behavior of colloids	Process: main processes include ferrallitization, base cation leaching, salinization, solonization, silification Change: moderates soil fertility, water holding, and carbon storage Change: presence of colloids used to discriminate between young and older soil landscapes	Effects the cycling and storage of nutrients and contaminants (ii) Provides building materials (v)
Soil mineral-organic complexes, soil biology and biodiversity	Process: main processes include paludization, melanization Change: indicator for soil land-use change and degradation	Provides nutrient sources for soil biodiversity (vi) Effects carbon storage mitigating climate change (iv)

TABLE 2 The what, so what, and who to *know*, *know of*, and be *aware of* soil

Knowing soil	The what	So what	Who
Aware of	 Driven by concepts of "care": those who care advocate, lobby, protect, ensuring soil is included in a narrative; soil knowledge that can be "valued"	 Diverse community: relevance of soil beyond an object and its functionality; value centers on their own values and effectiveness through building a narrative	 Graduates and practitioners: a novice, identify with other discipline knowledges, have a breadth in capabilities and make connection through soil, a narrative
Know of	 The utility, functional(ity) of soil, assessed and monitored through indicators (condition) and aware of its properties and attributes (capability)	 Community of stakeholders: focused on relevance, value, and effectiveness	 Graduates and practitioners: shared experience using their own discipline knowledge, breadth in values, and capabilities; "the business of soil"
Know	 Object of study, the science of soil: soil science or science of soil materials, assessed through its properties and attributes; concerned with soil's capabilities and its evolution	 Educational institutions: focused on discipline specific curriculum, contextual teaching, and learning outcomes; monitored through authentic assessment	 Graduates and practitioners: educational institutions focused on discipline-specific knowledge, soil science professionals, problem solvers, systems thinkers

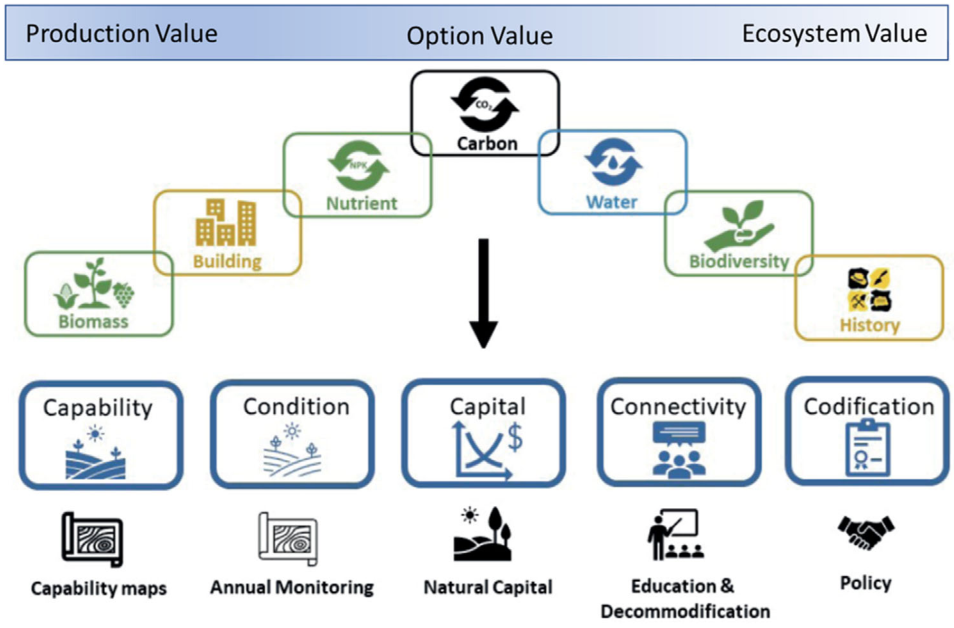

FIGURE 1 Schematic illustrating the multifunctionality of soil. The assessment and monitoring of soil uses the capability and condition dimensions of soil security and their interconnections, in turn providing production and ecosystem value (capital). The need to secure vulnerable soil functions uses policy frameworks (codification). Finally, increasing connectivity requires education and awareness (modified from Field, 2019)

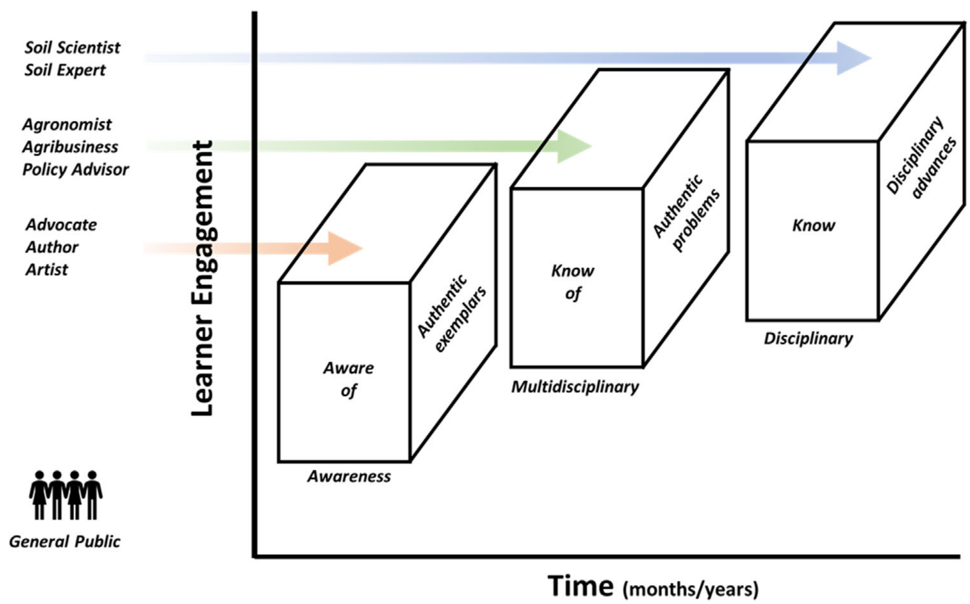

FIGURE 2 Modes of learning engagement describing those who over time will become *aware of*, *know of*, and developing expertise, to *know* the science of soil, illustrated with the professions that may characterize the depth of knowing (modified from Field, 2019)

A considerable literature has been developed regarding soil science education; however, to date, there are no reviews that seek to summarize and analyze that literature, particularly with an international perspective. Therefore, this paper develops ideas rooted in conceptual and methodological approaches from distinct perspectives and practices from different parts of the world. The major goals were to (a) summarize the historical context behind the development of soil education; (b) explore the current status of soil education, including activities used in content delivery; (c) investigate ways soil education has changed over time; (d) discuss suggestions to improve soil science education and awareness; and (e) offer insights on future needs given this exploration of the literature.

The ultimate idea behind all of this is to benefit and improve soil science education by providing a more complete understanding of the "big picture" in modern day soil education. While a comprehensive international perspective is beyond the ability of any single journal article, input from geographically diverse locations is provided. However, the reader is cautioned not to project findings and conclusions beyond the countries addressed in this review.

2 | PLACE OF SOIL SCIENCE WITHIN POSTSECONDARY EDUCATION

2.1 | Development of soil science education

Historically, soil science education was often based within agricultural programs, and in many parts of the world (e.g., Brazil, Japan, many programs in the United States) it is still housed in there. However, soil science has also become part of several other programs such as environmental sciences (e.g., Australia), geosciences (e.g., Canada, Germany, UK), and biological and ecological sciences (e.g., Mexico) (Table 3). In many countries, major debates are occurring over just where soil belongs within the academic spectrum. Therefore, a historical recounting of events that have driven soil science education and how that has changed over time is given here.

One of the key drivers for establishment of the discipline of soil science and its introduction to postsecondary institutions were soil surveys conducted in the 19th century to help farmers decide what crops and management practices were most suitable for the particular soil types on their farms and for taxation purposes. Those early works were mainly done by geologists who were skilled in the necessary field assessment methods, but who conceived soils mainly as the weathering products of geologic formations, defined by landform and lithologic composition (Brevik & Hartemink, 2010).

Modern soil science and its education, where soils are viewed as natural bodies worthy of study in their own right, was developed out of the soil survey work conducted under the leadership of V. V. Dokuchaev from 1882 to 1888. It focused on the Nizhniy Novgorod province in Russia with an aim to determine the qualities of the provincial soils with a precise marking of their boundaries, which in turn improved the basis for assessment and equalization of taxes (Yarilov, 1927). During this expedition new methodologies for soil mapping were created and developed together with a natural classification of soils. Dokuchaev was engaged in the development of agricultural education in Russia under the Ministry of Public Education and the Department of Agriculture. In 1892, he was appointed the director of the New Alexandria Institute of Agriculture and Forestry (i.e., Novoaleksandrovsk Institute) where he helped with reorganization of teaching and curricula. In 1894, the first department of genetic soil science was established at the New Alexandria Institute of Agriculture and Forestry with N. M. Sibirtsev as Chair; he developed the first soil science curriculum and wrote the first soil science textbook (Krupenikov, 1992). Following the October Revolution of 1917, many Russian scientists, including some soil scientists, fled to other countries, finding posts at universities and in government agencies and therefore spreading the influence of the Russian school of soil science (Simonson, 1997; Stelly, 1979; Trembach, 2006).

Organized national soil survey began in the United States in 1899 without prior knowledge of the work done in Russia. However, there were no U.S. university programs training students to become soil surveyors. Several institutions rapidly moved to provide the needed education. The USDA sent Dr. J. A. Bonsteel to Cornell University in 1903 to help begin a soil program (Lapham, 1949). The University of Wisconsin awarded their first Bachelor of Science in soil in 1905, their first Master of Science (MS) in 1906, and their first Doctor of Philosophy (PhD) in 1918 (Hartemink, 2021). Geologists had the field training that the U.S. Soil Survey was looking for, and G. N. Coffey was hired as a soil surveyor from the geology program at the University of North Carolina in 1900. Coffey also completed MS and PhD degrees in geology at George Washington University in 1907 and 1911, respectively, with both his graduate theses focusing on soil science issues (Brevik, 1999). As a pioneer in soil mapping and classification, Dr. Coffey provided expert advice on the first soil survey conducted in Canada by A. L. Galbraith in 1914 (Anderson & Smith, 2011). The University of North Carolina geology program would go on to send at least seven graduates to the U.S. Soil Survey program by 1902 and at least 11 overall, with several of these graduates (e.g., Coffey, Hugh Hammond Bennett, Williamson E. Hearn, and Thomas D. Rice) having distinguished soil science careers (Brevik, 2010). Another geology program that sent several students to the U.S. Soil Survey in the early 1900s was Earlham College, whose graduates included distinguished soil scientists such as Mark Baldwin, James Thorp, Francis Hole, and Ralph McCracken. As soil science education programs became increasingly associated with agriculture programs, these early geology-based soil programs ceased to exist (Brevik, 2010).

In the 1930s, the Dust Bowl led to increased interest in soil erosion studies within the United States. The U.S. Soil Conservation Service was formed under the direction of H. H. Bennett, and engineers, foresters, geomorphologists, wildlife biologists, and others were brought in to help address the erosion problems (Brevik, Fenton, et al., 2016). By the 1950s, it was also common to see land-use planners applying soil survey information to their work, and the information contained within those surveys evolved to reflect this (Simonson, 1989). The influence of this period is seen to the current day, with many soil scientists in the United States and Canada earning their degrees from biology, engineering, forestry,

TABLE 3 Number of units offering undergraduate soil science courses and programs by country

Country	Degree category								
	Agronomy and crop science[a]		Biological and ecological sciences, nature protection	Environmental sciences and geosciences[b]		Miscellaneous	Natural resources	Plant sciences, plant and soil science, horticulture	Soil science and soil and water science[c]
	Agriculture and agronomy	Crop and soil sciences		Environmental sciences	Geosciences				
Australia ($n = 34$)	10 (29%)	0	0	14 (41%)	1 (3%)	2 (6%)	0	5 (15%)	2 (6%)
Brazil ($n = 340$)	~280 (82%)	0	0	0	0	57 (18%; forestry)	0	0	0
Canada ($n = 54$)	4 (7%)	0	4 (7%)	11 (20%)	21 (39%)	9[d] (17%)	2 (4%)	0	3 (6%)
Germany ($n = 158$)	23 (15.5%)	1 (0.5%)	9 (6%)	11 (7%)	50 (32%)	26[e] (16%)	6 (3%)	23 (15%)	9 (6%)
Israel ($n = 2$)	0	0	0	0	0	1[f] (50%)	0	0	1 (50%)
Japan ($n = 0$)	0	0	0	0	0	0	0	0	0
Mexico ($n = 198$)	45 (23%)	0	52 (26%)	46 (23%)	17 (8.5%)	31[g] (16%)	3 (1.5%)	3 (1.5%)	1 (0.5%)
South Africa ($n = 16$)	5 (31%)	1 (6%)	0	2 (13%)	1 (6%)	0	0	1 (6%)	6 (38%)
U.K. ($n = 59$)	16 (27%)	0	3 (5%)	17 (29%)	19 (33%)	2[d] (3%)	0	2 (3%)	0
United States ($n = 77$)	26 (34%)	6 (8%)	1 (1%)	21 (27%)	1 (1%)	2 (3%)	0	11 (14%)	9 (12%)

Note. Data from Brevik et al. (2022)

[a]When combined, these two categories are the top type of units in Brazil, South Africa, and the United States.

[b]When combined, these two categories are the top type of units in all studied countries except Brazil, Israel, South Africa, and the United States.

[c]With the exception of South Africa and Israel, this is one of the least common types of units offering soil science courses and programs.

[d]In Canada and the U.K., category "miscellaneous" included forestry and science.

[e]In Germany, category "miscellaneous" included eight forestry programs.

[f]In Israel, category "miscellaneous" included civil and environmental engineering.

[g]In Mexico, category "miscellaneous" included environmental and forestry engineering.

geography, and other related programs (Brevik & Vaughan, 2020; Krzic et al., 2018). Another shift arrived in the 1980s as environmental issues became more recognized, and soils were increasingly included in environmental work (Brevik, Homburg, et al., 2016). Today, environmental degrees are one of the most common ways to get soil science training in the United States and several other countries (Table 3). However, despite the move to soil education in areas other than agricultural degree programs, soil education in the United States is still strongly associated with land grant universities, which are in turn strongly associated with agriculture (Brevik, Dolliver, et al., 2020). There are only three degrees titled "B.S. in Soil Science" offered in the United States today; most degrees that train students for a career in soil science are issued in a related field with some focus on soil science coursework (Brevik, 2019).

In the late 19th to early 20th century, soil science programs in Canada were mainly housed within faculties of agronomy. Similar to the United States, soil education was aligned with the initial soil survey work and had a strong agricultural focus (Anderson & Smith, 2011; Leskiw et al., 2020). The shift in where soil science programs were located in Canadian post-secondary institutions occurred in the late 1990s and early 2000s and was brought about by a decline in student enrollment in agronomy and subsequently soil science programs (Baveye et al., 2006). These declines were also reflective of a shift in student population from large numbers that initially originated from farming and rural communities to an increasing number coming from urban centers (Bard et al., 2005; McKenna & Brann, 1992). Those changes resulted in the current situation where there are just three soil science departments in Canada (Table 3), with most soil science units housed within geoscience and environmental programs (Diochon et al., 2017).

The history of soil science in Japan is closely related with the development of agricultural chemistry. Agricultural chemistry is a discipline introduced when the newly developed capitalist government was established after the long period of national isolation (1639–1853). After opening the country in 1853, Japan experienced an extremely rapid modernization. Around this time, agricultural schools, which later became universities, were established, and the government invited researchers from countries such as Germany and the United States to serve as teachers for the schools. Western soil science was also introduced to Japan in the same way (as a part of agricultural chemistry) (Kandatsu, 1987). Therefore, "soil science" is still close to the academic field of agricultural chemistry at Japanese universities, and is positioned as a part of other agricultural chemistry subdisciplines such as biochemistry, fermentation, brewing, food science, organic chemistry, etc. Currently, soil science is mostly taught by the Department of Agricultural Chemistry, Faculty of Agriculture, and it is included in a program that is dominated by students aiming for careers in food science and the cosmetics industry. Soil science may become less popular as the theme of graduation theses of recent students show a strong preference for laboratory rather than field work. Also, it might be difficult to motivate these students to learn the global scale important functions of soils, such as disaster defense and mitigation of climate change. On the other hand, although it may not be named "soil science," studies related to landslide disasters, earthquake countermeasures, etc., are linked to engineering and forestry and still strongly related to soil science research. Those fields are developing independently, in contrast to soil science in agricultural chemistry, because of the specific needs for Japan (e.g., typhoons, floods, and earthquakes). Therefore, soil researchers specializing in different soil science fields may not often collaborate as educators, and there are no "soil science" university courses in Japan covering the wide range of soil functions.

From the beginning, soil science education in Brazil has been housed in agricultural sciences programs as part of agronomy undergraduate degrees. The first degrees were established in the second half of the 19th century, but they were formalized in the national education system in 1910 (Capdeville, 1991). Because of the country's existing and potential for large extensions of agricultural land, which has been Brazil's main economic activity for most of its history, those degrees multiplied and today there are almost 300 programs that provide soil science education (Brevik et al.,2022). Soil science as a subject per se existed only as graduate courses after the second half of the 20th century and are all currently associated with agricultural departments. Soil science in Brazil has been strongly driven by a focus on the chemistry of soils and fertilizers, fostered by the adoption of monoculture cropping, external inputs, and mechanization in the 1960s, and then followed by soil genesis, soil survey, and classification (Capdeville, 1991; Toscano, 2003). This represents a different path than that followed by some other parts of the world, such as Canada, Russia, and the United States. A summary of the paths followed in these countries is given in Figure 3.

2.2 | Disciplinary subdivisions

Soil science has typically been divided into the discrete classical subdisciplines of soil chemistry, soil physics, pedology (soil genesis and classification), soil biology, and soil mineralogy (Churchman, 2010). Other specialized courses such as soil fertility, soil conservation, soil modeling, forest soils, remote sensing of soils, etc., may also be offered to provide options within a soil science curriculum, but they rely on the subdisciplinary core. Courses within academic units and chapters in textbooks have often been organized into these subdisciplines. However, Vogel et al. (2018) argued that this

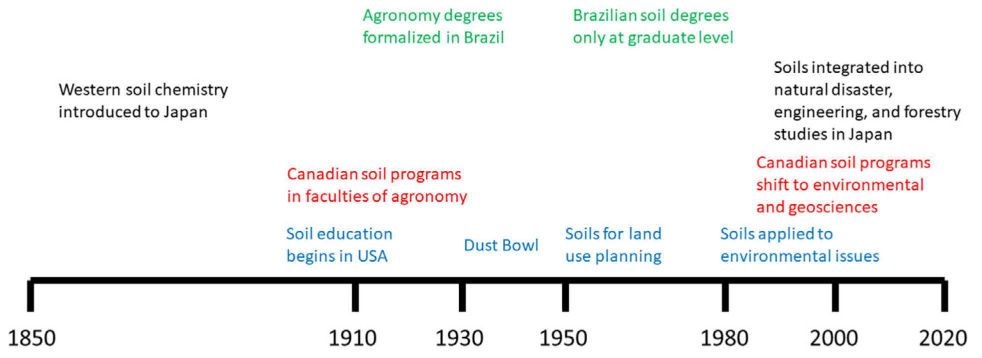

FIGURE 3 A timeline summarizing major moments that have influenced soil education in Brazil (green), Canada (red), Japan (black), and the United States (blue)

subdiscipline approach to soil science education has led to the loss of an integral and integrated understanding of the soil and its functioning. Approaching soil science education by presenting soils as part of a larger system allows greater understanding of their complexity and enhances understanding of systemic interrelations (Field et al., 2011; Turner, 2021).

This may be increasingly important as we see a shift in soil science teaching from disciplinary soil science majors to related disciplines (Diochon et al., 2017; Brevik et al.,2022); in other words, as we move from educating primarily those who need to *know* soil to professionals who need to *know of* soil (Table 2) (Field, 2019). This provides soil educators with a challenge: how to balance teaching in-depth soil science concepts with creating interest and a sense of wonder and appreciation about the soil and its roles in various global issues. At the same time, focusing soil science education on soil functions and real-life examples of those functions in a range of natural and managed ecosystems provides more relevance to the material covered in soil science courses and potentially enhances students' interest. This is where the concept of *be aware of*, *know of*, and *know* soil really comes into play—soil science education should cover topics in a way and at a depth that is appropriate to those being trained and the needs of the careers they are training for. This would also benefit from soil scientists being engaged with the education groups of professional societies of other disciplines within their countries that may offer soil-related coursework, such as the biology, ecology, geography, and geology societies. More on how to potentially achieve this by moving away from the traditional soil science subdivisions will be presented below.

2.3 | Modes of delivery

As instructors, we are constantly being challenged to find better ways to engage our students in the subject material being taught. A 2018 study of Canadian introductory soil science courses showed these courses are typically delivered as traditional lectures with associated laboratories and in some instances field trips (Krzic et al., 2018). A study in the United States found that most introductory soil science classroom hours were delivered in a traditional lecture format, but there was also a major component (44% of class time) delivered using one of a variety of active learning techniques (Jelinski et al., 2019). And a 2021 European study showed that traditional lectures are most common in soil science education, but programs are evolving to include more active learning methods (Villa et al., 2021). Active learning techniques and problem-based learning have been developed in Brazil and helped to bolster undergraduate student interest in soil science as well as other audiences that have engaged in short courses or other training in soils (Muggler, Gasparini, et al., 2022). While these techniques, particularly hands-on activities such as laboratories and field trips or other field work (Field et al., 2011; Hartemink et al., 2014; Field et al., 2017), are time-honored and effective ways to communicate material in an educational setting, the modern world offers many more options. Traditional soil science teaching has also effectively addressed the psychomotor (motor skills and actions that require physical coordination) and cognitive (intellectual side of learning) domains, but has not effectively addressed the affective (feelings, attitudes, emotions, and values related to learning) domain (Muggler, 2015; Jelinski et al., 2020). Some examples of innovations adopted by soil scientists as they educate students include problem-based learning, the studio approach of grouping lectures and labs, use of virtual soil trips, animated videos, 3D models, game-based learning through use of mobile technologies, collaboration with industry, flipped classrooms, and more. Examples of modes of delivery used in soil science education and presented in the soil education literature will be discussed below.

Soil judging has been used as part of field-based soil science education in the United States dating back to the 1960s, but has only been extensively used internationally since 2012 (Levin & Morgan, 2013). Soil judging has been anecdotally considered an effective way to enhance education and confidence in soil classification (Hill et al., 1984), profile description, and landscape interpretation (Rees & Johnson, 2020) for many years. Recent analysis has indicated that soil judging is in fact effective at improving multiple related skills (Rees & Johnson, 2020; Smith et al., 2020), including the field skills identified as lacking in recent graduates by employers (Masse et al., 2019; Brevik et al., 2022). Soil judging at the World Congress of Soil Science in 2022 will integrate soil and landscape interpretations with wider soil function concepts.

Online education began in the 1980s and grew rapidly with the development of the World Wide Web in the 1990s (Harasim, 2000), offering several possibilities for education that did not exist just a few years before. Well-developed online activities have been shown to enhance student learning in the sciences (Brevik, 2020; Chang & Wang, 2009; Mayer & Moreno, 2002; Vasiliadou, 2020), including soil science (Hegerfeld-Baker, 2013; King et al., 2014; Ulery et al., 2020). For example, the use of computer graphics and animated videos has been shown to be effective at helping introductory soil science students understand concepts such as cation exchange capacity and sorption (Ulery et al., 2020). Similarly, incorporation of mobile and digital game-based learning as supplements to field-based and in-class instruction have shown promise to enhance students' engagement and learning (King et al., 2014; Amargedon-Madison et al., 2018). Mobile devices, through their access to the internet, cameras, and the global positioning system, make it easy to gather, organize, and submit data from various kinds of observations, engaging students in citizen science activities, like documenting plant species, wildlife, or soil types. Future studies of these types of tools in soil education, including potential online laboratory education, has been encouraged (Brevik, Ulery, et al., 2020).

Another example of curriculum enhancement was suggested by Field et al. (2010), who proposed a Teaching-Research-Industry-Learning (TRIL) model that sought to bring academia and industrial partners that employed soil scientists together to produce graduates who were better prepared to succeed in soil science careers. This model includes graduates who are well-prepared to solve the complex problems encountered in the working world. The TRIL model was later used to develop a core body of soil knowledge that was relevant to the grains industry. It was concluded that TRIL provided a framework that better met industry needs and improved student learning (Field et al., 2017). Working with industry to identify educational needs will be important going forward (Diochon et al., 2017).

The high cost of textbooks is a hindrance to students. There are few open-source textbooks available for soil science (Moorberg, 2020), but recent additions include Moorberg (2019) and Krzic et al. (2021), which address soil and water conservation and introductory soil science from a Canadian perspective, respectively. There are also open access Sustainable Agriculture Research and Education resources, such as Clark (2007) and Magdoff and van Es (2021) that have been used as textbooks for soil science classes by some faculty, at least in the United States. The motivation behind the development of open access textbooks often includes the desire to provide students access to important resources in a way that does not disadvantage students who are unable to afford traditional textbooks (Moorberg, 2020). In addition to formal textbooks, soil science education has experienced a massive increase in blogs and internet sites related to soil. These can also be used as resources if they are of high quality (Margenot et al., 2016; Moorberg, 2020).

Flipped classrooms have been used in recent years in an attempt to increase student engagement in a subject. This technique has been used in introductory soil science classes with results reported in the soil education literature (Long et al., 2016; Ramirez et al., 2021). Student response to the flipped soil science classroom has typically been positive (Long et al., 2016; Ramirez et al., 2021) with measures of learning performance similar to traditional classes (Ramirez et al., 2021). Jelinski et al. (2019) reported that ~4% of classroom hours in introductory soil science classes taught in the United States were delivered using flipped classroom techniques.

The COVID-19 pandemic led to the rapid development of online educational resources and activities in soil science, pushing a number of instructors and institutions who had previously never given a lot of thought to the online delivery of programs (Mahler et al., 2021). Courses that were altered due to the COVID-19 pandemic and shifted to the online mode of delivery ranged from introductory to upper-level undergraduate and graduate, including lecture, laboratory, and field-based activities (Aleman et al., 2021; Brevik, Ulery, et al., 2020; de Koff, 2021; Schulze et al., 2021; Wolters & Lepcha, 2021; Wyatt, 2021). Activities such as soil judging were moved to distance delivery as well (Owen et al., 2021). Many instructors discovered teaching options or developed new educational resources during this emergency teaching situation they intend to continue using after COVID-19 restrictions end (Brevik, Ulery, et al., 2020; Brown & Krzic, 2021). Reactions of soil science students to online education during COVID-19 shutdowns generally indicated they preferred face-to-face classes and activities over the online options (Mashtare et al., 2021; Owen et al., 2021; Rees et al., 2021; Schulze et al., 2021; Wyatt, 2021). Students were also overall less engaged in their learning, although this did differ by mode of delivery, and students found synchronous content more engaging than asynchronous (Walker & Koralesky, 2021). However, it is important to realize that these online options were put together very quickly, and it has been argued that what happened in the spring of 2020 should be referred to as emergency learning rather than online learning (Hodges et al., 2020). In addition, not all students had ready access to the technology needed to use various online options (Boerngen & Rickard, 2021; Moorberg et al., 2021). Therefore, the reactions of students to online learning during the COVID-19 pandemic may not be representative of how they would react to well-planned online delivery. Moving forward will require careful reflection on what online educational resources developed during the pandemic should be kept and what should be revised or abandoned (McCauley, 2021).

3 | REASONS BEHIND CHANGES IN STUDENT ENROLLMENTS IN SOIL SCIENCE PROGRAMS

3.1 | Shifts in where soil science programs are housed

As previously mentioned, soil science programs were traditionally housed within faculties of agronomy or agriculture. In some countries such as Canada, Russia, and the United States, the emergence of soil science programs was associated with soil survey work, financed by governments and with a strong agricultural focus (Anderson & Smith, 2011; Brevik, 2010; Krupenikov, 1992; Leskiw et al., 2020). A notable decline in enrollment in soil science, agronomy, and crop science programs at some North American, Australian, and UK postsecondary institutions occurred during the late 1990s and early 2000s (Baveye et al., 2006) with corresponding declines in the enrollment of students in soil science courses. It is important to note that these declines in soil science enrollment were not universal; countries such as Brazil maintained healthy enrollment numbers during this time (Camargo et al., 2010). Many faculties of agricultural sciences responded to declining numbers by rebranding themselves as Environmental Sciences, Renewable Land Resources, Land and Food Systems, etc. (Brevik, Dolliver, et al., 2020), and this also involved relabeling of some of the soil science courses. This was done because there were indications that students had less interest in degree programs associated with agriculture and had increasing interest in environmental science or other fields that were seen as addressing global problems (Havlin et al., 2010; Miller, 2011). This is despite the fact that agricultural job opportunities are growing in the United States, and the median pay for agricultural scientists is well above the median for all occupations (U.S. Bureau of Labor Statistics, 2021). Declining student numbers are of concern because they have a direct effect on the amount of funding available to provide soil education in many countries, which in turn cascades through the educational system influencing the number of programs, faculty members and course instructors, etc. This dynamic has been observed in North America where declining enrollments, particularly in the 1990s and early 2000s, led to the reorganization or demise of many soil science programs (Baveye et al., 2006; Brevik, Homburg, et al., 2016; Diochon et al., 2017).

There have been significant reductions in public financial support for higher education in some countries over the last few decades (Hartemink & McBratney, 2008). In the 1980s, public universities in the United States received ~63% of their revenue from government sources (Mumper & Anderson, 1993), but today that has decreased to 31% as a national average (ranging from 14 to 56%, depending on the state) (Hanson, 2021). In some instances, budget cuts forced university administrators to focus on the majors of greatest enrollment, cutting those with low numbers of students such as soil science, while in other cases soil science courses ended up being housed within larger programs where they were amalgamated with other similar courses. For example, Canadian enrollment in soil science courses offered to environmental science and geoscience students is currently almost double that of majors from natural resource management and agronomy (Diochon et al., 2017). In some cases, the departments within a faculty of agriculture are also becoming more diverse and sophisticated—or arguably, complicated—and as a result, soil scientists are separated into different departments, each of them hosting different groups of students. For example, within a faculty of agriculture in a university in Japan, soil physicists tend to belong to the Department of Bioresource and Environmental Engineering, whereas soil biologists are in the Department of Bioscience and Chemistry. In cases like this example, students who want to study the whole soil system cannot choose an ideal department in which to pursue their undergraduate studies. In the United States, it is common to find soil classes offered in related programs such as environmental science, geography, and geology (Brevik, 2009). These shifts in where soil science courses or programs are housed within postsecondary institutions have also led to a greater diversity of students taking soil science courses relative to the times when soil science majors were almost exclusively housed within faculties of agronomy or agriculture (Diochon et al., 2017; Brevik et al., 2018), but the question remains whether these shifts are an ideal change towards the mitigation of the global issues related to soil, as mentioned previously.

3.2 | Changes in conceptual approach and pedagogics in soil science courses

In at least some universities, all these changes resulted in a shift in overall teaching of soil science from the deeper disciplinary focus to a more general approach to address the needs of related disciplines (e.g., geography, geology, environmental science, forestry, agriculture, natural resources, etc.) (Brevik et al., 2018). This development was accompanied by the challenges of balancing teaching in-depth soil science concepts with creating interest in and appreciation for the roles of soils in various global issues. This balance is particularly needed in the introductory soil science courses that are often left as the only remaining soil science course in many degree programs (Krzic et al., 2018). For example, such introductory soil science courses may emphasize the importance of carbon and nitrogen cycles in relation to soil, but might omit other very important aspects of soil science such as the cycles of micronutrients and mineralogy. This shift also creates an opportunity to revisit, rethink, and restructure soil science curricula, such as building it around soil functions, instead of the traditional approach focused on soil properties. A more systemic and integrated approach is necessary to tackle environmental issues that are related to soil.

One approach to restructuring of the soil science curricula could be adoption of the emerging concept of *know*, *know of*, and being *aware of* soil (Table 2) (Field, 2019). This concept is student-centered, and it frames learning environments focused on developing either deep soil science knowledge (*know* soil) or the application of soil science knowledge across a range of subjects where soil science is only part of learning (*know of* soil), as needed in the given student's educational goals. In turn, this allows development of a curricula with a system approach built on disciplinary expertise combined with a multidisciplinary learning environment, motivated by real-world issues. For this concept to be successful, teachers need to: (a) have expertise in soil science, (b) be willing to reflect on their own development as teachers, and (c) contribute to innovations in soil education (Field, 2019).

3.3 | Positive outcomes from the challenges soil science education has faced in the past

There has been a shift from degree programs with a focus on soil science to programs with a broader, environmental focus that include a reduced level of soil science training. Combined with the closure of governmental soil survey units and the retirements of pedologists without replacement throughout Canada, the UK, the United States, and other countries, these changes have resulted in a gradual erosion of field skills among new graduates (Masse et al., 2019). To address this issue, soil scientists from various postsecondary and government institutions in Canada have organized regional pedology field schools with learning objectives that include a refresher on soil genesis, field description, and classification (soil and ecosite), and the basics of interpreting soil survey and analyses information, with more in-depth coverage of soil mapping and soil-landscape classification. On the other hand, the Soil Science Society of America tried running a week-long soil science field course in the early 2010s at a location in Wisconsin (see https://www.soils.org/files/education/soil-science-in-the-field-syllabus.pdf). This field school struggled to enroll students and was discontinued. In countries such as Canada and United States, which cover large geographic areas, the regional field schools seem to have been more feasible to organize and deliver than national field schools. As identified by a survey carried out in Canada by Masse et al. (2019), a 5-d field course was considered to be the best length of time. To cover most of the soil landscapes, a potential rotation of host locations across the country could be considered.

In Brazil, there is still a need to gather and improve information on the soils across the country both for their management as well as for their governance. To achieve this, a national initiative to train and update soil surveyors, called National Soil Programme (PRONASSOLOS), started in 2015 and is being organized to provide training and updates for soil surveyors.

Universities are increasingly ranked and assessed against the Times Higher Education Impact Rankings (www.timeshighereducation.com), and many countries consider this ranking very important (De la Poza et al., 2021). The detailed methodology of the ranking system will not be discussed here, but studies of "soil" are clearly receiving heightened attention when compared with the "economic rationalism" approaches discussed above, and a strong soil program can aid a university's standing in the rankings. With the increasing importance of the United Nations Sustainable Development Goals (UNSDGs), soil science is clearly becoming an important topic (Keesstra et al., 2016). This is shown in that we are not producing enough soil science graduates to fill all the soil jobs that are available. Soils are linked to many of the UNSDGs, which provide opportunities for soil science education. This is a message to the soil science education community to actively recruit prospective students and to university administrators who make decisions on which academic programs are funded.

4 | HOW TO RAISE INTEREST AND ENGAGEMENT WITH SOIL SCIENCE

4.1 | Soil content in basic education curricula

As mentioned earlier in this paper, a prior awareness or knowledge about soil may be necessary to increase the student pipeline into university soil science programs. Usually, this comes from previous contact with soil in formal and non-formal education and in everyday life. A lack of exposure to soil within formal educational settings at the primary and secondary school level, which exists in many countries (Hayhoe, 2013), is thought to hinder development of an interest in soil science. For example, there is a lack of explicit reference to soil in national curricula in the UK at secondary and post-secondary levels. Soil is only implicitly referred to within the context of other topics such as ecosystems or the water cycle in geography and biology subjects in the General Certificate of Secondary Education (age 16). The environmental science subject at the Advanced level (ages 16–18) includes one or more topics specifically about soil. In other subjects, it is covered under other themes such as the carbon cycle in geography. Lobbying for the inclusion of specific soil themes in national school curricula is essential, alongside the need for adequate recruitment of and training for teachers. However, the long cycles of national curricula reviews prevent rapid proposals for reform and inclusion of soil science into current subject curricula or within newly proposed examination subjects. In Japan, the chances to learn about soil in the primary and secondary school curricula have decreased with each revision of the curriculum content, which happens about every 10 yr (Hirai & Mori, 2020).

In Canada and the United States, the primary and secondary school curricula are principally controlled at the provincial and state and local levels, respectively, rather than at the national level (Krzic et al., 2014). Soil is not part of the science curriculum in many states (Hayhoe, 2013), and when broaching the topic at a state curriculum meeting several years ago one of the authors was informed that soil was not part of the Earth science curriculum and there was no interest in discussion to add it. In an attempt to provide some recognition of soil within U.S. education, the Soil Science Society of America has developed a number of freely accessible educational materials for use in the classroom, available at https://www.soils4teachers.org/. These resources have been available since 2005 (Chapman, 2021) and have enjoyed some success (Margenot et al., 2016).

By contrast, soil content is present and formalized in the Brazil national basic education curriculum guidelines. It is presented in the natural sciences curricula at the primary level and the geography and biology curricula at the secondary level (Oliveira, 2019). Soil composition and soil types and their suitability to agriculture are commonly presented in schoolbooks together with threats to soil, such as erosion and pollution. In more recent governmental guidelines, the soil content was reduced or generally included as part of the environment and food and health curricula. Despite its formal regulation as basic educational content and its presence in schoolbooks, soil is commonly overlooked by teachers because in general, they do not have any education in soil science.

4.2 | Soil science outreach in primary and secondary education

There is a potential role for soil scientists in direct outreach in primary and secondary schools, exposing both teachers and students to soil science concepts that are relevant to the current curriculum (Martin et al., 2008; Margenot et al., 2016; Krzic et al., 2019; Sandén et al., 2020). This is typically only achieved at a small scale, where there are usually existing relationships between local schools (such as the university educators being parents of children at the primary or secondary school). In many cases, these activities favor younger children at the primary education level. However, there are examples of university faculty and students directly engaging with public school educators without a previously existing relationship. In Brazil, there are more than 100 soil education initiatives that work with schools (Lima et al., 2020), many of them housed in university soil science departments, museums, and science centers. Among other outreach activities, these groups promote extension courses for teachers to overcome their lack of education in soil science. A workshop in Japan led by university and museum faculty engaged students from the primary to university levels in exercises that used rice paddies and forested watersheds to demonstrate the importance of soil (Hirai & Mori, 2020). University faculty in Colombia worked with primary school students on projects that measured soil respiration, looked at the effect of cover on soil erosion, and investigated effects of soil nutrient deficiencies on bean growth (Londoño & Bolaños-Benavides, 2020). Another such example was in Kentucky, USA, where university educators and graduate students provided discipline-specific math and science expertise to middle grade educators (sixth to eighth years of public education, students typically aged ∼11–14) (Otieno & Wilder, 2010). Good results have been achieved when university students are involved in outreach activities aimed at basic education in primary and secondary schools and directed towards the general public, in a "teach to learn" approach, namely, enhanced student learning by both the middle grades and university students and improved communications and team-building skills on the part of the university students (Otieno & Wilder, 2010).

Another way to reach a broader group of primary and secondary teachers is through collaboration with provincial and state associations of science teachers as well as museums and not-for-profit organizations focused on promotion of science to the general public, such as Science World (Vancouver, Canada), Biosphere Environment Museum (Montreal, Canada), Pacific Science Center (Seattle, WA, USA), the St. Louis Science Center (St. Louis, MO, USA), Dokuchaev Central Museum of Soil (Saint Petersburg, Russia), World Soil Museum (Wageningen, The Netherlands), Brazilian Soil Museum (Seropédica, Brazil), Museum of Soils from Rio Grande do Sul (Santa Maria, Brazil), and the Museum of Soils and Tractors of the World (Kamifurano, Japan). Well-established natural resources education programs that incorporate soil science such as the National Conservation Foundation Envirothon (https://envirothon.org/) also provide an avenue to reach a broader audience of teachers and students. In the Envirothon, student teams, mentored by a teacher, participate in an outdoor, hands-on competition testing their knowledge in the following four core subject areas: aquatics, wildlife, forestry, and soil, along with a topic focused on a current environmental issue. Similarly, the Spanish Society of Soil Science has developed a number of soil contests for primary through secondary level students (Mataix-Solera et al., 2020). The long-term success of such collaborations is dependent on the following factors: (a) on-going interactions with the target audience via a range of events and media; (b) continued recruitment of new team members that will engage in these collaborations, preferably through coordinated effort by the national or state and provincial soil science societies; (c) continued development and updating of educational resources; and (d) providing soil scientists and students with training in science communication (Krzic et al., 2019).

4.3 | Public engagement to raise awareness of soil science

General engagement is about *being aware of* to *knowing of* soil and thus relevant concepts are needed to generate interest and appreciation of soil, using appropriate recognizable language (Brevik, Steffan, et al., 2019; Aparin & Sukhacheva, 2020). Settings for engagement include formal (museums, science centers) and informal (community gardens) spaces, and different types of engagement and messages are needed for the different audiences. Globally, there are 38 museums focused on soil, with attendance between 1,000 and 10,000 visitors per year; many visitors are comprised of organized visits of school and university groups (Richer-de-Forges et al., 2021). While these numbers are much less than some of the world's most famous museums, such as the 20–30 million who visit the Smithsonian Museums in a typical year (https://www.si.edu/newsdesk/about/stats) or 8–10 million annual visitors to the Louvre (https://www.statista.com/statistics/247419/yearly-visitors-to-the-louvre-in-paris/), this still represents important outreach. In addition, other museums may not be focused exclusively on soil but have strong soil programing with large numbers of visitors. For example, the St. Louis Science Center hosts the "Dig It! The Secrets of Soils" exhibit and has over 1 million visitors annually (https://www.slsc.org/wp-content/uploads/2018/08/slsc_opening_minds_to_science_2015.pdf). Other examples include nonpermanent exhibitions about soil at national or regional natural history or science museums (e.g., Stockinger, 2019). However, *being aware of* and *knowing of* soil should involve soil within communities via their lived experience of soil and using familiar language, rather than expecting people to visit places specifically to learn of soil or to understand different people's experiences and learn unfamiliar technical language. At this point, the focus of the soil science community should be to awaken people to soil (*be aware of*) or let people explore *knowing of* soil, not to push details about its science (*knowing* soil).

Soil suffers from a human tendency to be ignored or overlooked (soil blindness), similar to the phenomenon of plant blindness, or plant awareness disparity, the "failure of individuals to see or notice the plants in one's own environment" (Wandersee & Schussler, 2001, p. 3). Thus, soil education and awareness building should also attempt to overcome this disregard for soil by exploring the significance of soil to people. What makes soil meaningful? What are the bases for effective learning about soil? The answers are very much related to the subjective perceptions and life experiences carried by each individual, which includes local soil knowledge (Muggler, Lopes, et al., 2022; Huynh et al., 2020). Once people's interest in soil is awakened, this can develop a sensitization and awareness of soil (*be aware of* to *know of*), which could lead to *knowing* soil through soil science education.

By 2050, nearly 70% of the global population will live in cities, thus many citizens will lack a direct connectivity to soil. While the value of soil for regulating and supporting ecosystem services in cities is well recognized by soil scientists, cultural services and urban growing are rarely explored as urban soil services (O'Riordan et al., 2021). These are important gateway services for people living in urban environments to *know of* and to connect to soil. The act of growing and gardening involves direct exposure to and sensitization to soil, and over time the development of *knowing* soil comes in relation to growing plants. Gardening may be the greatest resource for engagement of the urban population with soil. In shared spaces, such as community gardens and allotments, informal knowledge exchange between members of the community, often without formal agricultural knowledge, allows people to learn how to work the soil from others via experimental and experiential knowledge processes (Ulug & Horlings, 2019).

Another approach to engagement involves including the public in citizen science projects, which have grown over the last decade (Golumbic et al., 2019). Although citizen science programs have helped address several science research issues, the original citizen science programs were focused on improving science education (Gallo & Waitt, 2011). Whether the primary intent is education or providing information to an active research project, potential benefits to citizen scientists working on a soil project include better understanding of the scientific concepts they helped investigate and enhanced connectivity between the participants and soil (Rossiter et al., 2015). Citizen science participation can also communicate complex or esoteric ideas in ways that are interesting and understandable (Jim, 2019). A particular challenge in citizen science is that there are often two goals, collecting solid scientific data and educating or raising awareness of the public that participates, and in attempting to balance these goals resources may be diverted from one to the other (Lakeman-Fraser et al., 2016). Several citizen science projects have been initiated regarding or including soil science, such as efforts to improve digital soil mapping (Rossiter et al., 2015), better understanding of environmental quality (Lakeman-Fraser et al., 2016), the impact of soil management on pollinators (Appenfeller et al., 2020), measuring soil greenhouse gas fluxes (Reed et al., 2018), and studying litter decomposition with the international tea bag project (Sandén et al., 2020), among others. Another example of an engaging citizen science campaign is the "Soil Your Undies" challenge that has been used in Canada, the United States, Australia, New Zealand, and Switzerland as a fun way to build public interest in soil health (Knox, 2020). Citizen science has been shown to be an effective way to educate the public about a number of scientific issues (Newman et al., 2012), but there is still a need to investigate its effectiveness specifically regarding soil science.

World Soil Day is held on 5 December each year since it was initiated by the 68th United Nations General Assembly, with the first World Soil Day taking place in 2014. The goal of World Soil Day is to focus attention on how important healthy soils are to humankind and promote sustainable soil management. Each World Soil Day has a specific theme, and a variety of resources are developed for public use, including educational resources for children (https://www.fao.org/world-soil-day/en/).

5 | LESSONS AND NEEDS IDENTIFIED IN THIS REVIEW

Several lessons were learned during this review. The soil education literature is replete with examples of new things various teachers are trying in their classrooms, including, in many cases, analyses of whether the new methods being used seem to increase student learning or performance (see Section 2.3). However, much less study has been conducted regarding whether instructors are likely to adopt new methods, or what types of information, education, or incentives would meaningfully encourage instructors to do so. While the soil education community has been discussing and documenting ways to enhance teaching and learning of soil science concepts for decades, we are still in a situation where the strong majority of soil science education seems to be delivered in the lecture format (Krzic et al., 2018; Jelinski et al., 2019; Villa et al., 2021). Therefore, there is a need for less "here is what I do" and more "here is how to embed different teaching approaches" in the soil education literature.

There is a need to evaluate the effectiveness of distance education options, especially for laboratory and field-based offerings. There are many options for distance delivery of course materials, but many focus on lecture delivery. Soil education has components that are very hands on and more difficult to offer through distance delivery, and few studies have assessed distance laboratory and field-based options and their effectiveness (see Section 2.3).

The literature on what makes soil science a unique discipline and thus, what should be taught as the core of a soil science curriculum, is also scarce (see Section 2.2). There are some, again limited, studies that indicate soil science training can be obtained from a wide range of academic disciplines or programs, even within a single country in some instances. So, when someone says they have a degree that qualifies them to be a soil scientist, what exactly does that mean? This may stem in part from the fact that soil science as a discipline evolved from several related disciplines (see Section 2.1). There is a need for soil scientists to debate what makes the soil science discipline unique, and for this discussion to inform our educational approach (see Sections 2.2, 3.2).

Declining enrollment in university-level soil science programs has been a major concern in many countries since about the 1980s. This might be due to students being generally less interested in soil science. One assumption about the cause of this disinterest is the failure to engage primary and secondary school students as well as the general public in soil science topics (see Section 4). However, few if any studies evaluate the effectiveness of such outreach efforts on attracting new students to university level soil science programs. Such studies are needed to allow for more efficient and meaningful education and outreach programs designed to build on the concepts of *aware of* and *know of* soil to result in attracting future students to soil science.

While including soil in the primary and secondary school curricula may be advantageous from the perspective of building future student demand for the discipline, teachers are needed at that level who have the knowledge, confidence, and motivation to advocate for and teach soil science. Soil is part of the Brazilian primary and secondary curricula, but many teachers have little to no direct soil education, so they avoid teaching soil or give it little teaching time. Soil is not an explicit part of the Canadian primary and secondary curricula, but soil science concepts appear in various agricultural or environmental courses. Again, the primary and secondary teachers often avoid these topics due to a lack of education. So, beyond simply including soil in the curricula at these educational levels, we also need to find mechanisms for primary and secondary teachers to become *aware of* and *know of* soil though training that allows them to feel comfortable teaching basic soil science material.

There is a need for a strong, coordinated effort to evaluate a wide range of soil science education issues in countries around the world, with the results of these studies published in readily accessible international journals. The soil education committee of the Canadian Society of Soil Science is an exemplar for these approaches through their systematic assessment and publication of soil science education in Canada (Krzic et al., 2014; Diochon et al., 2017; Krzic et al., 2018; Krzic et al., 2019; Masse et al., 2019). This evaluation of Canadian soil science education and its needs has also led to publication of a new textbook (Krzic et al., 2021). These studies are important in defining the challenges that face education in our discipline. However, these challenges are not the same in every country (see Sections 2.1, 3.1, 4.1), which is why widespread efforts to investigate challenges, establish base line data and evaluate interventions are required on a country-by-country basis.

One approach to address issues identified in this review may be to create a soil education think tank to ensure the inclusion of international and interdisciplinary stakeholders and perspectives. Such a think tank would also benefit from identifying a source of funding to enable research groups in various countries to conduct the kind of work needed to characterize the current state of soil science education in their respective nations.

In summary, we provide the following recommendations to stimulate critical reflection and scaffold a vision for the future of soil science education:

1. While promoting the achievements and innovations in soil education, attention also needs to focus on the professional development of soil educators to support them in output scholarship and use this to increase their professional development. This will also involve the need to…
2. Promote and support the development of educational materials and resources for soil within national representative bodies for primary and secondary education, tertiary and in-service training. This should be shared internationally to provide educators and learners with reliable and easily accessible material to encourage the incorporation of soil into early education opportunities. Such innovations will also stimulate the…
3. Regular reporting of national and regional soil education challenges and opportunities, which can populate a repository of current data that can be interrogated and critically analyzed to stimulate future educational opportunities. This needs to be supported by…
4. Scoping the need for an independent internationally representative think tank on Soil Education that provides critical review of its current status, opportunities for development, and provide unbiased, useful, relevant, and expert advice to international professional bodies.

6 | CONCLUDING STATEMENTS

Soil science education has changed considerably since its formal establishment in many countries during the late 1800s and early 1900s. From its initial focus on agricultural issues such as soil survey and soil fertility, soil science education has progressed to help train students to address a wide variety of problems that range from food security to environmental degradation, climate change, and even human health. Concomitant with this increase in problems addressed, soil science education has been conducted by an increasing array of academic disciplines. This has both strengths and weaknesses. Even as soil knowledge addresses a wide range of problems that are critical to the future of our planet, many also fear that a much needed holistic understanding of soil has not been widely established and is in fact being lost to the ultimate detriment of humanity.

This realization has led to many proposals concerning the future of soil science education. One such proposal is the need to identify just how much soil knowledge someone will need to work in their chosen profession, whether they will need to *know* soil (have an in-depth understanding) or *know of* soil (understand soil science basics and be able to apply that knowledge to targeted problems). It has also been suggested that soil education should focus less on the traditional subdisciplines, and more on soil functions because they accentuate the connections between environmental issues and human needs, and thus communicate why soil knowledge is important, building a link between people and soil. Regardless of the exact approach, it is certain that soil science education needs to go beyond the disciplinary limits of soil science, encompassing and traversing other knowledge areas and exploring educational and communication possibilities to and with other educational levels and practices.

There is also a pressing need to better engage the public and stakeholders in soil knowledge, particularly as our society becomes more urban and thus less connected to soil. Strategies to accomplish this include incorporating soil into primary and secondary school curricula, including appropriate soil education for primary and secondary teachers, soil related competitions and challenges for students at a variety of education levels, exposing the general public to soil information through organizations like museums, and getting people to participate in citizen science projects that include soil.

There are many future challenges in soil science education, but there are also many opportunities. As soil scientists, we need to actively engage in education and outreach and provide humankind with the types of soil information that will be crucial to the future of our planet and all its inhabitants. The information needed will change with time and application, and it will be important for the education community to keep pace with those changes.

AUTHOR CONTRIBUTIONS

Eric C. Brevik: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Writing – original draft; Writing – review & editing. Maja Krzic: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Writing – original draft; Writing – review & editing. Cristine Muggler: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Writing – original draft; Writing – review & editing. Damien Field: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Visualization; Writing – original draft; Writing – review &

editing. Jacqueline Hannam: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Writing – original draft; Writing – review & editing. Yoshi Uchida: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Writing – original draft; Writing – review & editing.

CONFLICT OF INTEREST

The author declare no conflict of interest.

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