Spectroscopic solutions for generating new global soil information

Yi Peng,[1,*] Eyal Ben-Dor,[2] Asim Biswas,[3] Sabine Chabrillat,[4,5] José A.M. Demattê,[6] Yufeng Ge,[7] Asa Gholizadeh,[8] Cecile Gomez,[9] Cesar Guerrero,[10] Jeffrey Herrick,[11] Jonathan J. Maynard,[12] Abdul Mounem Mouazen,[13] Yuxin Ma,[14] Alex B. McBratney,[15] Budiman Minasny,[15] Leonardo Ramirez-Lopez,[16,17] A.H. Jean Robertson,[18] Raphael A. Viscarra Rossel,[19] Zhou Shi,[20] Bo Stenberg,[21] Alexandre M.J.-C. Wadoux,[9] Leigh Ann Winowiecki,[22] and Ganlin Zhang[23,24,25]

[1]Food and Agriculture Organization of the United Nations, 00153 Rome, Italy
[2]Porter School of Environment and Earth Science Faculty of Exact Science, Tel Aviv University, Tel Aviv 699780, Israel
[3]School of Environmental Sciences, University of Guelph, Guelph, ON N1G 2W1, Canada
[4]Helmholtz Centre for Geosciences Research, Remote Sensing and Geoinformatics Section, 14473 Potsdam, Germany
[5]Leibniz University Hannover, Institute of Earth System Sciences, Department of Soil Sciences, 30419 Hannover, Germany
[6]Department of Soil Science, Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba 13 418-900, Brazil
[7]Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
[8]Department of Soil Science and Soil Protection, Czech University of Life Sciences Prague, Prague 16500, Czech Republic
[9]LISAH, University Montpellier, IRD, INRAE, Institut Agro, AgroParisTech, 34060 Montpellier, France
[10]Department of Agrochemistry and Environment, University Miguel Hernandez of Elche, 03202 Elche, Spain
[11]USDA-ARS Range Management Research Unit, Las Cruces, NM 88003, USA
[12]USDA-NRCS National Soil Survey Center, Tangent, OR 79389, USA
[13]Department of Environment, Faculty of Bioscience Engineering, Ghent University, 9000 Ghent, Belgium
[14]New South Wales Department of Climate Change, Energy, the Environment and Water, Parramatta, NSW 2150, Australia
[15]Sydney Institute of Agriculture & School of Life & Environmental Sciences, The University of Sydney, Sydney, NSW 2006, Australia
[16]Data Science Department, BUCHI Labortechnik AG, 9230 Flawil, Switzerland
[17]Imperial College London, Imperial Business School, London SW7 2AZ, UK
[18]The James Hutton Institute, Aberdeen AB15 8QH, Scotland
[19]Soil and Landscape Science, Curtin University, Perth, WA 6102, Australia
[20]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China
[21]Department of Soil and Environment, Swedish University of Agriculture Sciences, 53231 Skara, Sweden
[22]Soil and Land Health, World Agroforestry (ICRAF), Nairobi 00-100GPO, Kenya
[23]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China
[24]Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[25]University of the Chinese Academy of Sciences, Beijing 100049, China
*Correspondence: yi.peng@fao.org
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While global efforts to operationalize soil spectroscopy are progressing, cooperation is needed to fully leverage its potential for generating digital soil information to support sustainable soil management worldwide. The Global Soil Laboratory Network's soil spectroscopy initiative (GLOSOLAN-Spec), led by the Food and Agriculture Organization of the United Nations (FAO) through its Global Soil Partnership (GSP), is dedicated to the further development and adoption of soil spectroscopy by fostering international collaboration via a scientific community of practice to produce accurate and reliable soil information for sustainable soil management and decision-making. To support this effort, we, a global consortium of soil scientists under the auspices of the International Union of Soil Sciences (IUSS) and GLOSOLAN-Spec, aim to address seven key challenges hindering the adoption of soil spectroscopy worldwide. Here, we offer perspectives on what is needed to advance soil spectroscopy as a routine soil analysis method, emphasizing its potential to generate new and reliable spatial and temporal soil data.

As one of Earth's most vital natural capitals, soil provides food, fiber, and fresh water. The world's soil contributes to energy sustainability, climate stability, biodiversity, and the delivery of essential ecosystem services.[1] However, for securing the world's soil and ensuring its continued productivity, establishing comprehensive soil databases and spatial information systems representative of various spatial and temporal scales for evidence-based decision-making remains challenging. There is a pressing need for rapid and cost-effective soil analysis solutions worldwide.[2] Decades of research have demonstrated that soil spectroscopy in the visible-near infrared (vis-NIR) and mid-infrared (mid-IR) portions of the electromagnetic spectrum can help alleviate this urgent need.[3]

Soil spectra respond to the soil's mineral and organic composition and are affected by soil water and texture. Spectroscopy combined with multivariate statistics or machine learning can hence be used to model and accurately estimate a range of soil properties that depend on the composition of the soil matrix, e.g., soil organic carbon, clay, silt and sand contents, cation exchange capacity (CEC), pH, and $CaCO_3$. Thus, soil spectroscopy offers a cost-effective complement to conventional soil analytical methods for measuring chemical, physical, and biological properties. Such information is essential for monitoring, sustaining, and improving soil health, providing the foundation to address future challenges once soil spectroscopy becomes more widely adopted and firmly established (Figure 1).

TECHNOLOGY TRANSITION FROM ACADEMIC RESEARCH TO ROUTINE APPLICATION

Soil spectroscopy has evolved from a mainly academic pursuit to a technological endeavor used by researchers, national programs, and commercial enterprises yet often lacks significant cooperation. To realize its potential, however, a greater degree of community organization is needed through global initiatives where stakeholders may electively participate.

One of the primary actions necessary to achieve this goal is establishing an extensive network of high-quality soil spectroscopy laboratories that offer accurate and reliable routine analytical services to complement conventional soil laboratories more quickly and inexpensively. On the way to that goal, current stakeholder laboratories can participate in discussions on the need to align efforts and benefit from collective knowledge and experience. Meanwhile, as technology advances, new instruments are emerging for soil analysis. Affordable instruments will become increasingly available, enabling users to adopt this technology more effectively and practically.

ENHANCING EDUCATIONAL PROGRAMS

Aside from isolated examples of local capacity-building initiatives (e.g., at universities, research institutions, and organizations such as the USDA NRCS and ICRAF-CGIAR), there is no dedicated educational initiative to systematically develop capacity and expertise in soil spectroscopy. Governments, academic institutions, and funding organizations must prioritize and allocate resources to

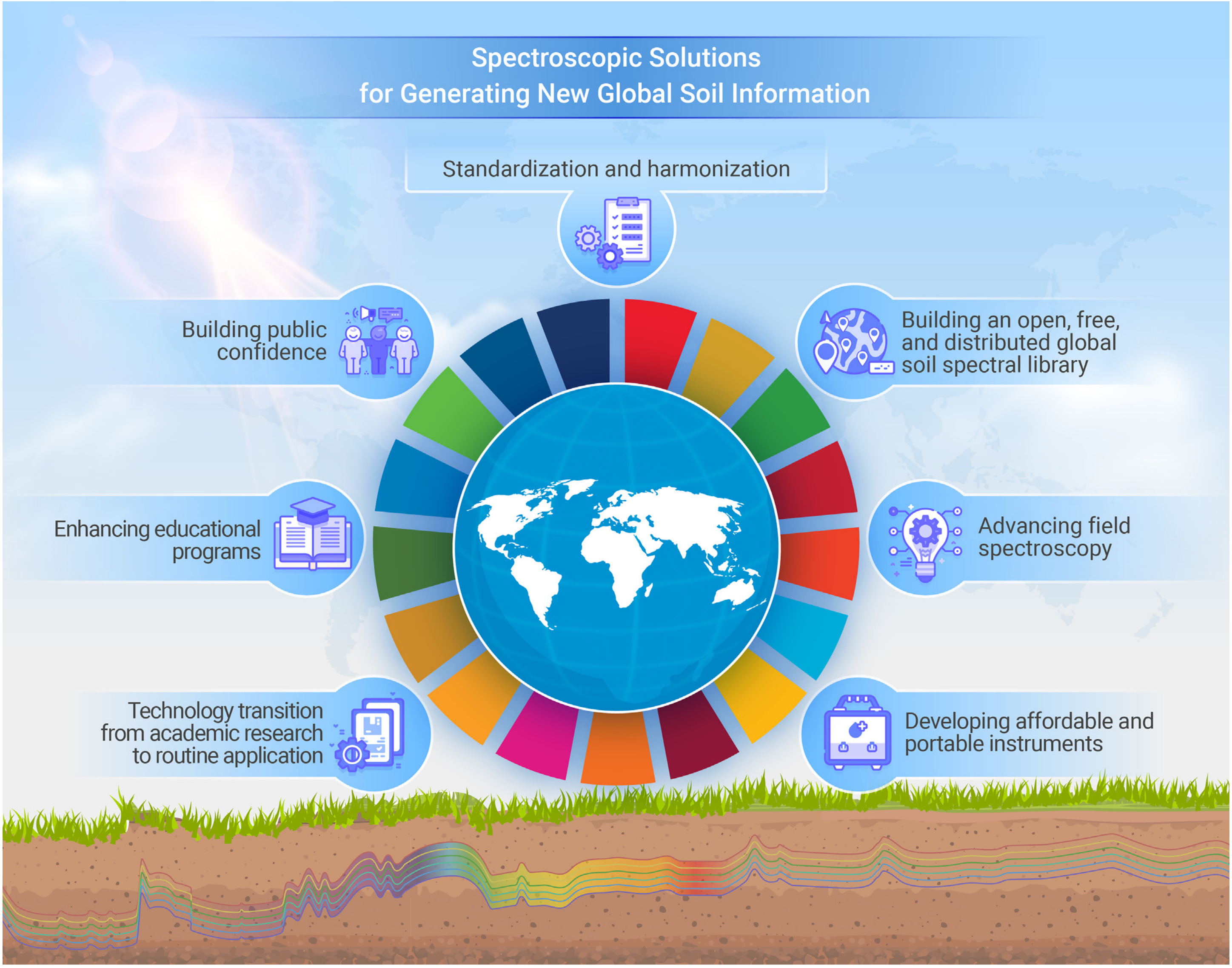

Figure 1. Seven major challenges hindering global adoption of soil spectroscopy

establish comprehensive educational and practical programs in soil spectroscopy. These programs should aim to train a new generation of soil scientists and practitioners with multi-disciplinary expertise, ensuring the effective global adoption and application of soil spectroscopy. International organizations and research institutes can support these efforts by providing training opportunities, including online and on-site courses, workshops, webinars, and laboratory and field exercises, to engage a broader range of professionals—such as laboratory and field technicians—and strengthen capacity across all levels.

BUILDING PUBLIC CONFIDENCE

Clear and transparent communication is crucial for building public trust in soil spectroscopy. Over the past 30 years, scientists have published extensive peer-reviewed research demonstrating the technology's utility, precision, and reliability while openly acknowledging its limitations. Soil spectroscopy can reliably estimate some, but not all, soil properties. Understanding and communicating the advantages and limitations of soil spectroscopy is essential. Global initiatives such as the Global Soil Laboratory Network's soil spectroscopy initiative (GLOSOLAN-Spec) must provide good practice guides for the standardized application of the technology, including soil sampling, sample preparation, data acquisition, interpretation, development of a spectral library, data management, spectroscopic calibration, validation, and uncertainty assessment. Promoting the successful application of soil spectroscopy through various media channels is also crucial, as it highlights how this technology complements traditional soil analytical methods and improves the efficiency of soil laboratories. Practical initiatives such as workshops, live demonstrations, and community forums can help demystify soil spectroscopy and foster greater stakeholder understanding. Governments, international organizations, and academic and research institutes can play a critical role in supporting the development and expansion of soil spectral libraries (SSLs) while building awareness and trust in soil spectroscopy. For companies and commercial laboratories to integrate spectroscopy into their soil analysis for various applications, it is vital to provide evidence that the technology is efficient and cost effective.

STANDARDIZATION AND HARMONIZATION

The effectiveness of spectroscopic models for soil property estimation depends on the quality and consistency of the spectra and the associated analytical measurements. Soil property values in SSLs are subject to errors because different laboratories use varying soil preparation procedures and analytical methods to analyze soil properties. Similarly, variations in sample preparation, instrumentation, measurement protocols, and other procedural elements can introduce systematic and random errors into soil spectra, leading to discrepancies in model performance across different laboratories. The overall quality of the data in SSLs is influenced by the level of quality control maintained at each facility, creating additional variability. For instance, spectroscopic models developed in one laboratory may perform poorly due to such inconsistencies when applied to spectra from another. Merging various SSLs into a single comprehensive library can introduce additional sources of variation, which can degrade the overall performance of the combined SSL. It is important to note that mathematical filters and transformations can correct for additive, multiplicative, and random errors in the spectra, but soil analytical errors are more difficult to correct. Calibration transfer between different manufacturers' spectrometers is less challenging as instrumentation improves and signal processing and machine learning methods develop.[4] However, developing a global soil spectroscopy laboratory network and standardizing and harmonizing soil spectroscopy remains essential. Initiatives like GLOSOLAN-Spec and GLOSOLAN must collaborate to establish laboratory proficiency testing programs that ensure the consistency and comparability of spectra and soil property values across different instruments and laboratories. Such efforts are critical to fostering reliable and interoperable soil spectroscopy globally.

AN OPEN, FREE, AND DISTRIBUTED GLOBAL SSL AND ESTIMATION PLATFORM

Over the last two decades, SSLs have been developed by institutions worldwide as practical tools to characterize soil and become an essential reference source for the estimation of soil properties[5] for digital soil mapping and modeling. The SSLs store extensive data from soil samples; each sample in the SSL includes a spectrum measured by a spectrometer and associated soil property values measured by conventional soil analytical methods. A well-constructed SSL can be used to create predictive multivariate models of soil properties. Depending on the need and scale of the application, the models can be statistical or machine learning methods. With robust modeling and validation practices, they can provide precise and unbiased estimates of soil properties for different applications (e.g., agricultural, ecological, and urban[6]) at global, regional, and local scales.

Establishing an SSL requires significant investment, often beyond the reach of many institutions and countries. The widespread use of public soil resources, such as the USDA NRCS Soil Survey, shows the benefits of voluntarily shared SSLs. Open sharing accelerates research. Current efforts to share SSLs have adopted a centralized approach, where international organizations have taken the lead in collating and maintaining a global SSL. While establishing open global SSLs is needed, many soil scientists and practitioners lack the expertise to analyze and model soil properties with spectra effectively. To make this technology accessible and beneficial worldwide, especially in developing countries where expensive laboratory analyses are unaffordable, we must develop SSLs alongside user-friendly estimation platforms. These platforms should enable non-experts to obtain the necessary soil information efficiently and allow models trained on extensive global SSLs to be adapted for local conditions, improving their accuracy and utility.[4] By integrating SSLs with an accessible estimation platform and using new, innovative modeling techniques, we can democratize soil spectroscopy, making it a practical tool for soil management globally. As we move toward a decentralized global data-sharing network, we will learn more about the condition and capacity of the world's soils.

DEVELOPING AFFORDABLE AND PORTABLE INSTRUMENTS

Recent advancements in physics and instrumentation have led to the development of portable and miniaturized spectrometers, which are significantly more affordable than traditional benchtop laboratory systems. Technologies such as Fourier transform IR (FT-IR) methods, solid-state detectors, and micro-electro-mechanical system (MEMS) spectrometers have been pivotal in this progress. These innovations enable the precise analysis of soil properties in a wide range of applications, reducing the need for extensive sample preparation and making soil spectroscopy more accessible, particularly in resource-limited settings. Nonetheless, the varying quality of these lower-cost sensors presents a significant challenge to their adoption, although research that assesses their performance is emerging. Validating the accuracy and long-term stability of these instruments requires soil science knowledge and expertise.[7] Collaboration between land managers, soil scientists, engineers, spectrometer researchers, and developers is crucial to enhance the robustness and development of these tools. Soil scientists provide knowledge about soil properties and the required accuracy for specific applications, while engineers and developers innovate spectrometer design and researchers refine the technology. Additionally, combining spectroscopy with other sensors, such as those measuring plant-available nutrients, can offer a more comprehensive analysis of soil conditions. This multi-sensor approach improves soil management by providing accurate and detailed information about soil conditions.

ADVANCING FIELD SPECTROSCOPY

Ultimately, we aim to bring spectroscopy directly to the field, enabling the *in situ* measurement of soil spectra in their natural state and applying SSLs to these field-measured spectra for estimating soil properties. This approach offers the advantage of removing the need to transport samples to a laboratory for further processing before recording the spectra. Despite its considerable promise, the practical deployment of field spectroscopy still faces challenges. Soil horizontal and vertical surfaces present challenges due to sealing and residues and variations in soil moisture, aggregation, and other factors.[8] This variability requires appropriate sampling strategies in the field to ensure representative measurements. A prerequisite for the successful application of field spectroscopy is to physically and mathematically filter out as much systematic and random noise as possible from the spectral data originating in the field before proceeding with modeling.[9] Managing soil moisture and other environmental effects on spectra will be even more crucial if laboratory-based SSLs are used for calibration and prediction using field spectra.[10] Transfer learning techniques can address the challenge of accurately capturing the local characteristics of soil properties at specific sites when applying a large SSL to a local application (e.g., at the farm scale).[4]

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DECLARATION OF INTERESTS

The authors declare no competing interests.