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Soil Science Issues

Top-Ranked Priority Research Questions for Soil Science in the 21st Century

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Soils provide critical support essential for life on earth, regulate processes across diverse terrestrial and aquatic ecosystems, and interact with the atmosphere. However, soil science is constrained by a variety of challenges including decreasing funding prospects and a declining number of new students and young professionals. Hence, there is a crucial need to revitalize the impact, relevance, and recognition of soil science as well as promote collaboration beyond traditionally defined soil science research disciplines. Such revitalization and collaboration may be fostered by a shift from discipline-focused soil science research to cross-disciplinary research approaches and issue-driven research. In this paper, we present the outcomes of an initiative to identify priority research questions as a tool for guiding future soil science research. The collaborative approach involved four stages including (i) survey-based solicitation of questions; (ii) criteria-based screening of submitted candidate questions, (iii) criteria-based ranking of screened questions, and (iv) final revision of top ranked questions. The 25 top ranked research questions emerged from 140 submitted candidate questions within five predetermined thematic areas that represent current and emerging research areas. We expect that the identified questions will inspire both existing and prospective researchers, enhance multi-disciplinary collaboration both within and outside soil science, draw the attention of grant-awarding bodies, and guide soil science research to address pressing societal, agricultural, and environmental challenges. Furthermore, we hope that the approach and findings presented in this paper will advance soil sciences by fostering improved collaboration among soil science practitioners and researchers, as well as with other sciences, policy experts, and emerging professionals (including students) to meet societal needs.

Abbreviations: CWG, core working group; EC, expert committee; GHG, greenhouse gases; GIS, geographical informational system; NAS, National Academy of Science, SIS, soil information systems.

Soils are biogeochemically dynamic entities that play an important role in sustaining life forms within the earth's critical zone by regulating processes in terrestrial ecosystems including freshwater and marine ecosystems. Yet, advancing soil science research and establishing its relevance in today's rapidly evolving research landscape presents diverse challenges. The growing expectations for tangible outputs despite shrinking financial resources, and a declining number of new and practicing soil scientists highlights the common issues that are frequently identified as major challenges for advancement of soil sciences (Baveye et al., 2006; Hartemink and McBratney, 2008; Havlin et al., 2010). Hence, the perception of soil science as a dynamic and rewarding professional career is declining, and the reputation of soil science as a discipline among peers in related fields and funding agencies is low (Or et al., 2011).

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Decline in the quality of soil science research in the past few years have been noted despite a measurable increase in the number of peer-reviewed research publications (Hartemink, 2006; Hartemink and McBratney, 2008). This seemingly paradoxical relationship between the quality and quantity of soil science publications could be attributed to the adoption of improved technologies to communicate and reproduce studies at different sites or ecosystems, without significant emergence of new research ideas (Hartemink, 2006; Hartemink and McBratney, 2008). However, there seems to be a renewed interest in both soils and soils-related research (Havlin et al., 2010; Sugden et al., 2004) due to the urgency of 21st century challenges, including climate change, land-use change, agricultural production, food security, environmental protection, ecosystem services, and energy production (Hartemink and McBratney, 2008; Or et al., 2011; Richter, 2007). This increased interest in soil science research reflects a broadening of the classical agricultural focus to a multi-disciplinary approach towards global environmental and societal challenges (Baveye et al., 2006; Grunwald and Lamsal, 2006; Hartemink, 2006). Sustaining these emerging interests requires further advancement in inter-disciplinary (among various soil science disciplines) and trans-disciplinary (among disciplines outside of soil science) research collaboration, with emphasis on addressing key research needs.

Within the last decade, considerable efforts have been made to define an agenda for soil science research (Hartemink, 2006; Rice et al., 2009) by proposing institutional, professional, and educational changes that can enhance the relevance and recognition of soil science in contemporary society (Baveye et al., 2006; Or et al., 2011). Through these efforts, themes and future directions for soil science research have been identified and discussed. However, to have outcomes relative to priority needs of the 21st century, the existing model of conducting research within specific disciplinary boundaries should give way to research efforts focused on strategic and priority societal needs (Bouma, 2010; Or et al., 2011). Within the domain of soil sciences, there has been no report of a dedicated attempt towards prioritizing research needs through identification of specific research questions. Therefore, in the year 2012, an effort was initiated to identify questions that may serve as a guide for prioritizing soil science research and optimize the allocation of diminishing resources to address contemporary societal challenges (Adewopo and Bhomia, 2012). The initiative, led by graduate students, was administratively supported by the Soil Science Society of America (SSSA). This paper presents 25 top priority research questions for soil science research, with detailed outcomes of this initiative. Although the list is not exhaustive, it is anticipated that the identified research questions will be useful to both researchers and graduate students and will guide funding agencies to strategically allocate resources to support research ideas that are most urgent and possess high potential for widespread impact. Furthermore, this may provide policy-makers with important perspectives towards optimizing the benefit of scientific research and innovations to the wider public.

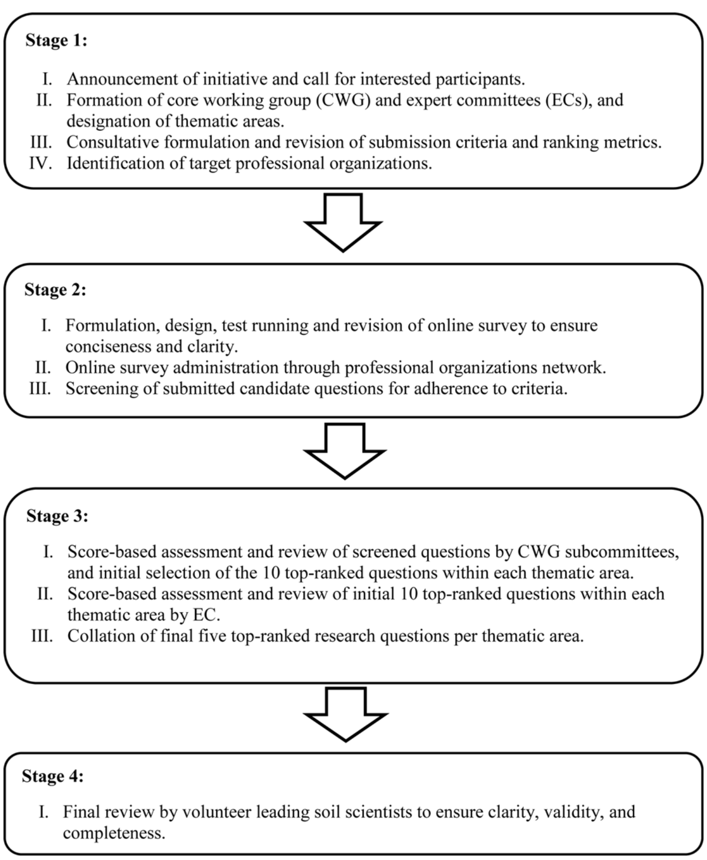

Fig. 1. Flowchart showing four-stage collaborative process adopted to identify 25 top priority research questions for soil science in the 21st century.

METHODS

This initiative was carried out through a four-stage collaboration between graduate students, researchers, soil science professionals, environmental consultants, and policy experts (Fig. 1). The first two stages were similar to the horizon-scanning approach for disciplinary priority setting in ecology, conservation, and agriculture (Pretty et al., 2010; Sutherland et al., 2009; Sutherland et al., 2006), where important questions were solicited from a group of leading researchers, policy experts, and organizational leaders. Stage 1 involved an announcement of the initiative and invitation for collaborators, and formation of a core working group (CWG) and two expert committees (ECs)—scientific EC and policy EC. The CWG consisted of 12 graduate students and an early career scientist, all selected through informal nomination/invitation or after a formal application. The scientific EC comprised of 16 scientists that are actively engaged in soils-related research. The policy EC comprised of three policy experts drawn from different institutional and disciplinary backgrounds. Potential members of the ECs were invited based on recommendations by the CWG and the final members were selected on the basis of research accomplishments, demonstrated interest in defining the future of soil science research, and experience within scientific (or science policy) arena. The question submission format and ranking criteria were developed by the CWG, and appropriate professional organizations were identified for solicitation of priority research questions through online survey. Stage 2 involved compilation of an initial set of research questions (candidate questions) by requesting submission from soil scientists and environmental professionals. An online survey form was created (see Supplemental Appendix 1.1–1.2 online) with the help of SSSA survey staff to collect candidate questions through a crowd-sourcing strategy. The online survey web link was shared widely with members of the American Geophysical Union, Ecological Society of America, Canadian Soil Science Society, SSSA, and societies that are engaged in or associated with soil science research. The survey was available for 4 wk (12 Sept.–15 Oct. 2012) and initial recipients were encouraged to share the survey link throughout their professional networks—an approach known as 'snowball sampling'(Berg, 1988). Submission of candidate questions was requested within five thematic areas identified during a global soil frontiers workshop by the National Academy of Sciences (NAS) (Rice et al., 2009). These five thematic areas were (i) soils as a key regulator of ecosystem functions, (ii) soil's role in public health and human well-being, (iii) soils mediating nutrient cycling, transport processes and plant–soil–microbial interactions, (iv) soil formation and degradation, and (v) soil information systems. Each survey respondent was allowed to submit a maximum of two questions within one or two thematic area(s) that matched their areas of expertise or research interest. Similar to Pretty et al. (2010), candidate questions were expected to meet five criteria including ability to address knowledge gaps, answerability, factuality, objectivity, and extent (Table 1). Few questions (~3% of candidate questions) were excluded from further consideration because they did not satisfy one or more of the submission criteria. Members of the CWG did not submit questions to avoid conflict of interest in the question screening process.

In Stage 3, the CWG was divided into five subcommittees comprised of two to three members each. Each subcommittee screened, reviewed, and edited candidate questions within an assigned thematic area. The questions were screened by assessing conformity to the afore-mentioned submission criteria. Popular databases, such as Web of Science and Google Scholar, were used to search for existing peer-reviewed literature and other published resources based on keywords contained in each question. Candidate questions that passed this screening process were further scrutinized and assigned scores (range = 0–10; higher scores indicative of a better expression of criteria) based on a set of five attributes (Table 1). These attributes were complementary to the submission criteria and were developed by the CWG members. An initial pool of 10 top-ranked questions per thematic area (16 in Thematic Area 3), based on CWG-assigned ranking scores, were selected for review by scientific and policy EC members. The scientific EC members assessed the questions within the specific thematic area that corresponded to their disciplinary background and preference, while policy EC members assessed questions across all thematic areas. Criteria-based scores were again assigned by EC members to each question (range = 0–10; higher scores indicative of a better expression of criteria), using a different set of ranking criteria for scientific and policy experts (Table 2 and Table 3, respectively). These criteria, developed by the CWG team and approved by the ECs, were used to assess screened and ranked questions. Subsequently, the five top-ranked questions per thematic area were selected based on cumulative ranking scores assigned by the ECs members.

In Stage 4, the final list of 25 priority research questions (i.e., five questions per thematic area) was shared with a volunteer group of leading soil scientists for a post-process review. The volunteers

Table 1. Criteria for screening and assigning a score to submitted questions by core working group (CWG) members.

Task	Criteria	Explanation
Screening (Yes/No) [Submitted candidate questions must meet all of these criteria to be selected for next stage]	Contribution	Address important gaps in knowledge (i.e., questions that have not already been adequately answered).
	Answerability	Be answerable through a realistic research design.
	Factuality	Have a factual answer that does not depend on value judgment.
	Objectivity	Not have "Yes" or "No" answer(s).
	Extent	Be realistic in scale and scope.
CWG Scoring (0–10)	Relevance	General relevance of each question to the soil sciences, and specifically to the particular thematic area. High score assigned if question is relevant in contemporary context (i.e., aims to address current and impending issues/problems, than more futuristic/less practical ideas). Higher scores to questions focused on tackling problems concerning large groups of stakeholders (e.g., agriculturists, foresters, land managers and environmental managers).
	Impact	The direct and indirect impacts of a particular question being addressed. Higher score to questions that aim to address far-reaching and urgent challenges such as food security, climate change, greenhouse gas emissions, and environmental degradation. Questions aimed towards finding direct solutions or advancing our understanding to better manage resources recieved higher scores.
	Novelty	Score assigned on the basis of question's capability to push the knowledge boundary. It is possible that a question that seems very novel (high score) could have limited relevance, mainly because not much is known/done in that area, but it cannot simultaneously have a low score on 'potential impacts'.
	Advancement of thematic area	Higher scores to questions that can directly contribute to the advancement of the specific thematic area. Questions that are aimed towards refining techniques, improving understanding of basic processes, or recognizing the 'unknowns' in our knowledge of systems were ranked higher.
	Frequency	Number of times a similar question is submitted (e.g. if submitted three times then assigned "3" points).

Table 2. Scientific expert committee (EC) criteria for assigning a score to initial top-ranked questions.

Task	Criteria	Explanation
EC Scoring- Scientific Assessment (0–10)	Feasibility	Feasibility of the proposed research question with respect to available research facilities, accessibility of appropriate technology, and other research resources. A question with a high score would be feasible in a contemporary or near future context.
	Funding prospect	Funding outlook/potential for the proposed research question. Higher scores were assigned to questions that have a greater likelihood of attracting funding in the near future.
	Potential impact	Extent to which the question will advance scientific knowledge and benefit the society. Higher scores were assigned to questions that aim to address pressing and urgent challenges. Also, questions aimed towards finding direct solutions or advancing scientific understanding for more sustainable resource management were given higher score.
	Inter-disciplinary merit	Likelihood that the question will facilitate inter-disciplinary collaboration within various thematic areas (and outside the realm of soil sciences). Higher scores were assigned to questions aimed at solving complex problems by promoting an inter-disciplinary approach.
	Scalability	Flexibility of the question in addressing problems across multiple scales. Scores were based on the capacity of a particular research question to be scaled up or down to meet local and regional demands. For instance, if the outcomes of a proposed research question are limited to either coarse or fine scales, low scores were assigned, whereas questions that will result in outcomes with a wide range of applicability were assigned higher scores.

were drawn from a pool of leading soil scientists that participated at an inter-disciplinary Critical Zone workshop organized by the Swiss Federal Institute of Technology, Zurich (ETH, Zurich) in April 2013. These scientists provided comments on the final list of questions to strengthen the scope and enhance clarity of identified research questions. Their suggestions were incorporated into the final list of 25 questions that is presented here.

RESULTS

At the closure of the survey, 140 candidate questions were submitted by 82 respondents. These questions were unevenly distributed across the five thematic areas (Fig. 2). We were unable to estimate the response rate due to the limitations of the crowd-sourcing and snowball sampling strategy, which preempted the possibility of knowing the actual number of potential respondents that received the invitation to access the survey link.

The thematic areas are preceded by a broad but brief overview of the research scope, with a focus on establishing its relevance. However, the introductions are mostly literature-based and in some instances, research needs gleaned from literature did not emerge as top-ranked research questions. Also, the final list of questions does not reflect a specific order of priority because we considered all top-ranked questions equally important and had no intention to elevate or relegate any research question or idea.

Thematic Area 1: Soils as a Key Regulator of Ecosystem Functions

The importance of soils in ecosystem function is well known (Bardgett, 2005), but current methodology is inadequate to quantitatively examine ecosystem services over various temporal and spatial scales. The debate regarding how we should best define the value of ecosystem services is ongoing (Farley, 2012). However, it is clear that ecosystem services are vital to the health and well-being of humans and other organisms within the biosphere (Dominati et al., 2010; Robinson and Lebron, 2010). Also, modern challenges facing ecological sustainability have moved several ecosystem functions to the forefront of current and future research needs. It is therefore important that we develop methodologies to adequately identify, measure, and assess the value of these services and functions.

In light of global climate change and the growing human population, it is crucial to determine different soils' responses to human-induced and natural changes, as well as the long-term impact of this response on ecosystem services (Richter, 2007). Such knowledge will help to evaluate the role of soils in ecosystem dynamics at local and global scales, particularly regarding nutrient cycling, erosion, water quality, and regulators of greenhouse gas (GHG) emissions.

The most recurring topic amongst candidate questions was related to soils as a regulation of carbon (C) cycling. Some opportunities and challenges associated with soil C sequestration were highlighted by Bruce et al. (1999) including management of cultivated soils and restoration of degraded lands. Although many researchers have studied how soils regulate C sequestration and GHG emissions, there is a need for improved understanding of the processes involved, and how these processes modulate overall ecosystem health (Lal and Follett, 2009). Other pressing knowledge gaps highlighted by researchers included an un-

Table 3. Policy expert committee (EC) criteria for assigning a score to initial top-ranked questions.

Task	Criteria	Explanation
EC Scoring- Policy Assessment (0–10)	Applicability	Extent to which the question apply to pressing societal needs and its potential to inform policy decisions in favor of soil science research.
	Appeal and relevance	The potential for the outcomes of the research question to remain congruent to policy interests over time, with respect to current and evolving political landscape.
	Institutional integration	The likelihood that addressing the research question will foster collaboration and integration of different institutions at different levels, in agreement with the existing policy directives. (Note: This is based on the need for improved institutional operational efficiency to optimize the use of taxpayers' money/public funds).

derstanding of soils and ecosystem functions within urban and suburban environments (Hazelton and Murphy, 2011), biofuel production systems (Lal and Stewart, 2010), and contaminated sites (Stegmann et al., 2001). Also, nutrient cycling has been a primary focus of soil research, but the demand for clean water and sustainable agricultural practices seems to dominate research prospects in this field. The five top-ranked questions within Thematic Area 1 are:

i. How do soil heterogeneity and dynamics affect the stability of large-scale ecosystem functions?

ii. How will below-ground biomass dynamics shift in response to climate change and nutrient enrichment over the next 20 to 40 yr?

iii. What are the impacts of bioenergy crop production on soil quality, nutrient cycling, GHG emissions, and long-term sustainability of different soil types?

iv. What are the critical levels of soil C below which soil ecosystem function is considered impaired for a given ecotope?

v. What processes control the coupling of soil organic matter (SOM) with climate change, and how will differences in biotic and abiotic components of ecosystems influence these processes?

Thematic Area 2: Soil's Role in Public Health and Human Well-being

Human health is commonly defined as 'a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity' (World Health Organization, 2006). Public health is an extension of that definition to include the health of a community as a whole, and environmental health is a sub-field focused on the health impacts of various environmental hazards. The various roles that soils play in protecting or threatening public health can be assessed according to the varying perspectives of multiple disciplines (e.g., environmental health, public health, and soil science). By recognizing and incorporating such multi-disciplinary perspectives, the inextricable links between soil health and public health can be more clearly elucidated.

Soil-related examples of the chemical, biological, physical, mechanical, and psychosocial hazards that are the preoccupation of environmental health professionals are often (but not always) easy to identify. Some examples include soil contamination by pharmaceuticals and personal care products (chemical), antibiotic resistant soil microbes (biological), radiation (physical), failure of earthen embankments and hillslopes (mechanical), and community displacement due to desertification and associated stress (psychosocial). The relationships between public health and soil science can also be identified using the core public health functions of assessment (e.g., soil mapping to predict disease vector distribution), policy development (e.g., risk-based soil screening levels), and assurance (e.g., health impact evaluation of soil remediation activities). However, the protective roles that soil plays in public health may be more readily apparent when examined through the lens of a soil scientist. For instance, public health-related examples of soil functions include, (i) provision

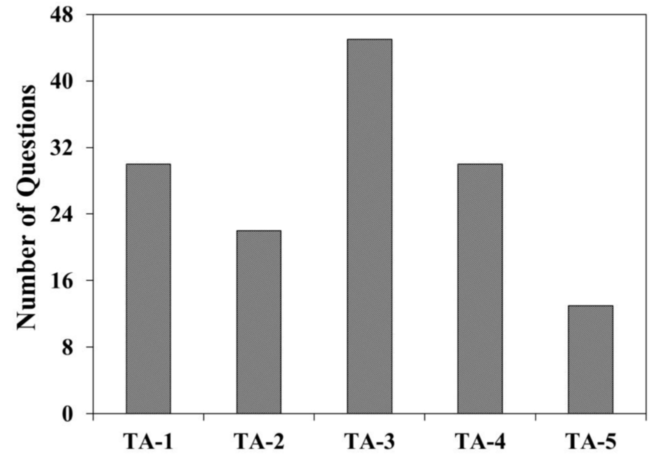

Fig. 2. Chart showing number of candidate questions submitted as top priority for soil science research across five thematic areas (TA). TA-1, Soils as a key regulator of ecosystem functions; TA-2, Soil's role in public health and human well-being; TA-3, Soils mediating nutrient cycling, transport processes, and plant-soil-microbial interactions; TA-4, Soil formation and degradation; TA-5, Soil Information Systems.

of medium for the growth of food crops and water storage; (ii) provision of shelter (engineering medium); (iii) recycling of nutrients and organic wastes; (iv) provision of habitat for soil biota (macro and microorganisms); and (v) water and air purification (Brady and Weil, 2008).

The linkages between soils and human health have long been appreciated, though not widely acknowledged or fully understood (Selinus et al., 2005). Hippocrates noted that water from particular soils contained harmful heavy metals and Marco Polo drew a connection between soil quality and bellicosity (Selinus et al., 2005). Societies through centuries and across continents consumed soil with the intent of supplementing nutritional needs or alleviating gastric pain, sometimes resulting in negative health consequences including death (Selinus et al., 2005). In more recent years, coordinated efforts recognizing the importance of understanding the relationships between soil science and public health, and the need for the two disciplines to collaborate in research and application have become increasingly evident—as highlighted by the NAS symposium on the connections between earth sciences, health, and policy (Academies, 2008) and peer-reviewed publications (Abrahams, 2002; Blum, 2005; Pepper et al., 2009)

It is increasingly important to address the intersections of soil and public health in light of climate change, population growth, and demographic shifts, changes in consumption patterns as well as an evolving global economy. The five top-ranked questions within Thematic Area 2 are:

i. What are the limits of soil productivity for global food production under alternative projected climate change scenarios and socio–economic constraints?

ii. What are the dominant controlling factors of the soil microbiome and how do soils mediate or inhibit the transmission of infectious diseases (e.g., transfer of antibiotic resistance)?

iii. What methodology and parameters should be used to assess the role and importance of soils to environmental health and human well-being?

iv. Can crops be developed to optimize uptake of specific nutrients from soils, and the resulting foods used to reduce the adverse health burden of nutrient deficiency in humans?

v. In response to the recent rise in popularity and extent of urban agriculture, what are the best management practices for safeguarding human and environmental health against adverse compaction, runoff, erosion, and nutrient losses in urban environments?

Thematic Area 3: Soils Mediating Nutrient Cycling, Transport Processes, and Plant–Soil–Microbial Interactions

Biotic and abiotic components within soil interact to mediate cycling pathways for important macronutrients and micronutrients. During these processes, soils facilitate important ecosystem services including C storage, transformation of environmental contaminants, and biogeochemical reactions that aid in nutrient cycling (Silver et al., 2010). However, these processes can be perturbed by anthropogenic activities, causing local, regional, and global scale impacts such as increased GHG emissions, contamination of drinking water, alteration of sea level and climate patterns, and eutrophication of lakes and oceans (Di and Cameron, 2002; Galloway, 2005; Hall and Matson, 1999; Schindler, 2006). Soil and plant residue management has been shown to be an effective tool to reduce GHG emissions, reduce nutrient fluxes to waterways, and promote C storage (Banwart, 2011; Lowrance et al., 1997; Nave et al., 2010; Syswerda et al., 2011). However, our ability to improve soil management to address emerging challenges depends on the mechanistic understanding of underlying processes, and development of tools to accurately monitor and model the complexity of the natural environment.

System changes such as shifting land-use and management practices can significantly alter nutrient pools and transport pathways. Land-use changes associated with increased urbanization will alter soil temperature and moisture regimes due to the urban heat island effect and modified hydrology (Walsh et al., 2009). Urbanization may also change the quantity and quality of organic inputs to soils while increasing the possibility of contamination by heavy metals, trace organic contaminants, and pathogens (Cachada et al., 2012; Pouyat et al., 2010). All of these changes will have an impact on nutrient cycling, C storage potential, contaminant transport, and microbial activity in soils (Grimm et al., 2008).

For better understanding of soil processes and its relationship with the global change scenarios described above, both micro-scale and macro-scale studies are required. Nutrient cycling in the environment occurs between various biotic and abiotic compartments such as plants, animals, microbes, lithosphere, hydrosphere, and atmosphere. The fluxes between these compartments are regulated by multiple factors including soil structure, microbial communities, redox dynamics, conductivity, and elemental coupling (Davidson et al., 2000; Dubinsky et al., 2010). Despite our improved understanding of these factors over the last century, the complexity and variability surrounding micro-scale dynamics in nutrient cycling is still poorly understood and major scaling issues are yet to be resolved. The five top questions within Thematic Area 3 are:

i. How can we mobilize and efficiently use phosphorus reserves in agricultural soils while minimizing losses through runoff?

ii. How can we improve soil tillage practices, residue management, and nutrient applications to promote natural resource sustainability and reduce negative environmental consequences while maintaining food production?

iii. How do soil properties impact mitigation of emerging contaminants (i.e., nanomaterials, pharmaceutical compounds)?

iv. What processes, methods, and tools will enable us to better quantify soil C storage, especially to detect slow long-term changes in soil C relative to short-term variability?

v. What processes control the movement of water vapor between soils and the atmosphere, and what are the key feedbacks between soil processes and climate patterns?

Thematic Area 4: Soil Formation and Degradation

The need to understand pedogenesis has been historically established in soil science (Darwin, 1892; Dokuchaev, 1967; Hilgard, 1860; Jenny, 1941). Through pedogenesis, a broad suite of biogeochemical and physical processes interact to create, alter, and destroy biologically active, spatially diverse, and well-organized material on Earth's surface that has been termed both 'soil' (Ramann, 1929) and 'regolith' (Merrill, 1897). Beyond regulating the existence and properties of soil, pedogenic processes also exert significant influence on Earth's atmosphere (Berner et al., 1983; Raymo and Ruddiman, 1992), biosphere (Turner et al., 2012; Wardle et al., 2004), hydrosphere (Raymond et al., 2008), and lithosphere (Bazilevskaya et al., 2013; Targulian, 2001).

Richter (2007) and Richter and Yaalon (2012) detail the past, present, and future views of pedogenesis. Historically, Jenny (1941) built on the work of Dokuchaev (1967) to provide a model of pedogenesis in which soil was viewed as a natural body formed and destroyed by five forming factors (climate, parent material, topography, biota, and time). Since then, views of pedogenesis have evolved to recognize soils as polygenetic systems that respond to variability in the forming factors (Cline, 1961; Targulian and Sokolov, 1978). Most recently, an appreciation for the profound and long lasting impacts of humans on pedogenesis has been articulated (Reséndiz-Paz et al., 2013; Schlesinger, 1990) and soils are understood to be human-impacted natural bodies with emphasis on humans as a soil forming factor (Amundson and Jenny, 1991; Dudal et al., 2002; Richter, 2007; Richter and Yaalon, 2012).

As expressed by Daniels and Hammer (1992), one cannot hope to interpret soil systems accurately without understanding how the landscape and soils have co-evolved. Soils are subjected to natural and human-derived generative and degradative processes through centuries and decades (Richter and Markewitz, 2001; Smith, 1980; Trimble, 1974) which operate in soil environments that have previously experienced variable pedogenic processes for thousands or even millions of years (Bacon et al., 2012; Cline, 1961). Understanding how such temporally distinct processes are interacting with one another concurrently presents a great challenge and a great opportunity to future studies of soil formation and degradation. The five priority research questions for this thematic area indicate the need to study generative and degradative pedogenic processes as they have changed in the past, as they are changing currently, and as they will change in the future to shape Earth's soil. The five top questions within Thematic Area 4 are:

i. What are the long-term cumulative effects of intensive agricultural management systems on soil?

ii. How can we incorporate long-term climatic and geologic processes and contemporary anthropogenic impacts into integrated models of soil properties?

iii .What is the economic cost of soil degradation (e.g., erosion) relative to the value of crop production?

iv. What are the consequences of anthropogenic perturbation and change of soil properties for future food production and ecological sustainability?

v. How can we improve or preserve the resilience of agricultural and forest soils under changing climatic conditions?

Thematic Area 5: Soil Information Systems

Soil information systems (SIS) research is broadly defined as the incorporation of soil science within geographic information systems (GIS) (Burrough, 1991; DeGloria and Wagenet, 1996; Grunwald and Lamsal, 2006), which encompasses spatial data collection, spatial statistics, spatial modeling, data display, as well as management and ethical issues, including data integrity and usage (Burrough, 1991; Goodchild, 1992). The questions of *where* and *when* processes operate are basic concepts that underpin practically every investigation of soil science. Full utilization of the vast volume of data acquired on the spatial and temporal dynamics of soil properties requires innovative techniques of data storage, management, processing, and representation. Also, analytical techniques for interpreting patterns are critical to derive relevant information from collected data, particularly in support of the research areas identified above. Understanding the causes of spatial patterns will aid process level understanding, which is indispensable for the prediction of soil properties at locations that present practical challenges to measure in time or space (Jenny, 1941).

In the coming years, SIS research will play a pivotal role in fostering a holistic understanding of soils' physical, chemical, and biological properties that are measured with different tools and instruments, ranging from in situ probes to remote sensing technologies. Inherent to this eclectic set of tools, soil data are collected using a variety of methodologies and at different scales. Thus, there is a critical need to convert and standardize collected data for synthesis and interpretation. Modeling has been an indispensable aspect of traditional soil mapping (Dokuchaev, 1967; Huggett, 1975), and will continue to be a critical component of SIS, because it provides the means to fill existing knowledge gaps based on limited observations of complex systems. In addition, modeling can provide alternate scenarios for specific decision-making needs through simulations. Digital soil mapping has emerged as one of the prominent applications of geospatial modeling. It utilizes observed soil and environmental data to produce geographic representations of soil properties (Malone et al., 2013; McBratney et al., 2003; Scull et al., 2003), which can be used as parameters for other models to address relevant research needs. The impetus for such geographic soil data is illustrated by the digital soil map of the world project (Sanchez et al., 2009).

In our contemporary, information–intensive society, SIS will need to meet societal needs by providing innovative and succinct approaches to communicate results of soil research and ancillary data to the public, with a clearly defined assessment of associated uncertainties. Therefore, current issues in SIS incorporate both the scientific analysis of complex spatial data and effective communication of that information to end-users. The five top questions within Thematic Area 5 are:

i. How can cyber-infrastructure and data mining techniques aid in revealing patterns in soils, soil formation, soil degradation, soil functions, etc. along all relevant dimensions (x, y, z, time and environmental gradients)?

ii. How does the spatial and temporal scaling behavior of soil C change in response to anthropogenic-induced stressors?

iii. How can newly available large datasets on soil properties (including real time biological, physical, and chemical properties) be used for real-time and effective management of global soil resources?

iv. Based on archived and new remotely and proximately sensed data, how can geospatial modeling or simulation techniques provide better understanding about links between soil quality, soil management, and climate?

v. How can the global soil science community better engage and share information with the public and broader scientific communities, including earth sciences, hydrology, and environmental engineering?

DISCUSSION

Identifying priority research challenges within a scientific area is a daunting task, but the outcomes could present unparalleled opportunities for advancing the science. Approaching such a task with a focus on a specific discipline, as implemented for soil physics (Jury et al., 2011), could be beneficial in fostering more collaboration within the discipline for new discoveries. However, the uniqueness of soil science lies in its rich blend of pedology, biology, chemistry, physics, mathematics, and social sciences, including communication (Nielsen, 1987). This underscores an important consideration that soil science may only advance by further establishing and nurturing connections with diverse disciplines through research collaboration framed within the context of urgent societal needs. Essentially, such multi-disciplinary approaches may range from application of complex principles in physics, biology, chemistry, mathematics, etc. to integration of strategies and frameworks drawn from social sciences to address the grand challenges of 21st century (SSSA, 2009).

The number of candidate questions submitted were within the range of candidate questions collected by the British Ecological Society for biodiversity conservation, natural sciences, and social disciplines during a similar priority setting exercise (Sutherland et al., 2011a, 2011b, 2010). Interestingly, some questions that were presented as high priority for policy relevance in ecology (under ecosystem services; Sutherland et al., 2006) and for global agriculture (under soil nutrition and erosion; Pretty et al., 2010) also emerged in the final list of priority questions presented here. This overlap in research priorities suggests that trans-disciplinary collaboration is needed and likely indispensable for addressing research needs.

The overall quality and scope of the final questions largely depended on the pool of candidate questions submitted. Revisions of the main focus of questions by CWG and EC members were intentionally restricted; hence the original content of the final questions was preserved. It can be argued that some of the questions represent a status quo, especially relative to areas where research attention has been directed for decades. However, it is likely that such research needs made it to the final list because they continue to be relevant or have connection with other emerging research needs. Furthermore, different aspects of an emerging research need may be pertinent to different soil science disciplines; hence, such need(s) may resonate across several thematic areas. Climate change was a consistently reoccurring topic across all thematic areas (Questions ii, i, v, v, and iv in Thematic Areas 1, 2, 3, 4, and 5, respectively). This may indicate the need for improved collaboration of soil scientists with climate scientists to address these research needs. Soils are an important sink for atmospheric CO_2 and constitute a critical ecological component that can strongly attenuate or accentuate climatic feedbacks (de Graaff et al., 2006; Lal and Follett, 2009). However, the dynamic processes within the pedosphere and the diversity of soil types are yet to be adequately represented in climate models for predicting impacts of anthropogenic or naturally occurring changes in climatic patterns. Furthermore, though there were instances of overlap in the final list of questions across the thematic areas, such as the topic of soil C being relevant to addressing ecosystem function–(Thematic Area 1), as well as nutrient cycling (Thematic Area 3), we ensured that related questions across thematic areas are unique in terms of their broader focus and specificity to the thematic area under which they emerged.

In contrast to similar initiatives (Sutherland et al., 2011a), where focal participants coordinated with their professional networks and physically gathered in a workshop to scrutinize and vote on questions, our approach allowed for the implementation of this initiative with limited resources and beyond organizational boundaries. The process was conducted through virtual collaboration and electronic consultation (including emails and internet-based tools). The main challenge associated with the electronic crowd-sourcing strategy relates to our inability to directly target or communicate with specific survey recipients to encourage them to submit candidate questions. Despite our efforts to reach large professional networks with the survey web link, the number of responses was below our initial expectation. This could have been due to the fact that participation was not incentivized, or it could be a typical example of low response rates to e-mail based surveys (Sheehan, 2001). However, this approach offers the advantage of voluntary participation and likelihood of reaching survey respondents that are committed to ensure that their submitted questions are congruent with the specified submission criteria and relevant to the overall goal of the initiative. The screening of submitted candidate questions by the CWG helped to ensure the integrity of questions relative to the submission criteria before score-based assessment and ranking. It was challenging to reconcile submitted questions that covered similar topics but focused on different spatial scales and research scope, a situation also encountered by researchers who conducted similar exercises (Pretty et al., 2010; Sutherland et al., 2009; Sutherland et al., 2006). Where possible, we revised location-specific questions and consolidated questions that were similar in scope. Revision and consolidation of questions were considered necessary to avoid redundancy and to ensure that ranked questions possess substance and meaning. Furthermore, we anticipated that the final list could become a communication tool to highlight pivotal research gaps in soil science. Hence, it is aimed to succinctly convey the research needs to broad scientific and non-scientific audiences.

LIMITATIONS AND CAVEATS

The general limitations associated with the methodology applied in this project have been noted in Sutherland et al. (2013). However, our methodology could also have another limitation pertaining to the five predefined thematic areas. These thematic areas were defined as the frontiers of soil science research (needs and opportunities) during an international and inter-disciplinary workshop, which was designed to advance soil sciences, and involved the participation of over 120 experts from soil science or related disciplines representing different countries (Rice et al., 2009). Although, the themes may not represent the entire breadth of soil science and may be limiting in their scope, we adopted them as an objective framework for organizing the solicited questions during the submission process, based on an established and credible source. However, as with any classification system, there is the likelihood of under-representation or non-representation when predefining complex interests or ideas.

Potential bias stemming from the perspectives and interests of the conveners (NAS) or participants of the frontier-defining workshop may have naturally influenced the themes that we adopted. Also, there is the potential for unintentional omission or under-representation of important issues, especially if prospective participants were unable to recognize their research questions' connection to any of the five thematic areas. It is intriguing that water quantity and quality issues were not prevalent in the top priority questions, despite being known to be an important societal issue connected to both soils and climate. A possible solution to these limitations for a future exercise could be to solicit candidate questions without predefining thematic areas, and conducting a post-processing by sorting the questions based on frequency of keywords and core research focus.

The disparity in the number of questions submitted per thematic area may be related to the theme's research scope and disciplines represented, with a higher number of questions submitted in thematic areas that have broad disciplinary scope, in contrast to more focused thematic areas (Fig. 2). This disparity in the number of submitted questions per thematic area may merely reflect the number of researchers whose research interest falls within each thematic area, but should not be misconceived as an indication of greater or lower preponderance of research needs. Also, this disparity may have potentially enhanced scrutiny of some thematic areas. For example, five final questions were selected out of 45 submitted questions in Thematic Area 3, whereas five final questions were selected out of 13 submitted questions in Thematic Area 5. Nevertheless, such potential bias in scrutiny was minimized because all questions were subjected to the same screening and ranking criteria, while relevant but related questions were consolidated to ensure that they were not artificially filtered out.

We recognize that due to the pre-defined thematic areas and the smaller than anticipated pool of candidate questions, not all research gaps involving soil science were represented in the 25 questions presented. It is probable that critical questions and societal needs involving soil science were not included in the final 25 questions. The inadvertent omission of a research topic from this top priority list should not be misconstrued as a lack of importance. The interaction of soil with all aspects of our environment and the dynamic nature of soil science renders the creation of a succinct list of research questions very challenging. The list of priority questions produced by this study should be viewed as a starting point for conversations about the relevance of soil science in addressing contemporary issues.

CONCLUSIONS

Based on a distinctive collaborative strategy, we identified 25 priority research questions for soil science in the 21st century. Certainly, the list of questions does not encapsulate all the evolving social and environmental needs that could be addressed in soil sciences. We would like to emphasize that while submission of candidate questions may be influenced by the thematic areas, to the best of our knowledge, the methodologies used and outcomes presented are not reflective of any personal or organizational interest or persuasion. Rather, they portray a synergistic effort and conscientiously designed workflow that minimized the potential for bias or subjective ideologies. We do not have any reason to suspect that there was any bias in disciplinary and geographic representation at the NAS workshop where thematic areas were identified.

We anticipate that the final list of priority research questions will aid soil science students and researchers to align their research with existing knowledge gaps. These identified priorities may also guide funding bodies to support research ideas that are of immediate importance and bear potential for long-term relevance to our society. Further, we believe that this list may gain attention from those interested in these issues without being fully aware of soil science's role in addressing them. We hope that this initiative will add value to ongoing efforts to raise the scientific and professional profile of soil science. The list offers an opportunity for soil science research to address evolving demands and address contemporary challenges. Some of the research questions will require collaboration with multiple disciplines within and outside soil science. Inter-disciplinary and trans-disciplinary collaboration among sciences has been recognized as an inevitable pathway to advance soil science (Rice et al., 2009). This can enhance the holistic understanding of soil's pivotal role in ecological interactions, agricultural production, and engineering application, as well as help elucidate its contribution to environmental sustainability. We hope that pursuing these questions will foster collaborations among scientists and policymakers beyond soil science disciplines, and will lead to advancement of our knowledge frontiers to enable us to address pertinent social, ecological, and economic challenges.

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