A Process Toward Strengthening National Soil Information Services (SIS)

NEW EVIDENCE FOR A SIS DEVELOPMENT FRAMEWORK

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A Process Toward Strengthening National Soil Information Services (SIS): New evidence for a SIS development framework

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Project partners

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The lead implementing partner for this project is CABI, in collaboration with the ISRIC - World Soil Information, including commissioned inputs from University of California, Davis and individual consultants who provided subject area and technical expertise.

This report is an intermediate output of the ***Process Toward Strengthening National Soil Information Services*** project.

List of abbreviations

API .... Application Programming Interface
The foundation....................... The Bill and Melinda Gates Foundation
FAIR data principles............... Findable, Accessible, Interoperable, Reusable
GIS .... Geographic Information System
ISRIC... International Soil Reference and Information Centre
IT .... Information Technology
SIS... Soil Information System
SIW .... Soil Information Workflow

Glossary of terms

Enabling environment: the underlying social, political, institutional, and financial context that influences, enables, or inhibits one or more of the stages of SIS development.

Enabling environment component: an information category collected about each of the nine selected countries that allowed systematic comparison of the various enabling environments and the resultant SISs.

Enabling environment criterion: A set of 26 specific criteria were developed from the enabling environment components which were used to compare the nine countries and to identify differences and similarities. The identification of these enabling environment criteria was done through an inductive, iterative process of observing emergent themes in the interviews and conducting additional desk research and consultations with experts regarding these themes. These criteria were further classified into either conditions or outcomes.

Enabling environment conditions: A subset of the enabling environment criteria that refer to characteristics of the social, institutional, or funding context prior to or during the active phases of the SIS development effort.

Enabling environment outcomes: A subset of the enabling environment criteria that refer to characteristics of the SIS itself that have resulted from the particular mix of conditions in the given country. For SIS that currently exist or are being actively developed, the outcomes themselves may become part of the enabling environment conditions that influence further investment or activities.

Soil Information System (SIS): A SIS is defined as an integrated digital information system that facilitates the storage, analysis, management and dissemination and use of soil data and information. A SIS ideally incorporates feedback for improvement, such as a mechanism for ongoing contributions of new data or long-term plans for the evolution of certain features or information products. The system often aims to provide users with access to a wide range of soil-related data and information, including soil properties, classifications, maps, and associated environmental data. It may contain multiple data sets, models, and tools in support of improved decision making by end-users. This definition primarily refers to the technological aspects.

SIS archetype: a profile of commonly co-occurring contextual factors and country-level enabling environment criteria that lead to differential outcomes for SISs.

Soil information system champion: an institution, community of institutions, or individual with an institutional backing that advocates for the SIS during disruptions in financial and political support, and facilitates the filling of gaps in technical capacities and expertise through contacts with the national and international soil data community.

Soil information workflow (SIW) and stages of soil information development: These refer to ISRIC's report detailing the eight phases of successful SIS development: user assessment, data collection, laboratory analysis, soil archiving, data organization, modelling and mapping, applying soil information, and data and information serving.

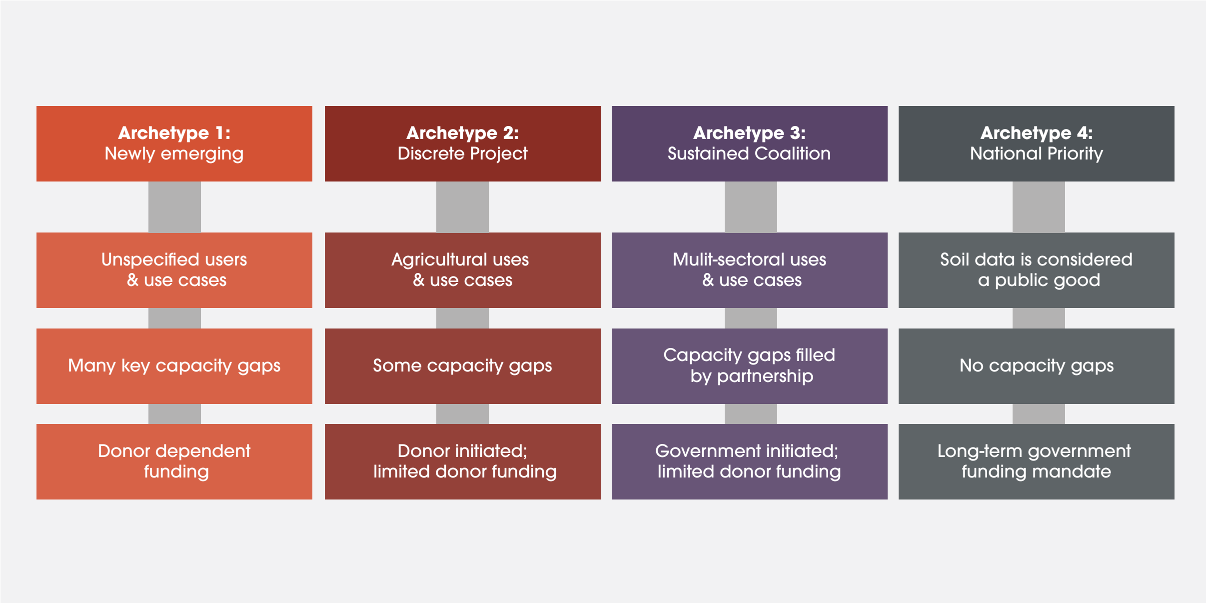
SIS roles: Functions filled, or areas of expertise provided, by individual people in a SIS.

Executive summary

Many initiatives have been developed across Africa to produce, organize, and leverage soil information by developing soil information systems (SISs).

SISs aim to make soil data and information (e.g., physical and chemical soil properties, nutrients, and water dynamics) available to users through an online portal, service, or website. SISs can inform decision-making at multiple levels in agriculture, commercial and industrial development, environmental conservation and management, and land use, and be leveraged in many other ways by additional users.

A SIS is a technological output, but often it is also a process by which people and institutions must collaborate, explore, iteratively refine, and implement plans for data development, all while balancing multiple evolving sets of needs, setbacks, resources, and priorities. When designing new SIS interventions, a common misstep is to omit an assessment of in-country needs, stakeholders, and enabling environment factors, and instead to go straight to implementing solution-driven technologies.. Though ambitious and sophisticated technological solutions may be useful in many contexts, we hypothesize that sustained process and people capacity building approaches are just as essential for the development of successful SISs. A **Process Toward Strengthening National Soil Information Services** is a project led by CABI and ISRIC – World Soil Information, supported by the Bill & Melinda Gates Foundation, comprising several workstreams that contribute to testing this hypothesis, developing general archetypes and a framework, and scaling these innovations in line with the foundation's goals.



Workstream 1 (WS1) conducted a literature review of the history of soil information development, and reviewed nine countries with an existing SIS to characterize the variations in the underlying enabling environments for SIS development. Desk research was conducted and original data were collected via 13 semi-structured interviews. The responses were transcribed and synthesized into nine country summaries (Appendix 5) which describe the enabling environments at a country level. Enabling environment criteria are classified as underlying contextual conditions (e.g., soil data demand, funding source, human technical capacity, institutional environment, digital infrastructure) and SIS outcomes (e.g., data availability, business model and sustainability, data governance and privacy policies).

Workstream 2 (WS2) summarizes the state of the art of SIS technological options. The resulting report (Appendix 1) puts forth eight stages of SIS development which are typically present in successful SIS: user assessment, data collection, laboratory analysis, soil archiving, data organization, modeling and mapping, applying soil information, and data services and information provision.

Workstream 3 (WS3) investigates and characterizes the connections between various SIS enabling environment conditions and outcomes (WS1) and the stages of SIS development (WS2). The enabling environment criteria, the interview responses, and the SIS development stages were compared and analyzed to generate four archetypes representative of SIS development, summarized in the figure above. The conclusions and synthesis of this report will be used to develop a reproducible framework for guiding SIS investment plans to finalize this workstream.

Limitations to this work include small sample sizes in the number of countries reviewed and the number of interviewees. Potential bias in interviewee responses, and subjectivity in analytical framework development and analysis of interviews are further limitations that are common to qualitative data collection and analysis processes, which we aimed to mitigate through internal and external peer review.

Key Findings

Three primary synthesis insights were gleaned from our analysis in the context of previous related research.

1 Benchmarking SIS development efforts on existing soil information and users' decision-support needs

The first is that defining SIS intervention success is complex – there is no "gold standard" SIS – and should be evaluated by comparing the SIS's functions and information serving capability with the country's user-decision needs and user groups in the context of the enabling environment. Most, if not all, countries in Africa already hold some amount of legacy soil data, whether in hard copy materials or digitized, which could help SIS developers to benchmark the status of soil data and to assess which next steps are needed. Soil data development up to a specific stage – a set of high-quality maps, or single-time-point data on soil chemical and physical properties plus interpretation aids – can sufficiently enable some users to access and use soil information for decision-making.

2 Long-term buy-in and facilitation by a SIS champion

Second, in the analysis three enabling environment components were particularly informative for grouping countries into archetypes: the **initial funding source for the SIS**, **technical expertise and capacities**, and the **presence of a SIS champion or advocate**. Whether the SIS was funded by donors or the national government seemed to play a large role in the overall commitment and long-term investment of project partners. While donor funding is often critical for the initial development of soil data systems, sustainability of a SIS is also reliant on long-term (i.e. on the order of 10 years or more) commitments in coordination with internal organizations and/or national systems and on the early development of a plan for sustaining the SIS after the initial project is concluded. A SIS champion can greatly help to steward a SIS effort forward through funding and technical capacity shortfalls by liaising with stakeholders at various levels across the system, from farmers to external partners to national government.

3 Value attribution and clarity of purpose for soil data

Understanding the value of soil information for stakeholders is a critical step to setting directions for the SIS effort and to establishing a business case for the development of soil data. The value of soil data is not limited to individuals' and organizations' willingness to pay – a larger range of benefits of soil data should be considered. For example, use cases identified by interviewees in our study include support for agricultural extension workers, who can leverage SIS to improve farmer livelihoods which in turn supports economic development on local and regional scales. However, data development efforts are often not clearly matched to the specific decisions that users need to take. Stepwise and evidence-based linkages of soil data to such user decision processes will help SIS donors, implementers, and users build rational arguments for investing in specific aspects of soil data and information.

Our results, together with insights from prior research, highlight three suggestions for planners and implementers of SIS:

1. Comprehensively assess potential soil data users, use cases, and the **decisions that potential users are taking** that could be improved using soil information. This can be approached through identifying the country's position among the archetypes identified in our analysis, and through adapting established decision analysis approaches to understand the value of soil information for each group of stakeholders in the context of the enabling environment.
2. **Identify and centralise existing and legacy soil data** in the country, digitize where needed, and develop interpretive aids that enable users to benefit from these data in the relatively short term.
3. Identify and support a **SIS champion** who can progressively facilitate buy-in and cooperation among stakeholders at various levels, from farmers to district-level planners to NGOs to the national government.

RECOMMENDATIONS FOR SIS SUCCESS

1. Introduction

1.1 Background and goals

Many initiatives have been developed across Africa to produce, organize, and leverage soil information by developing soil information systems (SISs). These aim to make soil data available to users through an online portal, service, or website, and are often assisted by innovative digital soil mapping techniques. Data and information describing soil properties, nutrients, water dynamics, and other characteristics are mobilized to make more informed decisions about agriculture, commercial and industrial development, environmental management, and land use. Investments in data generation and infrastructure have become a staple component in ongoing agendas toward improving soil health, farmer livelihoods, and national development.[1]

There is not a one-size-fits-all technology or approach to SIS development across countries. When designing new technology-oriented initiatives, including SIS, a common misstep is to skip a comprehensive in-country stakeholder assessment, and to go straight to implementing solution-driven technical tools, apps, or digital platforms without a full understanding of user readiness to adopt and uptake the technology.[2, 3] Though ambitious and sophisticated technological solutions may be the right fit for many situations, *process and people capacity approaches are* also essential for the development of SIS initiatives that are supported and sustained in the long term. *Process and people capacity development* must be considered at among several types of stakeholders – for example, government planners, national scientists, district level planners, NGOs, extension organizations, farmers, and the general public. While it is accepted that capacity building is not a fast process and may take years, an underlying principle is that external resources are relied upon for a time-limited and not indefinite period.[4]

Process- and people-capacity perspectives occur at least three levels: individual (establishment of adequate skills, knowledge, competencies, and attitudes), organizational (establishment of efficient structures, processes and procedures), institutional level (establishment of adequate institutions, laws and regulations).[5] An equally important fourth level is the political will to apply pressure to those institutions, laws, and regulations.[6] Process design involves identifying all of the individual activities that are needed to fulfill the SIS objectives, deciding on the sequence in which these activities are to be performed, and who is going to do them, and identifying risks and contingencies. We posit that a framework assessing these levels at the start of a SIS intervention can help guide thinking and dialogue, and facilitate taking the right next steps, tailored to in-country context, to understand the users and use cases for soil data to lead to better SIS roadmap design options. Roadmap options tailored to a specific country's enabling environment may range, for example, from high to low tech system infrastructure, policy support for data accessibility, or increased capacity development.

1 McCampbell, M., Adewopo, J., Klerkx, L., & Leeuwis, C. (2023). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. The Journal of Agricultural Education and Extension, 29(1), 29–51. https://doi.org/10.1080/1389224X.2021.1984955

2 Steinke, J., van Etten, J., Müller, A., Ortiz-Crespo, B., van de Gevel, J., Silvestri, S., & Priebe, J. (2021). Tapping the full potential of the digital revolution for agricultural extension: an emerging innovation agenda. International Journal of Agricultural Sustainability, 19(5–6), 549–565. https://doi.org/10.1080/14735903.2020.1738754

3 McCampbell, M., Adewopo, J., Klerkx, L., & Leeuwis, C. (2023). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. The Journal of Agricultural Education and Extension, 29(1), 29–51. https://doi.org/10.1080/1389224X.2021.1984955

4 Crisp, B.R., Swerissen, H. and Duckett, S.J., 2000. Four approaches to capacity building in health: consequences for measurement and accountability. Health promotion international, 15(2), pp.99-107. https://doi.org/10.1093/heapro/15.2.99

5 United Nations Development Group (UNDG). Capacity Development: The United Nations Development Assistance Framework (UNDAF) Companion Framework. Accessed 5 January 2024 at https://unsdg.un.org/sites/default/files/UNDG-UNDAF-Companion-Pieces-8-Capacity-Development.pdf

6 Jonathan Crouch, personal correspondence 9 March 2024.

Although the value of SIS assets and technologies are well-recognized, there is room for improvement to 1) to be more responsive and adaptive to local users and use cases for soil information and 2) encourage greater intentionality and efficiency in the development of data assets. Constraints that limit the potential effectiveness of SIS interventions are many, including capacity gaps, data quality, governance, standards, data security and privacy, the national legal and policy environment, retaining human resources, and technical infrastructure and equipment.

A Process Toward Strengthening National Soil Information Services is a project supported by the Bill & Melinda Gates Foundation performing a comprehensive review of existing SIS and current technological approaches for soil information. The goal is to identify which SIS intervention approaches have worked in the past, which have been met with challenges, where the common stumbling blocks are, and what contextual factors in a country are key considerations in new or renewed SIS efforts. Insights from this review will contribute to the development of a replicable framework for approaching SIS intervention design. The aim of the framework is to guide dialogue, thinking and initial planning that can lead to more sustainable, fit-for-purpose soil information solutions and, ultimately, greater benefits to users of soil information.

The initial stage of this project comprised evidence-gathering and synthesis in two thematic workstreams (Figure 1). *Workstream 1*, led and implemented by CABI with contributions from a team of subcontractors at University of California, Davis, endeavored to identify the social factors, institutional arrangements, funding dynamics, and technical and infrastructural capacities that play a key role in the successful establishment of a SIS. *Workstream 2*, led and implemented by ISRIC – World Soil Information, identified and documented the methods, standards, and tools available for soil data and information development. ISRIC's resulting publication, ***Development Options for a Soil Information Workflow and System***, is referenced throughout this report (Appendix 1).

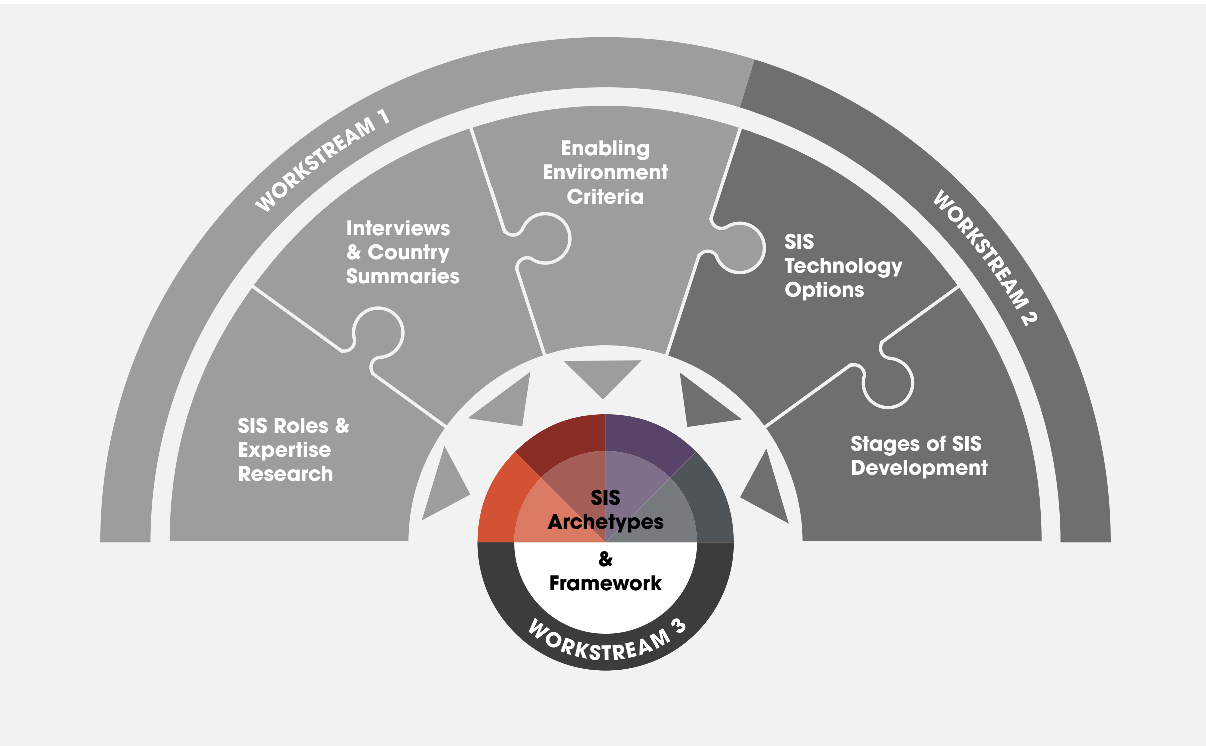


Figure 1: Relationships among components of Workstreams 1, 2, and 3.

This report contains a summary of work conducted by CABI and associates under Workstream 1 and Workstream 3. Desk research and consolidation of expert knowledge contributed to a list of ***SIS roles*** and required capacities. Key informant interviews were conducted with SIS developers in each of nine countries, and each country's ***SIS enabling environment*** was summarized in a brief case study. A systematic process was developed to identify the social, institutional, and financial ***enabling environment criteria***, and to connect these criteria with various SIS outcomes. The identification and application of these criteria to existing SIS cases allowed for the development of ***SIS archetypes*** which describe commonly co-occurring contextual factors and country-level conditions that lead to differential outcomes for SISs. Finally, in this report we extend and integrate these archetypes and insights with the technological considerations and key stages of SIS development from Workstream 2. Therefore this report serves as a summary of findings and insights from Workstream 1 and as a bridging document for Workstreams 1 and 2, which allows for the extension of integrated socio-technical insights about SIS development that will inform an improved SIS intervention framework and tailored country-specific roadmaps (Workstream 3; Figure 1).

1.2 Summaries of Workstream 1 and Workstream 2

The work conducted here and summarized in this report draws upon previous work completed under the ***Process Toward Strengthening National Soil Information Services*** project. In Workstream 1, collaborators from ISRIC – World Soil Information conducted a review of the literature on the history of soil information development. Additionally, collaborators from the University of California, Davis conducted an initial review of political-ecological considerations for soil data and SIS development. In Workstream 2, partners from ISRIC – World Soil Information developed a comprehensive soil information workflow (SIW) – a set of key components in development of a soil information system, along with detailed description and discussion of the methods, tools, and standards currently available.

1.2.1 Workstream 1: History of soil information development

Soil mapping, classification, and pedologic modeling are fundamental components of soil science, providing essential information for land management, environmental protection, and agricultural productivity.[7] The history of soil information systems can be traced back to ancient civilizations, where simple methods of soil classification were used to assess soil fertility and suitability for agriculture.[8] However, it was not until the late 19th and early 20th centuries that systematic efforts to map and classify soils began to emerge, driven by the need to address soil degradation and food security issues arising from rapid population growth and agricultural intensification.[9] Starting in the 1970s, these systematic data mapping and classification efforts began to be organized into soil information systems (SISs).[10]

The establishment of the U.S. Soil Survey in the early 20th century marked a significant milestone in the history of soil mapping and classification.[7] Led by pioneers such as Whitney[9]

7 Brevik, E. C., Calzolari, C., Miller, B. A., Pereira, P., Kabala, C., Baumgarten, A., & Jordán, A. (2016). Soil mapping, classification, and pedologic modeling: History and future directions. Geoderma, 264, 256-274

8 Smith, G. D. (1986). The Guy Smith interviews: rationale for concepts in soil taxonomy. In: Forbes, T.R. (Ed.), New York State College of Agriculture and Life Sciences. Cornell University, Ithaca, NY.

9 Whitney, M. (1909). Soils of the United States. U.S. Department of Agriculture, Bureau of Soils Bulletin 55. U.S. Government Printing Office, Washington, D.C.

10 Heuvelink, G. B. M., Brus, D. J., De Vries, F., Kempen, B., Knotters, M., Vasat, R., & Walvoort, D. J. J. (2010). Implications of digital soil mapping for soil information systems.

and Simonson[11], soil surveyors developed standardized methods for mapping soil types and delineating soil associations based on observable characteristics such as color, texture, and structure. These efforts laid the foundation for the development of comprehensive soil classification systems, culminating in the publication of the Soil Taxonomy and the Keys to Soil Taxonomy by the USDA Soil Survey.[12, 13]

The latter half of the 20th century witnessed significant advancements in remote sensing technologies, revolutionizing the field of soil mapping and classification.[7] Remote sensing techniques, such as aerial photography and satellite imagery, provided researchers with new tools for assessing soil properties over large spatial scales.[14] These developments paved the way for the emergence of digital soil mapping techniques, which integrate remote sensing data with geographic information systems (GIS) and statistical modeling approaches to produce high-resolution soil maps.[15] The adoption of digital soil mapping has led to improvements in soil classification accuracy and spatial resolution, enabling more informed decision-making in land management and resource conservation.[16]

In recent decades, there has been growing recognition of the importance of integrating pedologic models into soil information systems. Pedologic models, such as soil-landscape models and process-based models, simulate the formation and behavior of soils based on underlying biophysical processes.[17] By incorporating pedologic models into soil mapping and classification workflows, researchers can better understand the factors influencing soil variability and predict soil properties across diverse landscapes.[18] Furthermore, pedologic models facilitate the development of soil management strategies tailored to specific soil conditions, thereby enhancing agricultural productivity and environmental sustainability.[19]

Looking ahead, several challenges and opportunities lie ahead for soil information systems. One key challenge is the need to improve the accuracy and resolution of soil maps, particularly in regions with complex topography and heterogeneous soil properties.[20] Advances in sensor technologies, machine learning algorithms, and data assimilation techniques hold promise for addressing these challenges and expanding the applicability of digital soil mapping approaches.[16] Additionally, there is a growing need to enhance the interoperability and accessibility of soil information systems, enabling stakeholders to easily access and exchange soil data for various applications.[21, 22] By addressing these challenges and embracing emerging technologies, soil scientists can continue to advance our understanding of soil processes and support sustainable land management practices in a rapidly changing world.

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11 Simonson, R.W., 1952. Lessons from the first half century of Soil Survey: II. mapping of soils. Soil Sci. 74 (4), 323–330.

12 Soil Survey Staff. (1960). Soil Classification, A Comprehensive System, 7th Approximation. Soil Conservation Service, USDA, Washington, DC.

13 Soil Survey Staff. (2014). Keys to Soil Taxonomy. 12th ed. USDA-Natural Resources Conservation Service, Washington, D.C.

14 Seelan, S. K., Lagette, S., Casady, G. M., & Seielstad, G. A. (2003). Remote sensing applications for precision agriculture: a learning community approach. Remote Sensing of Environment, 88(1-2), 157-169.

15 McBratney, A. B., Mendonça-Santos, M. D. L., & Minasny, B. (2003). On digital soil mapping. Geoderma, 117(1-2), 3-52.

16 Hengl, T., Mendes de Jesus, J., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E.,Samuel-Rosa, A., Kempen, B., Leenars, J.G.B., Walsh, M.G., Ruiperez Gonzalez, M., 2014. SoilGrids 1 km – global soil information based in automated mapping. PLoS ONE 9, e105992. http://dx.doi.org/10.1371/journal.pone.0105992.

17 Wilding, L. P. (1994). Factors of soil formation: contributions to pedology. Factors of Soil Formation: A Fiftieth Anniversary Retrospective. SSSA Special Publication 33. Soil Science Society of America, Madison, WI.

18 Thompson, J. A., & Kolka, R. (2005). Soil carbon storage estimation in a forested watershed using quantitative soil-landscape modeling. Soil Science Society of America Journal, 69(4), 1086-1093.

19 Stafford, J. V. (2000). Implementing precision agriculture in the 21st century. Journal of Agricultural Engineering Research, 76(3), 267-275.

20 Hartemink, A.E., McBratney, A.B., 2008. A soil science renaissance. Geoderma 148,123–129. http://dx.doi.org/10.1016/j.geoderma.2008.10.006.

21 Bouma, J., 2010. Implications of the knowledge paradox for soil science. Adv. Agron. 106, 143–171.

22 Bouma, J., 2014. Soil science contributions towards Sustainable Development Goals and their implementation: linking soil functions with ecosystem services. J. Plant Nutr. Soil Sci. 177, 111–120.

1.2.2 Workstream 1: Global overview of soil information

Collaborators from the University of California, Davis gathered literature and background information on soil data development from across the international soil data community. As part of this effort, they summarized two global-scale soil information systems in detail as follows.

The Global Soil Information System (GLOSIS) was established as a federation of soil information systems with the aims of supporting soil data standards, providing infrastructure for a global soil data system, and enabling open data exchange. The World Soil Information Service (WoSIS) is an effort led by ISRIC to consolidate, harmonize, and share soil point data, and provide quality-assessed data for digital soil mapping and modeling. A further review of soil surveys on the African continent shows that many countries have developed soil surveys and datasets at increasingly higher spatial resolutions, with applications in agricultural extension, research, soil conservation efforts, and farm- and landscape-level soil management. While these efforts represent the increasing interest in soils and soil data worldwide, the need remains for platforms and approaches to developing soil information that include more holistic interpretations of the body of soil in a given location, and that consider the human, institutional, and societal considerations and dimensions of soils.

Emergent from this review were several themes that describe the social and institutional challenges for soil data development. These include:

- Data openness, sovereignty, and security
- Sustaining a SIS past the initial investment
- Lack of perspective on holistic and place-based soil wellbeing
- Institutional environments and coalitions
- Lack of multidisciplinary perspectives and information
- Lack of representation of local and indigenous knowledge

These emergent themes were used as one of the initial inputs for subsequent work by CABI to develop a further process of key informant interviews and analysis of specific criteria indicative of the enabling environment for SIS development in a range of country contexts. That work is detailed in the Approach and Methods section of this report. Appendix 8 contains a summary of the usage metrics for selected global and continental soil information products, and examples of their use cases and applications.

1.2.3 Workstream 2: Soil data technologies and the soil information workflow (SIW)

In their report titled ***Development Options for a Soil Information Workflow and System***, ISRIC – World Soil Information developed a detailed review of methods, approaches, and tools for developing soil information. One of the goals of their work was to aid the design of a SIS for soil data practitioners, SIS users, and SIS producers. The report provides an extensive and thorough overview of the decision points, tools, resources, and results of successful SIS definition, alongside clarifying definitions of important concepts. The report is structured around eight components of successful SIS development, which together are referred to as the Soil Information Workflow (SIW) (Figure 2).

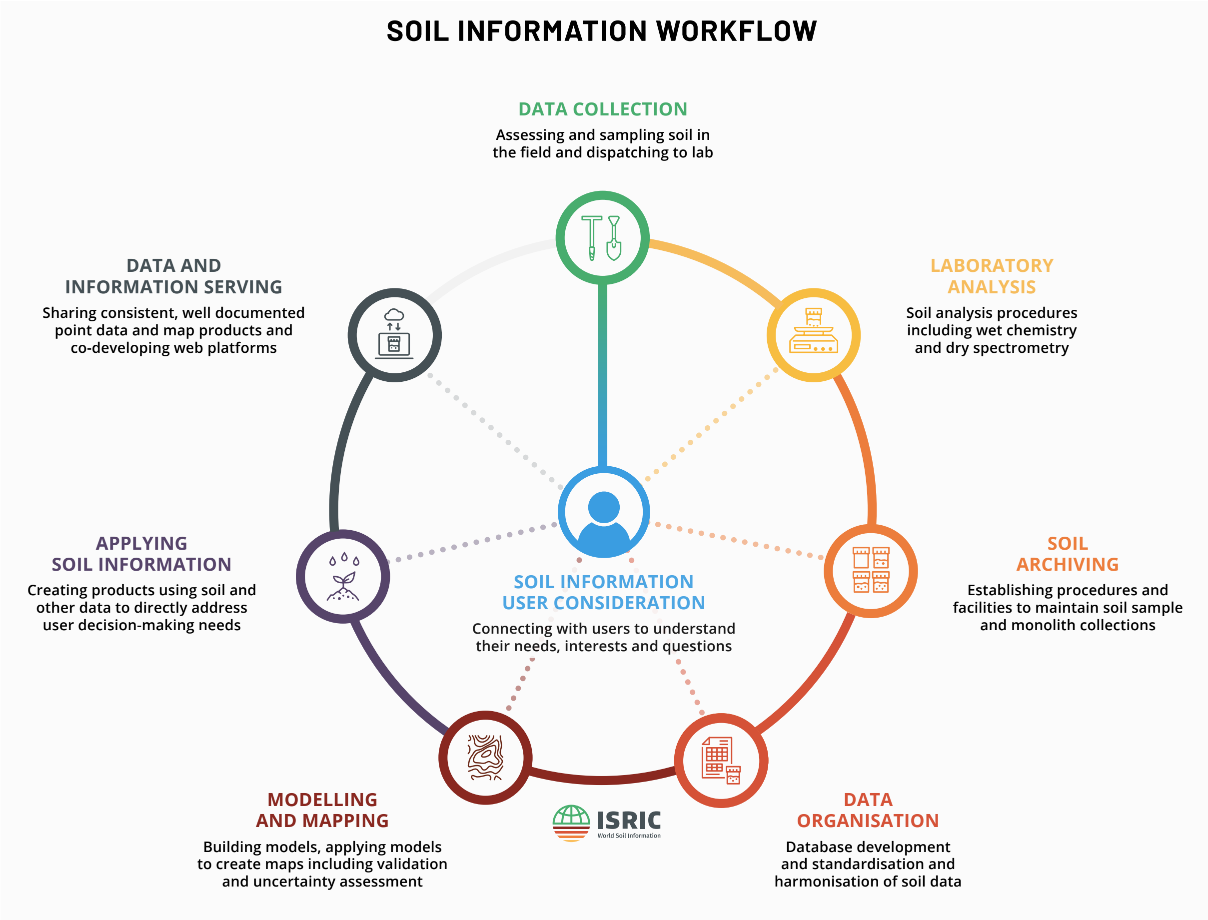

Figure 2: Soil Information workflow components. Implementation often starts in the center and proceeds clockwise; however, there is no required sequence of the components and they can be conducted in any order.

User consideration is the central component in the workflow, and is often conducted before other components and then repeated at intervals. User consideration consists of six sub-steps outlined below. In two appendices of the report, ISRIC included sample user assessment tools that can be adapted for use in a reproducible SIS framework (*Workstream 3*) and which can generate a tailored roadmap (*Workstream 4*).[23] It is important that all stages in the process refer back to User consideration, including users and their needs and use cases, as it is often difficult for users to state their full, comprehensive vision for the SIS at the start. Repeated assessments of user consideration ensure that, as the system or project develops, users can continually evaluate it against their needs.

User consideration is central to a successful SIS, and includes the following steps:

1. Investigate potential success and sustainability of the SIS; (e.g., goals, funding commitment, budget, human capacity, technical infrastructure and equipment, legal and policy setting)
2. Define the use cases; (e.g., fertility management)
3. Identify potential users; (e.g., policy makers in the Ministry of Agriculture)
4. Collect users' needs; (e.g., surveys, interviews, workshops, focus group discussions)
5. Define SIS requirements to address the needs; (e.g., SIS metrics, functionality of SIS, data formats, user interface)
6. SIS adoption and feedback by end-users (e.g., sustainability considerations of the SIS, capacity building of end user)

23 The user assessment and workshop agenda for a tailored roadmap were used in the Data for land decisions: New land, soil and crop (LSC) information services in East Africa project. More information at: https://lsc-hubs.org

Although there is a logical flow to the components in the soil information workflow, with some components building on the achievement of others, the components are not required to be conducted in a specific sequence. After user consideration, often the next component addressed in the workflow is **data collection**, which includes deciding on the new data needed and best methods to collect it, soil sampling protocols, and metadata collection. Some best practices mentioned in the report are to use digital data collection apps or tools rather than pencil and paper, as this improves data quality and standardization.

The third component in the SIW is **laboratory analysis** (e.g., wet chemistry, spectroscopy, measurements of water holding capacity, engineering properties) of soil samples collected during the previous step's data collection field campaign. This section summarizes lab methods, quality assurance and control methods, calibration, quantification of laboratory measurement errors and variability, and standard operating procedures that deliver consistent and comparable results of sufficient or high quality within and between labs in time and on a wide range of soil properties. Like for the data collection component, this section of the report concludes with a repository of relevant tools for laboratory soil data organization and analysis.

The fourth component is **soil archiving**, which is the organized storage of raw soil specimens, lab samples, and soil documents relevant to the data in the SIS. Archiving physical soil material allows comparative analysis on laboratory measurement method and calibration, land management impact, and variation in time and space. This section describes methods of archiving and digitization, requirements of storage facilities, organizations serving as examples of libraries and reference institutions, and tools for soil preservation.[24]

The fifth component describes **data organization**; this includes concepts of database design, data security, data integrity, standardization, metadata, and various standards and tools available to facilitate data organization. The FAIR (findable, accessible, interoperable, and re-usable) principles are described in this section, and repositories are described and recommended.

The sixth component is **modeling and mapping**, which refers to the extrapolation of GIS point data and polygons represented over the landscape. This delineation of homogeneous polygons (in terms of morphology and composition) can be done through geostatistical modeling and/or supported by satellite-based remote sensing or aerial photography. The modeling refers to inferring the spatial distribution of soil classes and properties from their position in the landscape as well as effects of other soil forming factors, such as parent material, climate, vegetation, fauna (including human activities) and (geological) time. Concepts of uncertainty quantification, accuracy, validation, resolution, scale, and machine learning are described, followed by an extensive list of tools, workflows, and repositories.

The seventh component is **applying soil information**. This section introduces tools, challenges, and examples of soil information applications that inform decision-making processes related to policy development, planning, and monitoring of the environment. Examples are decision support systems, apps, scenario models, dashboards, handbooks, planning, and recommendations. The section concludes with a list of challenges which often block this step, including lack of reliable, harmonized, current data, integration of soil data with other relevant data, lack of human resources, and cyber-attacks.

The last component discussed in the workflow is **data and information serving**, which is publishing or making soil data available to the organization, partners, and the general public. It introduces

24 The topic of soil archiving was not frequently raised in the interviews informing this analysis, as physical soil archiving is not often one of the initial steps in the development of new soil information systems in low-resource settings. Therefore, although soil archiving is one of the eight key stages in the soil information workflow, it is not included in the analysis for this work.

various standards and tools available to facilitate data and information sharing, with more detailed technical resources for developers throughout the section. It also includes a discussion of APIs, ontologies, spatial data community data conventions, catalog tools, relevant software for hosting data repositories, map and dashboard software, and soil data licenses.

The eight components identified in ISRIC's report serve as a blueprint for technological aspects of SIS design, but they are not set in stone. A user assessment, like the ones in the report's appendices, will determine the SIS users and use cases, which then allow for a more tailored SIS roadmap. Based on the user assessment, SIS project teams can iterate on the Soil Information Workflow, change the sequence of the steps, or determine how far along the workflow stages a SIS will aim to get to during a given phase of funding.

1.3 Building on prior work: objectives for this project and report

The Workstream 1 and Workstream 2 reports summarized above provided an important evidence base for the further specification of key aspects of the ***enabling environment*** for SIS development that influence the progress and sustainability of SISs. In this report, we describe our work to build on these contributions by addressing the following sequence of objectives:

1. Gather evidence addressing the social, institutional, and political considerations influencing extant SISs in a range of country contexts
2. Consolidate and standardize evidence to define a comprehensive list of criteria, then use this to characterize country contexts and their SISs
3. Combining the list of criteria and the technological stages identified in ISRIC's SIW, develop an analytical frame that allows for the systematic comparison of SIS across countries
4. Identify SIS archetypes: groups of countries defined by their shared criteria and characteristics of their resulting SISs
5. Synthesize insights from across the SIS archetypes and interview data that can inform an improved framework for future SIS intervention design that incorporates both socio-institutional and technological considerations

2 Approach and methods

Evidence from existing digital SIS across a range of geographies was gathered through semi-structured interviews with SIS developers in a representative set of nine countries.

Evidence from interviews with SIS developers across nine countries was then processed and standardized into an analytical framework for generating insights about the ***enabling environment*** for the progress of SIS development. This section describes the approaches and methods used for the gathering of data via interviews, the development of the analytical framework, and the processing and analysis of interview data. These methodological stages are summarized in Figure 3.

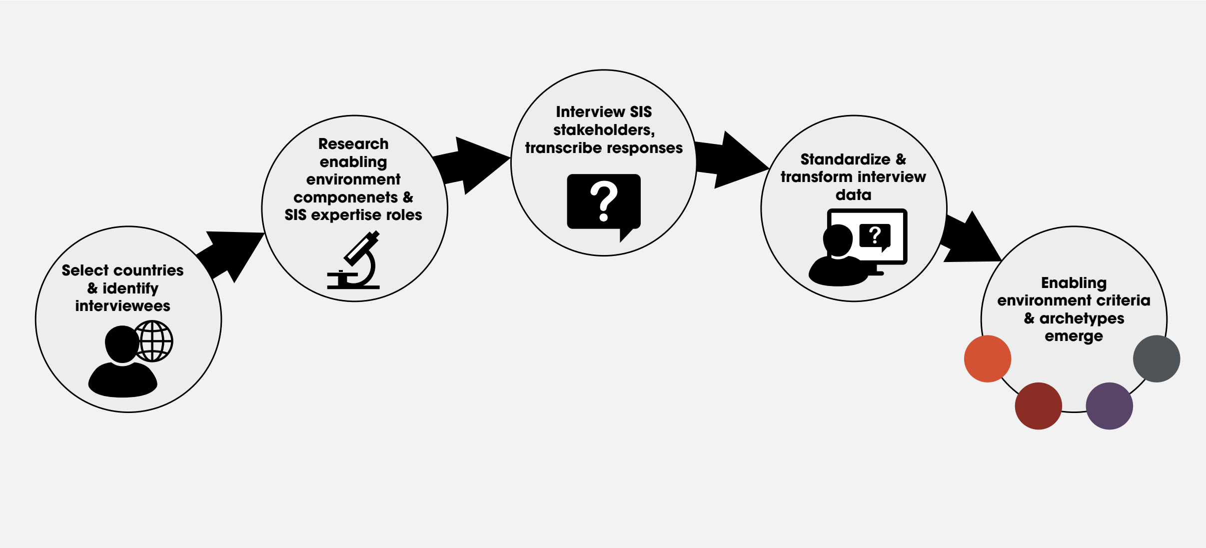

Figure 3: Stages of the methodological approach used in this work.

2.1 Country selection and identification of SIS representatives for interviews

Nine countries were selected for inclusion in our review. Countries were selected on the basis of connections with the project team's professional networks, with further criteria used to ensure a range of representative SIS conditions, including:

- SIS data is accessible under various conditions – open access, paid, user-registered
- Federated vs centralised architecture
- User groups
- Motivations and/or aims of the SIS effort
- SIS age and project continuity
- Various business models
- Various sources of initial funding
- Proximity or integration with other soils and data activities
- Alliance for a Green Revolution in Africa (AGRA) countries and/or previous foundation SIS investments

The countries and SIS selected for inclusion in our review were:

- Australia: Australian National Soil Information System (ANSIS)[25]
- Ethiopia: National Soil Information System of Ethiopia (NSIS)[26]
- Ghana: Ghana Soil Information Hub[27]
- Lesotho: Lesotho Soil Information System (LeSIS)[28]
- New Zealand: National Soil Data Repository (NSDR)[29]
- Rwanda: Rwanda Soil Information Service (RwaSIS)[30]
- Tanzania: Tanzania Soil Information Service (TanSIS)[31]
- Uganda: Uganda Soil Information System (USIS)[32]
- United States: Web Soil Survey[33] and Soil Data Access[34]

To aid the identification and classification of interviewees, we developed a generalized list of ***SIS roles*** that describes the types of actors and individuals that are typically involved in the development of a SIS. Examples of SIS roles are decision makers, who guide the high-level characteristics and positioning of the SIS project, and developers, who refine and implement the vision for the SIS that is set out by decision-makers. Additional SIS roles are listed and defined in Appendix 2. Between one and three individuals were identified who were involved with each of the above SISs. Individuals were identified through compiling first- and second-degree contacts from within the professional networks of project team members in CABI and ISRIC. The most common SIS role held by potential interviewees was SIS developer. These individuals were contacted by email with an invitation to participate in a 90-minute informational interview conducted virtually using Zoom or Microsoft Teams.

2.2 Data collection: Informational interviews with SIS stakeholders in nine countries

Starting from the list of themes that emerged in the global overview of soil data and information previously conducted in Workstream 1, the CABI project team and partners refined an initial focal list of social, institutional, and financial considerations for SISs that may be of potential importance for this review. This list served as the basis for the iterative development of a set of information categories – here termed ***enabling environment components*** – to be collected about each of the nine selected countries that would allow us to systematically compare their enabling environments and their resultant SISs.

The iteration of these components was conducted primarily through two approaches: 1) an initial stage of desk research to gather information that is freely available online characterizing the above nine SIS, and 2) informal conversations with soil data and development experts within the CABI and ISRIC professional networks. The final set of enabling environment components identified through this iterative process was then used to develop a semi-structured interview guide to be used for further information-gathering for each country. The final set of enabling environment components which were assessed for each country included:

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25 ANSIS: https://ansis.net/
26 Ethiopia NSIS: https://nsis.moa.gov.et/
27 Ghana Soil Information Hub: https://www.csirsoilinfo.org/
28 LeSIS: https://lesis.gov.ls/
29 National Soil Data Repository: https://viewer-nsdr.landcareresearch.co.nz/
30 RwaSIS: https://osf.io/y9zut/
31 TanSIS: https://osf.io/4ngau/
32 USIS: https://lwasajames.wixsite.com/usis
33 Web Soil Survey: https://websoilsurvey.nrcs.usda.gov/app/
34 Soil Data Access: https://sdmdataaccess.nrcs.usda.gov/

1. The institutional environment around soils and soil data; past, current, and future commitment of institutional partners
2. Initial funding for the SIS
3. The business case for the SIS; current and future financial model and sustainability
4. Users and beneficiaries: soil data users, user needs, and primary use cases
5. Data and information availability and accessibility within the SIS
6. Data governance, policies, and licensing
7. Technical expertise and capacities for building and maintaining the SIS
8. Digital and computing infrastructure

Across these components we developed a set of 37 questions to be posed during interviews. Based on our knowledge of each SIS obtained through initial desk research, this full set of questions was reduced to only those relevant for each country and interviewee. For example, for a SIS with no web interface, questions about how usage and download metrics are tracked were removed. The interview guide for SIS developers – the most common role among our interviewees – included a subset of 22 questions draw from the full set of 37 questions, which can be found in Appendix 3.

Individuals who responded to the email invitation for an interview were scheduled within the subsequent 1-2 weeks following the initial contact. A total of 13 interviews were conducted across the 9 countries. All interviews were co-conducted in English by a team of two or three project team members from among CABI core staff, CABI associates, and ISRIC partner team members. All interviews were conducted between late September and late November 2023. Verbal permission was obtained from each interviewee for the audio recording of the interview, on the condition that the recording would be used exclusively by the project team for the extraction of comprehensive information from the conversation. Interviews were then manually transcribed in verbatim from the audio into text. Audio files were destroyed after the completion of transcriptions.

2.3 Data processing and analytical framework development

As expected under a semi-structured interview approach, data gathered across interviewees ranged from succinct and targeted to verbose and expansive. Often an interviewee would answer one question in the course of responding to another; or make a statement late in the interview that related to a question posed early in the interview. With the goal of understanding patterns, similarities, and differences in SIS across countries, the next step was to transform the interview data into a form that could allow for a cross-country comparison and identification of patterns, similarities, and differences that could enable the formation of SIS archetypes. To achieve this, we used an inductive qualitative content analysis (QCA) procedure adapted from established methods in the social sciences literature.[35]

The first step in QCA is to unitize the text of the interview transcript. The unit of analysis refers to the basic unit of text to be classified during content analysis. QCA typically uses individual themes as the unit for analysis, rather than a linguistic unit such as a word, sentence or paragraph. In our data, interviewee's expression of a theme might be found in a single word, a sentence, or an entire paragraph of the interview transcript. Thus the classification of text from the interview transcript may be conducted with text units of any size, so long as the text represents a single theme or issue of relevance to the research.

35 E.g.: Erlingsson, C., Brysiewicz, P., 2017. A hands-on guide to doing content analysis. Afr. J. Emerg. Med. 7, 93–99. https://doi.org/10.1016/j.afjem.2017.08.001

After an initial familiarization reading of an entire interview transcript, the analyst re-read the transcript and identified units of text that refer to one of the eight enabling environment components listed above. These units of text were copy-pasted into a working spreadsheet organized by EE components, so that the correspondence between the interviewee's remarks and the EE components could be clearly identified.

Then, within the text classified into each EE component, the analyst observed and synthesized sub-themes, termed here as ***enabling environment (EE) criteria***, that were raised by interviewees (Figure 4). For example, within the component *digital and computing infrastructure*, we found that interviewees often made distinctions between the currently available IT infrastructure, and what would be further needed in order to expand or enhance the SIS from its current state. In response to this observation across interviews, we defined these as two separate EE criteria within the *digital and computing infrastructure* component.

Technical expertise and capacities within the country are critical factors in development project success. In development of EE criteria, ISRIC's stages of the soil information development workflow were used to identify key technical roles and expertise areas that are important for SIS development. The mapping of these technical roles and expertise areas onto the stages of soil information development is included in Appendix 4.

The above procedure was repeated until the set of EE criteria had reached a point of saturation – no new EE criteria were emerging from new interview data. In this analysis, this point of saturation was reached within 6 interviews. At this point the full set of EE criteria were examined for redundancies and gaps, and refined into a final set of 26 criteria. Each criterion in this final set represents a specific and non-overlapping unit of meaning in the context of SIS development that emerged from interviews conducted in the nine selected countries.

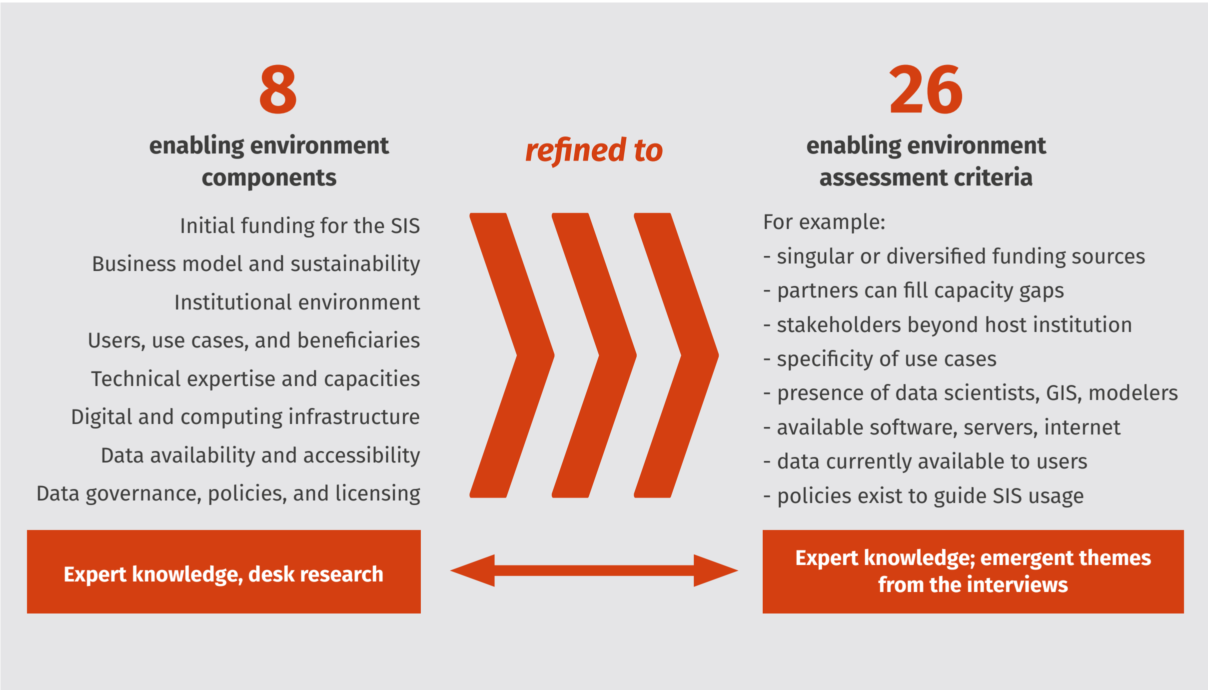

Figure 4: Enabling environment components were refined into a larger set of criteria through an iterative process of inductive theme emergence from interviews and consultation with experts within and adjacent to the project team.

Enabling environment criteria were classified as either **conditions** or **outcomes**. Conditions are characteristics of the social, institutional, or funding context *prior to or during the active phases of the SIS development effort*. Outcomes are the characteristics of the SIS itself that have *resulted from the particular mix of conditions in the given country at the time of the SIS development effort*. Especially in SIS that currently exist or are being actively developed, the outcomes themselves may become part of the enabling environment conditions that influence further investment or activities. For example, a SIS developed up to a particular stage can serve as a critical source of evidence for national government or partners to argue for further investment in soil data in a country. Therefore both the conditions influencing the SIS effort and the outcomes characteristic of the resulting SIS are included in the definition of the enabling environment in this work. The enabling environment criteria used in our analysis are shown in Table 1.

Table 1: Enabling environment components and criteria developed inductively through interviews and then applied to all interview data, as described above and illustrated in Figure 4. Criteria are listed by their classification as condition or outcome. Criteria are also shown in Appendix 6.

Enabling environment component	Enabling environment criterion
Condition	
Business model and sustainability	Capacities lacking internally are filled by external partners, trainings, or by hiring private sector contractors
Digital and computing infrastructure	Internal availability of IT infrastructure and equipment for current SIS needs: e.g., computers, software, servers, reliable internet connectivity
	Internal availability of IT infrastructure and equipment to expand and grow the SIS from its current state
Initial funding for the SIS	Funding source for initial SIS effort
Institutional environment	Presence of a SIS/soil data champion
	Clarity about who the current institutional host of the SIS is
Technical expertise and capacities	Capacities existing internally for User consideration
	Capacities existing internally for Data collection
	Capacities existing internally for Laboratory analysis
	Capacities existing internally for Data organization
	Capacities existing internally for Modeling and mapping
	Capacities existing internally for Applying soil information
	Capacities existing internally for Data and information serving
	Internal availability of scientific physical & material resources: laboratories, equipment, supplies
	Capacity for local creation and retention of expertise needed to sustain a SIS
Users, use cases, and beneficiaries	Formal user needs assessment was completed
	Use cases identified that motivate(d) the SIS
	User groups of the SIS identified - current and/or target
Outcome	

(*Table continued on next page*)

Enabling environment component	Enabling environment criterion
Business model and sustainability	Continuity of the SIS / soil data: presence of, e.g., legacy soil data and/or other existing projects in soils or agronomy domains indicating history and continued interest
	Stable funding source identified for SIS operation and maintenance
	Funding source identified for enhancements & additions
Institutional environment	Evidence of institutional partners of the SIS outside the host institution
Users, use cases, and beneficiaries	Evidence that the SIS is currently used to meet needs of any user groups or use cases
Data availability and accessibility	Data currently accessible to users
	Open-access types and formats of data
	Stage of ISRIC's SIW reached
Data governance, policies, and licensing	Policies or practices are in place to guide SIS metadata, data access, privacy, and use

After the establishment of this analytical framework, based on EE components and criteria, we then re-applied the full set of EE criteria to the entire corpus of interview text data, including those interviews which were used in the EE criteria development process. For each country, we mapped each text unit expression by the interviewee into the 26 enabling environment criteria (Table 1). Following the procedures outlined in Erlingsson and Brysiewicz[35], we then synthesized the compiled text units for each enabling environment criterion (Table 2, column 2) into a concise statement of the status of the criterion for that country (Table 2, column 4).

Table 2: Generalized analytical framework developed for extracting standardized information from interview transcripts for each country. For each row in the table, the analytical procedure followed the steps as described from left to right. The below exercise was repeated for each of the nine selected countries.

Enabling environment criterion	Country A: Relevant statements from interviewees	Country A: Synthesis of relevant statements	Country A: Concise statement of criterion
Criterion 1	Statements from interviewees addressing criterion 1	Synthesis of interviewee statements about criterion 1	Concise statement of criterion 1 response
Criterion 2	Statements from interviewees addressing criterion 2	Synthesis of interviewee statements about criterion 2	Concise statement of criterion 2 response
Criterion 3	Statements from interviewees addressing criterion 3	Synthesis of interviewee statements about criterion 3	Concise statement of criterion 3 response
[Criteria 4-25]	[...]	[...]	[...]
Criterion 26	Statements from interviewees addressing criterion 26	Synthesis of interviewee statements about criterion 26	Concise statement of criterion 26 response

This mapping of text units from interviews onto the 26 enabling environment criteria was repeated for each of the nine countries. This process yielded a table of concise criterion statements for each country, which could then be compared to the other countries (Table 3).

Table 3: Generalized framework for comparison of enabling environment criteria across countries. For each of the nine countries A through I, Column 4 from Table 2 above was appended here to Table 3. This allowed for the by-criterion comparison of enabling environments across countries.

Enabling environment criterion	Country A: Concise statement of criterion	Country B: Concise statement of criterion	[Countries C - H]	Country I: Concise statement of criterion
Criterion 1	Criterion 1 : country A	Criterion 1 : country B	[...]	Criterion 1 : country I
Criterion 2	Criterion 2 : country A	Criterion 2 : country B	[...]	Criterion 2 : country I
Criterion 3	Criterion 3 : country A	Criterion 3 : country B	[...]	Criterion 3 : country I
[Criteria 4-25]	[...]	[...]	[...]	[...]
Criterion 26	Criterion 26 : country A	Criterion 26 : country B	[...]	Criterion 26 : country I

2.4 Development of SIS archetypes

The resulting table contained a matrix with 9 countries in columns and 26 EE criteria in rows. Further examination of this matrix and sorting of the data were used to recognize patterns across criteria and countries that led to the identification of archetypes. Two types of patterns emerged describing enabling environments in the nine countries. Working row-wise in the table (represented here by Table 3 above), the first pattern to emerge was criteria that frequently co-occur: for example, criterion 1 usually had a specific value when criterion 2 had a specific value. The second pattern was found in column-wise similarities and differences in the overall criteria profiles between countries: for example, country A has many shared criteria values with country B, and countries A and B share few criteria with country H.

These observations of patterns of co-occurring criteria were used to group countries by similarities in their enabling environment criteria (Appendix 6). Each of these groups represents a ***SIS archetype***: a typical profile of enabling environment criteria which is descriptive of the co-occurrence of SIS conditions and SIS outcomes. To formulate archetypes, we identified the range of values across the nine countries for each of the 26 archetypes represented by a row in Table 3. For example, for the criterion *Funding source for initial SIS effort*, three distinct values existed among the countries: *donor funding*, *government funding*, or a mix of *donor and government funding*. Thus, for this criterion, countries fell into three groups.

This process was repeated for each of the 26 criteria. Some EE criteria had more groups than others – for example, *current institutional host of the SIS* had the same value across all countries, while *use cases that motivate(d) the SIS* had eight unique values across the nine countries. In the case of these EE criteria with many unique values, we took the further step of subjectively grouping values by their similarities. For example, *use cases that motivate(d) the SIS* contained many of the same themes – fertilizer recommendations, agricultural advisory, land use planning, soil acidity management – in differing combinations by country. We observed that use cases more directly associated with farmers' actions – fertilizer recommendations, soil nutrient management, agricultural advisory services – occurred together in several countries, while these use cases rarely co-occurred with more policy-oriented use cases such as farm-level sustainability credentials or spatial land use planning. These observations allowed us to define a range of use cases aggregated into a smaller set of values across the nine countries.

With the ranges and grouped values identified for all 26 criteria, we then sorted countries by the number and selection of criteria values they shared: countries with similar profiles of EE criteria were grouped together to form an archetype, and this was repeated until all countries had been sorted into a group on the basis of the similarities in EE criteria. Across the nine countries, using this process we identified four SIS archetypes that are indicative of enabling environment conditions. These four SIS archetypes are further described in the Results section.

2.5 Integration of SIS archetypes with soil information workflow components

Drawing on the SIS enabling environment criteria classified as outcomes, the final stage of analysis and review was to identify the ***soil information workflow (SIW) components*** that each SIS has achieved. The criteria descriptive of the current circumstances and characteristics of each SIS were used to link each SIS archetype to the components of ISRIC's SIW. For example, a SIS that currently exists only as a collection of unprocessed data posted online includes the *data organization* component in the SIW, but does not include the *modeling and mapping* component. This mapping of SISs onto the SIW components based on their technological components enabled us to relate the social, institutional, and financial enabling environment conditions with the technological outcomes for each given SIS.

2.6 Limitations in approach and methods

Several limitations are common to the qualitative assessment of interview data and to the inductive approaches we used to develop the analytical framework. The following limitations should be noted and considered when reviewing the results and insights generated from this work.

2.6.1 Small sample sizes: countries and interviewees

Our project scope and timeline translated into constraints in sample size, in terms of both the number of countries and the numbers of interviewees per country. In general, small sample sizes create the possibility that the data are not fully representative of the range of SIS scenarios and realities that exist, and that the individuals we interviewed are not able to fully or accurately represent the perspectives of the wider set of individuals that worked with the given SIS. It is likely, therefore, that our information gained through interviews and desk research is incomplete. While we targeted the selection of countries using the criteria listed above, we also used the project team's professional networks to facilitate contacts with in-country SIS developers. Anticipating the potential limitations introduced by these approaches, the selection of countries was conducted with attention to ensuring that a range of geographies are represented in our set. Additionally, special focus was placed on identifying enabling environment components that are relevant to the context of developing SISs in African countries. Individuals invited for interviews in each country were prioritized based on our prior information about their role in the SIS and how likely they were to be knowledgeable of a large range of the enabling environment components driving our inquiry. While these efforts do not fully address the potential issues created by small sample sizes, the selection of countries and individuals around the goals of this work will nonetheless generate useful insights and analytical frameworks for those with similar goals in future SIS development.

2.6.2 Potential sources of bias in interviewee responses

Interviewees were selected based on our knowledge of their roles in their respective SIS, and on their proximity to the CABI and ISRIC project teams in a larger professional network of soil data experts. It is important to acknowledge that, while strong and extensive, the CABI and ISRIC professional networks may not include all relevant SIS stakeholders in the countries selected for this work; there may be individuals in these countries who are more knowledgeable of the enabling environment components who we did not access for this review. Individuals in the CABI and ISRIC networks may be more (or less) likely to report positively (or negatively) about various aspects of their SIS and country contexts, based on their prior experiences of interacting with CABI and ISRIC. Individuals representing a specific SIS may also be influenced by other individuals in their country or SIS project to report positively (or negatively) about aspects of their SIS.

To mitigate the effects of these limitations, questions in the interview guide were developed with specific phrasing to attempt to elicit, to the extent possible, fact-based responses from interviewees, and to avoid questions that ask the interviewee to speculate or to offer their personal opinion or perspective. We also provided assurance that the transcript from the interview would be kept private within the project team, and that information from interviewees would be reported in aggregate, without linkage to the interviewee nor to their country. High-level summaries of the current SIS in each of the nine countries is available in Appendix 5.

2.6.3 Subjectivity in analytical framework development and analysis of interviews

Nearly all qualitative analyses involve at least one step of analysis or interpretation that is conducted by an analyst subjectively applying meaning to a piece of data, or making a decision about how data are organized. In many cases, qualitative research done in teams includes the repetition of analysis of the same data by multiple analysts, which can reveal differences in how individual analysts interpret a piece of data and allow for corrections in erroneous or incomplete interpretation. In this work, a single analyst was responsible for the development of the interview guide and for the analysis and interpretation of data from interviews. While the analyst holds expertise relevant to several areas of this work, including soil science, spatial data science, social science, qualitative data analysis methods, and agricultural development in Africa, the possibility remains that the insights generated in this work are subject to the analyst's own perspectives and blind spots. This potential limitation was addressed through three strategies. First, under established best practices for qualitative research, the analyst continually reflected on their own potential biases that may be introduced into the data handling and analysis at each stage.[36,37] Second, the analyst comprehensively documented their development of processes for organizing and analyzing the data. Third, this documentation and the intermediate draft versions of all outputs, including the analysis framework and resulting insights, were shared at intervals with the rest of the project team for feedback and revision.

36 Creswell, J.W. and Poth, C.N., 2016. ***Qualitative inquiry and research design: Choosing among five approaches***. Sage publications.

37 May, T. and Perry, B., 2014. ***Reflexivity and the practice of qualitative research. The SAGE handbook of qualitative data analysis***, 109, pp.109-122.

3. Results: Four SIS archetypes

Enabling environment conditions and outcomes were assessed for each country. Similarities and differences between countries, and the co-occurrence of specific criteria across countries, demonstrated that there are four broad SIS archetypes across the nine countries in our analysis.

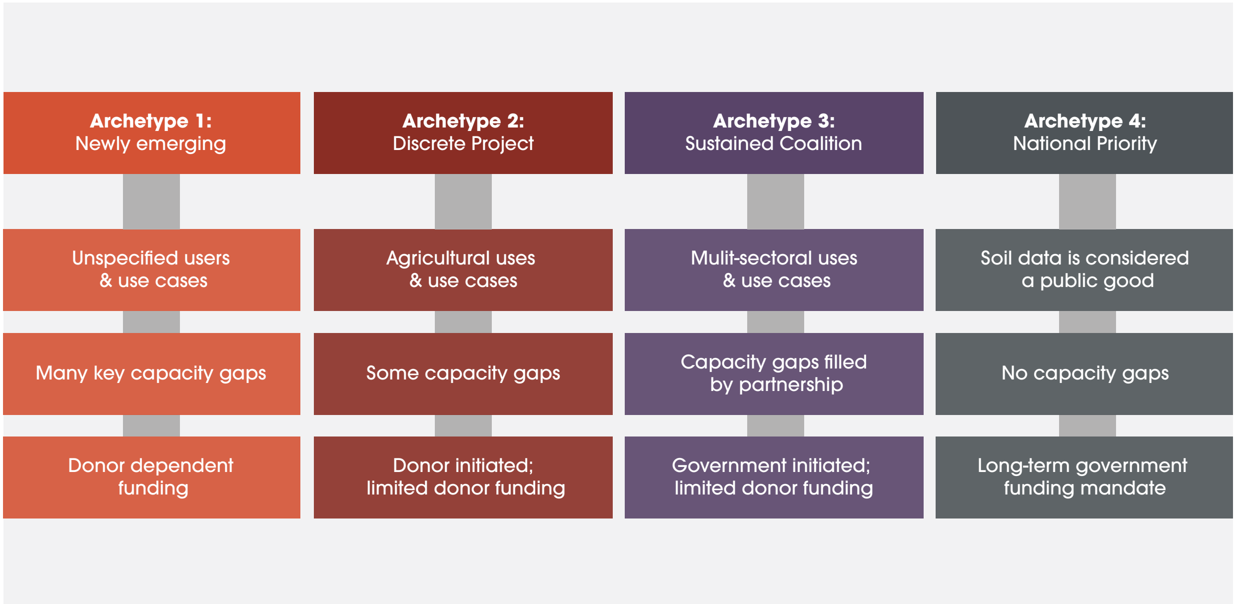

Figure 5: Four archetypes of SIS development emergent from analysis of existing SISs in nine countries.

Figure 5 shows a high-level overview of the four emergent archetypes of SIS development. In Archetype 1, underspecified users and use cases, large gaps in technical expertise and capacities, and a continued reliance on donor funding indicate that interest in a SIS is newly emerging. Countries in Archetype 2 have more clear specifications of users and a greater level of key capacities, and pursue the development of a SIS as a discrete, time-bounded project without specific plans or funding for a long-term effort. After the project period has ended, the minimal maintenance of, for example, hosting data and static maps online is supported by the national government. Archetype 3 countries overcome capacity gaps by marshaling a community of internal and external partners, who form a sustained coalition of institutions that supports the long-term development and evolution of the SIS. In Archetype 4 countries, the maintenance of long-term soil data sets is part of the core function of the government and is approached as a national priority, enabled to a great degree by the larger resource and capacity base that these countries enjoy.

In the following sections, each archetype is briefly described in narrative, supplemented with three sets of supporting characteristics: 1) list of enabling environment conditions, 2) list of enabling environment outcomes, and 3) linkage of the resulting SIS to the components of the SIW. The full set of 26 criteria underlying this analysis is available in Appendix 6.

3.1 Archetype 1: SIS is newly emerging

The presence and maturity of institutions and economic sectors that depend on soil for their business or other objectives often drive soil data demand. However, in countries where awareness of the utility and benefits of soil data are only now emerging, the capacities to meet this demand may still be lacking. Archetype 1 is defined by shortages in several important criteria in the SIS enabling environment (e.g., funding, technical capacities, lack of user assessment, and a lack of a SIS champion) that would need to be addressed to develop a SIS that matches needs of users and is sustainable. For these countries in our analysis, the initial ambitions for a new SIS include the creation of a nationally representative data set, data storage and serving capabilities, and derivative information products. These ambitions exceeded the limitations in technical and human capacities, and led the SIS effort to become stalled before many of the SIW components could be achieved. This situation leads to longer-term challenges for the SIS in advancing beyond a simple repository of raw or digital soil data and may require continued investment from external partners not only in the SIS itself, but in building technical capacities and supporting employment opportunities for capable SIS developers and soil data specialists.

3.1.1 Enabling environment criteria in Archetype 1: conditions

- **Funding source for initial SIS effort**: Initial primary funding is provided by an external donor organization, with limited national government funding or in-kind support. Funding for the initial SIS effort may be spent out before an operational SIS is achieved, requiring further investment in the future.
- **User groups of the SIS**: User groups are fully understood during project design and planning. Often assumptions are made about who will find value in the SIS, and decisions that potential users need to take that rely on soil data are not well understood.
- **Use cases that motivate(d) the SIS**: Similar to user groups, the use cases for soil data are often not well specified, but are generally assumed to relate to agricultural sector policy and agricultural production; for example, improved fertilizer recommendations, soil nutrient management, or soil erosion management.
- **SIS or soil data champion**: Aside from the in-country owner or host of the SIS project, there are few or no institutions functioning as a SIS champion that have an active motivation to support soil information development for their own agendas or stakeholders. However, individual SIS champions may emerge: people who have both an inherent interest in soils, and the connections and capability to liaise among stakeholders at several levels to encourage momentum for the SIS.
- **Technical expertise and capacities**: Capacities may exist for field soil survey, data collection, and laboratory activities, but gaps often exist in areas critical for quality control and consistency in sample handling and analysis. The skills to organize, manage, and analyze digital soil data are limited within in-country institutions, with notable gaps in roles of data scientists, database designers, and other expertise that are needed for processing soil data and making it accessible and usable by others in a digital system. This shortage of expertise cannot easily be overcome by the in-country training of new generations of soil scientists and data specialists, and larger economic-structural conditions may lead to a “brain drain” in which capable technical experts are drawn away by more advantageous employment opportunities elsewhere.

3.1.2 Enabling environment criteria in Archetype 1: outcomes

- Continuity of soil data / SIS effort: Legacy soil data is available but remains scattered across institutions, and/or exists primarily in hard copy formats. Initial funded SIS effort, while effective at advancing some capacity-building and other objectives, does not achieve an operational digital SIS that compiles and supplements legacy data.

- SIS status: Currently a digital SIS is not operational as a system tailored to user needs, and making it operational would require external partners and/or additional funds. Data that have been cleaned and minimally processed may be posted online on sites such as OSF, but lack user guidance, documentation, and (in some cases) metadata.
- Data types and availability: Data exist and can be accessed online, but only in raw formats (such as soil property measurements collected into a CSV file) that may require additional user knowledge or data literacy to be able to derive meaningful information or apply in decision-making. Data quality control, if conducted, is not well documented.
- Use of the SIS to meet user needs: Use cases are not well understood. Data may be accessed by government and other stakeholders, but there is no demonstrated application of the data in accessible public-facing projects or products.
- Data governance, policies, and licensing: No data governance plan or policy in place; data are freely available online.

3.1.3 Technological components of soil information development under Archetype 1

Table 4: Linkage of enabling environment criteria with each component of the soil information development workflow under SIS Archetype 1.

Soil information development stage	Status	Enabling environment criteria linkages: *In this archetype…*
User consideration	*Not attempted*	*… user needs are not well understood: a full stakeholder assessment is not conducted, and a consensus understanding of needs among in-country stakeholders is not well established*
Data collection	*Yes*	*… capacities for field data collection exist, and data has been collected and stored; however, sampling schema and data quality are uncertain*
Laboratory analysis	*Yes*	*… laboratories exist and are equipped with basic requirements for making wet chemistry measurements; however quality and consistency of laboratory procedures is unknown, leading to uncertainty about data quality*
Data organization	*Yes*	*… capacities for organizing raw data in a computer system or server exist. Hypothetically, this enables others to view and/or download the raw data. However, in this archetype the technical capacities for further organization of the data are limited: development of databases, standardization and harmonization of data, documentation and metadata, etc. These limitations result in the SIS effort becoming stalled at the stage of data organization, and not advancing into additional stages of data products and synthesis insights.*
Modelling and mapping	*No*	*… technical skills related to data science, spatial analysis, and digital mapping are very limited.*
Applying soil information	*Yes - Limited*	*… digital soil data may be accessed and used to derive information, but this is limited to organizations and individuals who have the necessary levels of expertise; general-purpose informational products for a wider user group are not available*
Data and information serving	*No*	*… data may be available online for download in raw formats, but there is no SIS platform or system specifically designed for the delivery of the data to users.*

3.2 Archetype 2: SIS is approached as a discrete project

While valuable insights can be gained from the long-term observation of soils in a particular place, under severe resource and capacity constraints it may not be feasible to develop soil data as a long-term commitment. In Archetype 2 there are several limitations in the SIS enabling environment that pose a challenge for the development of a SIS past the data organization stage (e.g., relatively low technical skills available in-country, lack of SIS champion, and only a single user). However, developing a SIS up to this stage, and approaching it as a discrete and time-bound project, may be sufficient depending on the intended use cases for soil data. Critically, in this archetype there is a relatively low level of institutional involvement or interest in soil data outside of government. Without a champion, a SIS is vulnerable to transitions in government, which may bring changes in policy agendas and funding that impact the sustainability of the SIS.

3.2.1 Enabling environment criteria in Archetype 2: conditions

- **Funding source for initial SIS effort**: Majority (or all) of the initial funding comes from a donor organization, with little to no national system investment.
- **User groups of the SIS**: Unclear, but likely the national government's agricultural and land use policymakers.
- **Use cases that motivate(d) the SIS**: Use cases are not well defined, but generally seem to be envisioned as a mix of improved fertilizer recommendations, soil nutrient management, agricultural advisory, optimal site selection for industrial, settlement, extractives, and/or agricultural development.
- **SIS or soil data champion**: Aside from the institutional owner or host of the SIS, there may exist additional institutions with a mandate or agenda related to soils; however, limitations in funding, soil data demand (e.g., users and use cases), and motivation may inhibit institutions from actively advocating for soil data development efforts. SIS champions may emerge as individuals working within organizations related to agriculture or land resources.
- **Technical expertise and capacities**: Sufficient capacities exist for conducting field soil surveys, laboratory activities, and for compiling data into an organized repository or computer system. These capacities have been supported largely through the activities of external development donors and implementers, who have provided sufficient training and networks to enable a relatively small set of in-country experts to be developed. There are technical universities and training institutions that currently, or have the potential to, educate an emergent cohort of local experts in soil sciences, data science, digital soil mapping, etc. that could support a sustainable SIS into the future. However, the retirement of soil surveyors, especially without the transfer of their skills to up-and-coming specialists and the provision of accessible interpretations of their soil survey information to users, is one pathway for the loss of critical in-country expertise. Retaining highly skilled technical people in SIS projects is also challenging due to more advantageous employment opportunities elsewhere.

3.2.2 Enabling environment criteria in Archetype 2: outcomes

- **Continuity of soil data / SIS effort**: The resources available for the initial SIS effort are sufficient to progress to the stage of cleaned data and basic or static maps, which can be hosted online or made available to potential users with minimal ongoing costs. Reaching this stage demonstrates local interest and capacities, which can motivate further investment by the national government or other internal or external partners.
- **SIS status**: System is operational, and maintenance is funded by one or more national government entities.
- **SIS enhancements**: Feature additions, expansions of current tools and apps, and other improvements on the system are reliant on specific project-based funding and/or external partners.
- **Data types and availability**: Data exist and can be accessed, but open data are only in limited forms:

static maps or images that can be viewed on a website and downloaded as JPG or PDF files. Further access to data may be granted, but users must make a request through a web form. It is unclear whether and how often such requests are granted.

- **Use of the SIS to meet user needs**: SIS data are accessed and used for one or more applications within the country; SIS developers can cite specific examples of usage.
- **Data governance, policies, and licensing**: No specific data governance plan or policy in place; in some cases data are fully open, and in others it is fully restricted.

3.2.3 Technological components in soil information development under Archetype 2

Table 5: Linkage of enabling environment criteria with each component of the soil information development workflow under SIS Archetype 2

Soil information development stage	Progress	Enabling environment criteria linkages: *In this archetype...*
User consideration	*Not attempted*	*... user needs are not well understood: a formal, targeted needs assessment not conducted.*
Data collection	*Yes*	*... Data have been collected and stored. A sampling scheme exists. Data quality control is uncertain.*
Laboratory analysis	*Yes*	*... labs are equipped with basic requirements for making measurements e.g. wet chemistry, equipment, supplies. Capable soil scientists and lab technicians exist, but retention is a challenge and training pipelines are limited.*
Data organization	*Yes*	*... capacities exist for organizing raw data in a computer system, and generating static images or maps. Hypothetically, this enables others to view and/or download the raw data. However, development of databases, standardization and harmonization of data, documentation and metadata limitations result in the SIS effort not progressing into additional stages of data products and synthesis insights.*
Modelling and mapping	*Yes*	*... technical capacities for data science and spatial analysis exist, which are sufficient to develop static and interactive maps and related information such as crop suitability indices. Free or low-cost, off-the-shelf tools and online mapping platforms are leveraged. Beyond this spatial visualization of the data, there are limited data that are openly available for download. A lack of technical capacities and resources for more advanced modeling presents a challenge for generating more advanced soil information products.*
Applying soil information	*Yes - limited*	*... data are accessed by government and researchers for specific projects or applications. However, more general-use information products that serve a broader range of users are not yet available.*
Data and information serving	*No*	*... data are available for visualization on a website, in some cases with download capability. However, a dedicated platform designed for user needs is not yet developed to deliver data and information products.*

3.3 Archetype 3: SIS is sustained by an institutional coalition

The sustained involvement and support of institutions–both within and outside of the national government–is a key factor in the success of a SIS, especially through fluctuations in funding and political support. Countries fitting Archetype 3 have a connection to a sustained coalition of institutions and networks to enable a ***soil information champion***–an institution, or community of institutions, that advocates for soil data development and for the SIS. In this archetype, the country's connections with external partners are strong, which facilitates the transfer of technical knowledge and expertise that can fill gaps in capacities for building and maintaining a SIS.

3.3.1 Enabling environment criteria in Archetype 3: conditions

- **Funding source for initial SIS effort**: Initiated and funded primarily by the national government, with some donor support in specific aspects such as technical capacity-building or institutional community facilitation.
- **User groups of the SIS**: A clear appetite for soil data exists among user groups including national government, agricultural advisory, private sector, and internal and external research institutes. Although a formal assessment of soil data users is not typical of this archetype, the community of soil-adjacent practitioners, policymakers, and other stakeholders are able to articulate specific needs and requirements.
- **Use cases that motivate(d) the SIS**: Mix of agricultural production, yield forecasting, land use planning, and broader strategic objectives linked with other ongoing development efforts, such as primary research, soil health initiatives, local and regional community development.
- **SIS or soil data champion**: Multiple coordinated institutional supporters exist, including local and international organizations that have a history of successful collaboration.
- **Technical expertise and capacities**: Sufficient capacities exist for conducting large-scale field soil surveys, laboratory activities, and for compiling and organizing data into a repository. Further, in-country experts are present to implement analyses and transformations of the data toward the development of models and maps that provide utility for a range of potential users. While there are technical universities and training institutions that have the potential to educate new cohorts of experts, with a SIS that is more advanced in its achievement of stages of the SIW, a greater level of expertise is required to transform raw data into useful formats and applications. The growth of a new generation of experts takes time; in the meantime, gaps in the necessary specialized skills and expertise are filled by experts from external partner organizations.

3.3.2 Enabling environment criteria in Archetype 3: outcomes

- **Continuity of soil data / SIS effort**: Initial launch and early stages of the SIS are supported by multiple institutions, including a strong interest and investment by the national government itself. This, and the presence of an institutional champion that advocates for the SIS, allows for the project to be sustained through ebbs and flows of funding and motivation.
- **SIS status**: The system is operational, and maintenance is funded by one or more national government entities for at least the near-term foreseeable future.
- **SIS enhancements**: The development of additional features, tools, apps, or other capabilities are reliant on projects and/or external partners for funding and support.
- **Data types and availabilit**y: Data exist and can be accessed in multiple formats online that can be viewed and downloaded by users; additional derived information products are available.
- **Use of the SIS to meet user needs**: Examples exist to show that the SIS data are accessed and used for one or more use cases.

- **Data governance, policies, and licensing**: Access is provided via online registration; soil data sharing and governance policy have been developed to manage the needs of multiple data stakeholders.

3.3.3 Technological components in soil information development under Archetype 3

Table 6: Linkage of enabling environment criteria with each stage of the soil information development workflow under SIS Archetype 3.

Soil information development stage	Status	Enabling environment criteria linkages: *In this archetype...*
User consideration	*Not attempted*	*... While a formal, targeted needs assessment may not have been conducted, ongoing efforts in relevant domains such as natural resources management, a strong agricultural advisory/extension, program, etc. are suggestive of likely users and applications of soil data.*
Data collection	*Yes*	*... capacities for field data collection exist, and a significant amount of nationally representative data has been collected and stored.*
Laboratory analysis	*Yes*	*... laboratories exist and have capable technicians, and labs are equipped with basic requirements for making measurements e.g. wet chemistry, equipment, supplies.*
Data organization	*Yes*	*... capacities for organizing raw data into a computer system or soil information database, standardization and harmonization of data, and exploratory analyses are sufficient to maintain the system and for ongoing addition of new data as it comes from soil survey and laboratory analyses.*
Modelling and mapping	*Yes - partial*	*... human capacities for data science and spatial analysis are sufficient to develop soil maps and useful models that serve multiple applications. These capacities may be achieved through training and capacity-building activities conducted by external partners. Expansion of the SIS, enhancements, and addition of new tools or applications will require the involvement of additional external partner organizations that can train and advise on the necessary technical skills.*
Applying soil information	*Yes*	*... products using soil and related data in the SIS are created and used for one or more applications, such as agricultural decision support tools and research involving landscape and biogeochemical modeling. There is strong potential for use of the data to expand to additional users and use cases.*
Data and information serving	*Yes - partial*	*... technical capacities for data documentation and metadata inclusion exist; however, the application of metadata and standards is not yet fully realized.*

3.4 Archetype 4: SIS is a function of the national government

When pursued as a long-term project that is supported by the government as a national priority, soil data development has the potential to deliver significant and diverse benefits to civil society. In Archetype 4, a long-term investment in large-scale, high-quality soil data is supported by the national government with public funding. Soil data are valued for their potential contributions to a range of national-level agendas and activities. The capacities to build, maintain, and enhance a SIS are available in-country. Several coordinated institutional supporters, within and outside government, serve as champions, facilitators, and educators for the expansion of SIS data and products.

3.4.1 Enabling environment criteria in Archetype 4: conditions

- **Funding source for initial SIS effort**: National government is the primary source of funding and the owner of the SIS.
- **User groups of the SIS**: Multiple user groups require soil data, including agricultural and conservation policymakers, private sector agronomists, water and irrigation districts, land use planners, and researchers. Institutions and individuals involved in SIS development are soil scientists and data scientists, which allows for informed perspectives on who needs access to soil data and for what objectives.
- **Use cases that motivate(d) the SIS**: Applications of soil data by stakeholders in government include agricultural policymaking, technical advisory for farmers and private landowners, public land management and conservation; additional use cases include business strategy development for private sector organizations and academic research.
- **SIS or soil data champion**: While the national government entity that owns and hosts the SIS is the most prominent institutional actor, there are multiple other institutions and organizations that hold a stake in soil data and contribute to dialogue and development of the SIS.
- **Technical expertise and capacities**: In a well-resourced setting with funding processes and mechanisms in place to support the long-term development of soil data and a SIS, shortages of human expertise to support the initial build, maintenance, and expansion of the SIS are few. In such cases, the national government may procure specialist expertise from the private sector, e.g. for app development.

3.4.2 Enabling environment criteria in Archetype 4: outcomes

- **Continuity of soil data / SIS effort**: Earlier projects in soils or agronomy data and information provide one source of motivation for the initial SIS effort, by framing the SIS as a project to compile, standardize, and gain more value from existing or legacy data. Linking the new SIS with earlier efforts also entrains support from the set of institutions involved in those efforts, which can evolve into a community of soils data and help to maintain the continuity of the SIS through changes in government and funding support.
- **SIS status**: System operational, and maintenance is funded by the national government with mechanisms in place for maintaining a funding stream for sustaining the SIS.
- **SIS enhancements**: There is provision for enhancements of the SIS via funding processes of the national government.
- **Data types and availability**: Data exist and can be accessed in multiple formats that can be viewed and downloaded by users; additional derivative information products, tools, and apps are also available and tailored to specific use cases.
- **Use of the SIS to meet user needs**: Numerous examples exist to show that soil data are used in a range of applications; mechanisms are built into the SIS for the collection of input and feedback from users, which is reviewed by SIS developers and incorporated into system improvements.
- **Data governance, policies, and licensing**: National policy exists for managing the access and use of soil and other environmental data; within the SIS, processes are in place to balance the data privacy and accessibility needs of a range of stakeholders.

3.4.3 Technological components in soil information development under Archetype 4

Table 7: Linkage of enabling environment criteria with each stage of the soil information development workflow under SIS Archetype 4.

Soil information development stage	Status	Enabling environment criteria linkages: *In this archetype…*
User consideration	*Yes*	*… user groups of soil data are known and understood through at least one formal, targeted needs assessment conducted. Metrics on the usage of data and products (e.g. website hits, downloads, etc.) are collected continuously. Further understanding of users and usage is gained through formal feedback mechanisms such as a web form for feature requests or bug reports. The developers of the SIS are themselves also experienced users of soil data and hold an understanding of what data types, formats, channels, etc. are needed for typical applications of soil information.*
Data collection	*Yes*	*… capacities for field data collection exist, and a significant amount of nationally representative data has been collected and stored.*
Laboratory analysis	*Yes*	*… laboratories exist and have capable technicians, and labs are equipped with requirements for making measurements e.g. wet chemistry, equipment, supplies, along with dry chemistry capabilities and advanced methods.*
Data organization	*Yes*	*… technical capacities for organizing raw data into a soil information database, standardization and harmonization of data, and exploratory analyses are sufficient to maintain and improve the system, and for the ongoing addition of new data as it comes from soil survey and laboratory analyses. There is a sufficient level of resourcing for IT infrastructure, computing environment, software, hardware, etc. to develop complex, distributed systems for data capture, processing, and storage.*
Modelling and mapping	*Yes*	*… human capacities for data science and spatial analysis are sufficient to develop soil maps and useful models that serve multiple applications. These capacities are developed in an ongoing way through an established pipeline or system of training and retaining experts. Expansion of the SIS, enhancements, and addition of new tools or applications is achievable either through hiring new talent into SIS project teams or procuring software and feature development services from private sector contractors.*
Applying soil information	*Yes*	*… products using soil and related data in the SIS are created and used for multiple applications, such as agricultural decision support tools, policy development, land use planning, natural resource conservation, and research involving landscape, hydrogeological, and biogeochemical modeling. There is strong potential for use of the data to expand to additional users and use cases.*
Data and information serving	*Yes*	*… the technical, IT, and administrative capacities exist to conduct ongoing quality control and quality assurance protocols with soil data. SIS managers deliver consistent data and information products to users via platforms and applications that link to a central or distributed database, providing a relatively user-friendly interface for non-specialists to access soil data. Policies exist to govern access to soil data which aim to balance the data protection and data openness interests of a range of soil data stakeholders.*

4. Synthesis and discussion

Archetypes were identified in this analysis to represent a set of enabling environment conditions in countries that co-occurred with specific outcomes for their SIS. Archetypes are broadly applicable, which is useful for revealing patterns and making descriptive classifications of unique country's historical and cultural contexts.

In our study, archetypes are a generalised analytical framing for anticipating the range and scale of activities that would be needed to develop a new SIS initiative that meets user needs and is sustainable. That said, archetypes are not prescriptive or rigidly specific, and most (if not all) countries will have characteristics of two or more archetypes. Rather, archetypes are best used to open discussions on SIS design and for structuring decision processes. We anticipate that the work reported here will undergo further refinement and validation of the archetypes we identified, and will serve as a basis for building structured, rational, and evidence-based arguments for improved SIS development approaches that account for socio-political context.

Each SIS development archetype describes a set of countries whose enabling environments and SIS outcomes are *more like each other* than they are *like other countries*. A country with an enabling environment resembling archetype 1 will have different requirements for intervention than a country resembling archetype 3, because an archetype 3 country already has (for example) strong connections with a network of institutions that can support or potentially serve as SIS champions. Identifying a country's characteristics that fall into one or more archetypes, based on an initial assessment of its enabling environment, can aid SIS planners in identifying the aspects of a SIS project that will need greater focus or additional resources.

In our analysis no two countries were identical in their enabling environments--small variations existed between countries within archetypes. For example, country B shared some characteristics with archetype 2 (countries C, D, and E), but the majority of its enabling environment criteria were more alike to country A – so in our analysis, country B was classified into archetype 1 (see Appendix 6). Country B is therefore located "on the line" between archetypes 1 and 2.

These variations underscore the utility of using not only the archetype, but also the set of enabling environment criteria, to assess the way forward for SIS design in a given country. While an archetype 1 country will generally have major capacity gaps in technological expertise, an assessment at the level of enabling environment criteria can reveal which areas of expertise are potentially already sufficient, and which will need capacity-building or facilitation. For example, country B is classified into archetype 1 because of its numerous technical capacity limitations, but country B does have existing capacity in IT infrastructure and systems for storing and serving data. However, these capacities are held by a division of the government other than the one hosting the SIS, and further facilitation between these divisions of government is needed to develop agreements for the use of those IT systems. If Country B is "on the line" between archetypes 1 and 2, a comprehensive assessment of the enabling environment criteria will reveal these kinds of nuances that point toward more specific action areas and priorities, either for a completely new SIS development effort or for improving the performance or function of an existing SIS.

Several broad insights emerged from our consideration of these archetypes in the context of prior research and learnings among the soil data community. The insights described below involve 1) benchmarking SIS development efforts on existing soil information and users' needs, 2) long-term buy-in and facilitation by a SIS champion, and 3) value attribution and clarity of purpose for soil data.

4.1 Benchmarking SIS development efforts on existing soil information and users' decision-support needs

> While it may be initially intuitive to assign a differing value of "success" to these different SIS outcomes, our analysis suggests that the success of a SIS intervention may be better evaluated by comparing these outcomes with the decision processes and use cases of stakeholders.

The four archetypes characterise SISs that vary widely in their levels of complexity and technological sophistication. SISs from archetype 2 countries include soil information workflow components up to digital data organization, with static maps of soil properties and a limited amount of data available for user download. Archetype 4 countries include all stages of the soil information workflow, with highly interactive SIS interfaces, dynamic maps, and user-queryable databases. While it may be initially intuitive to assign a differing value of "success" to these different SIS outcomes, our analysis suggests that the success of a SIS intervention may be better evaluated by comparing these outcomes with the decision processes and use cases of stakeholders. SISs in countries within archetype 2 may hold less digitised soil data and have fewer options for users to interact with it, yet still meet some user needs, for example, in visualizing the geographic distribution of soil classes in the landscape or in providing clear rating tables that enable users to interpret soil maps for specific uses.

Such a SIS may successfully meet the needs of users and use cases in the present, and serve as a foundation for adaptive development of soil data as users and use cases evolve into the future. Especially in contexts where it is not initially well-specified how soil data will be integrated into decision support processes (see section Value attribution of soil data below), a stepwise and adaptive approach can help developers avoid inappropriately targeting a SIS toward unverified assumptions about present and future users of the data and information. **The initial stages of SIS planning can usefully ask: what is the earliest or simplest stage of SIS development that we need to achieve to meet users' needs? What is a feasible goal stage that is responsive to the identified soil data demand?**[38]

In many countries, this simplest first stage of SIS development may aim to centralize all existing and legacy soil data and maps, and supplement them with rating tables and other aids that immediately enable users to interpret and apply this information. **Most, if not all, countries in Africa already hold some amount of legacy soil data, whether in hard copy materials or digitized, which could be compiled to help SIS developers to benchmark the status of soil data and assess which next steps are needed**. Our evidence suggests it may be quite rare, especially among countries with limited resources, to fully plan and implement a fully digitally integrated SIS platform with interpreted data and information products when starting from the earliest stages. Examples of more complex digital SISs, under archetypes 3 and 4, are all systems that evolved out of a longer history of earlier SIS efforts, or which have received sustained long-term support from a range of internal and external partners to persist through changes in the enabling environment conditions.

38 Chapter 2: User Consideration in "Development options for a Soil Information Workflow and System" contains detailed guidelines, scoping questions, and other useful resources for this stage of SIS planning.

> Soil data development up to a specific stage can sufficiently enable some users to access and use soil information for decision-making.

However, our analysis also shows that progressing to highly technologically advanced stages of soil data development may not be necessary for meeting users' needs for soil data. Instead, examples of "quick wins," particularly in archetype 2, show us that soil data development up to a specific stage – a set of high-quality maps, or single-time-point data on soil chemical and physical properties plus interpretation aids – can sufficiently enable some users to access and use soil information for decision-making. For example, the interviewee in country D (archetype 2) noted that their digitized soil maps had been used by land use planners to establish an initial estimation of soil engineering properties for a particular region, which increased the efficiency of a subsequent field observation campaign. Such engagement with a relatively simple SIS can motivate new soil data demand among additional SIS users or potential investors, though our interview evidence does not identify a discrete point along the SIW where this occurs. Rather, as evidenced also by country E in our analysis, it seems that simpler SISs that are demonstrating value to their users can act as a signal to external donors and potential partners that a national SIS project may have sufficient momentum to warrant more investment in scaling and scoping to a more advanced system.

To many of us with experience in rural and agricultural development, highlighting the importance of assessing soil data users and their decision-support needs may land as a truism. Indeed, decades of evidence underscore the value of stakeholder assessments and tailored approaches to the development of digital tools for agriculture, soils, and related domains.[39] Yet, despite this wealth of collective experience, the data collected for our analysis continue to reinforce that evaluations of potential users of soil data are superficial and not well integrated into implementation plans, with apparent assumptions often made about SIS users in the course of grantmaking and intervention design.

Based on these observations, we suggest that the archetypes that emerged from our analysis can be used, in tandem with the set of enabling environment criteria, to develop an initial estimation of a country's status regarding existing and legacy soil data and potential use cases or decision needs.

4.2 Long-term buy-in and facilitation by a SIS champion

In our analysis, three enabling environment components were particularly informative in grouping countries into archetypes: *Initial funding for the SIS*, *technical expertise and capacities*, and *institutional environment*. The initial funding in archetypes 1 and 2 was largely from donor organizations external to the country, who supported activities in the early stages of the SIW such as data collection and laboratory analysis. In archetype 3, the national government was the primary funder, and donor contributions were made to specific technical or facilitation components of the project. Countries in archetype 4 have SISs that are largely or entirely funded through the government. Although we did not have access to project proposals or scoping documents and our interview data is limited, these distinctions in funding mix – in particular between archetypes 1-2 versus archetype 3 – are suggestive of the key role that funding sources play in the overall commitment and long term investment of project partners. Donor funding is often critical for the initial development of soil data systems, but the **sustainability of a SIS is also reliant on long-term (i.e. on the order of 10 years or more) commitments in coordination with internal organizations and/**

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39 Rose, D. C., Parker, C., Fodery, J., Park, C., Sutherland, W. J., & Dicks, L. V. (2018). Involving stakeholders in agricultural decision support systems: Improving user-centred design. ***International Journal of Agricultural Management***, 6(1029-2019-924), 80-89

or national systems and on the early development of a plan for sustaining the SIS after the initial project is concluded. Even in archetype 4 countries, where soil data is well integrated in the national agenda, challenges arise in sustaining the SIS through transitions between funding cycles or turnovers in government. In addition to supporting the initial establishment and capacity-building for a SIS, donors can play a role in buffering interruptions due to these larger systemic dynamics.

It is here that the role of a SIS champion – an advocating institution who supports the cause of the SIS – can be especially important in ensuring the continuation of the SIS beyond the involvement of external donor organizations. Our data show that, for nearly all countries we examined, there have been variations in the levels of buy-in and commitment that in-country organizations hold for soil data and the SIS. These variations can arise from changing funding streams and by turnovers in government, leading to soil data having higher or lower priority in funding and political agendas. As one interviewee noted:

> *[Our organization] took ownership of the SIS [when other institutions stepped back]. You need a champion organization that backs it. We've struggled even within [our institutional network] at times, to say why we are maintaining this national system.*

In archetypes 3 and 4, the advocacy by a SIS champion enabled the continuity of a minimum set of activities and maintenance for the SIS during lean periods:

> *The recognition at various levels of government that soils are important has been key. That high level buy-in waxes and wanes as governments change. [...] To maintain that interest, that connection to policy, is really hard. But it's really important because you need that thing that's going to engender people's interest. You need champions within policy arenas that drive that agenda.*

In archetypes 3 and 4, these basic operating activities were supported primarily by the national government or other internal actors, rather than by donors, underscoring the importance of a minimum level of in-country government buy-in for the sustainability of the SIS. Typically the soil information needed – basic soil survey and soil properties – are common across a wide range of use cases and decision needs. Such data are then interpreted and applied in distinct ways to serve specific users or decision needs. **A SIS champion, for example, a dedicated professional soil scientist with the ability to liaise with stakeholders at various levels across the system, can play a critical role in this capacity by actively engaging with potential users ranging from government policymakers to farmers**. With this unique position in the system, the SIS champion synthesizes the more user- and use-case-specific insights that are needed to properly tailor SIS development activities, and to continuously incorporate user and stakeholder feedback as the SIS evolves into the future.

ROLE OF THE SIS CHAMPION

Figure 6: A SIS champion actively engages with stakeholders ranging from national and international soil data community to farmers.

SIS champions are also important in mitigating the gaps in technical expertise and capacity that can be a challenge to building and sustaining a SIS. In countries in archetypes 1 and 2, interviewees pointed to gaps in technical capacities – especially data analysts, programmers, modelers, and related roles – as a key barrier for the progress of digital SIS development. In archetype 3, some of these roles could be filled in-country, and the SIS champion addressed remaining gaps by facilitating access to specialist training and coordinating external partner organizations to make specific technical contributions to the digital SIS platforms:

> *For the technical enhancements we would like to make on the SIS, there is limited national technical capacity, and hence we are working [through our networks] to secure a SIS enhancement project with [another organization based internationally].*

In archetype 4, countries are generally sufficiently well-resourced to meet the technical demands of a SIS, and any gaps in the SIS project were readily filled by hiring private sector contractors. While a SIS champion can greatly help to steward a SIS project forward through funding and capacity shortfalls, our analysis also highlights the critical importance of accounting for the mix of in-country and external technical capacities that are available for both the initial SIS build and its long-term maintenance and enhancement. Not all countries will require the support of external partners to fill capacity gaps, but for those that do, this support can be critical to the progress of the SIS.

Regionally coordinated SIS development is one promising approach to mitigating many of the challenges found in national-scale SIS initiatives. A regional coalition among multiple countries may achieve greater efficiencies in a SIS development effort, as compared with countries undertaking individual initiatives. For example, countries that possess greater capacities in aspects of SIS development can provide soil analysis services, capacity-building, and other forms of support for others with more limited capacities in those areas. Countries that coordinate on the use of protocols and techniques for soil analysis can achieve greater data quality and consistency, either by centralising sample analyses in a small number of laboratories or by following standardised methodologies. Additionally, many countries in Africa encompass regions with similar climate, vegetation, geology, and soils. In these cases, soils sampled from one country may be highly informative about ecologically similar regions in a neighboring country. Even where initial pledges of support are made, national buy-in and ownership of the SIS are often difficult to sustain because of arising competition for resources and changes in political agendas. Regional approaches may also help buffer the SIS against these factors by creating longer-term institutional agreements and expectations between countries. Finally, a SIS champion from one country, perhaps working in concert with their counterparts in other countries, may be a great asset to maintaining these long-term regional arrangements.

Avoiding the situation found in our analysis under archetypes 1 and 2 – the SIS becoming "stuck" at an early stage of its technological development – depends on making specific, well-informed sustainability plans. These plans should establish commitments around how the SIS will be financed after the project ends, and how key technical roles and expertise areas will be secured. These specific plans, in turn, rely on making a comprehensive and realistic assessment of SIS user needs, internal technical resources, and potential external sources of technical capacity and human resource support.

4.3 Value attribution and clarity of purpose for soil data

What is the value of soil data for farmers, policymakers, NGOs, and other users? Although interviewees in our study named broad use cases for the data in their SIS – land use planning, erosion mitigation, fertilizer recommendations – few pointed to specific ways that more or better soil data would be critical to improving decisions in these or other areas. As an interviewee from archetype 1 responded when asked to name specific applications of their SIS:

> *Information is like a sword. It can be used to answer people's questions, especially for fertilizer use, inputs, and formulation of fertilizer. It can also serve as baseline information. If it's well kept, it can be referenced again after 15 years to see changes, improvement, deterioration. It will guide soil health management at individual, community, and regional levels for decision making.*

It is likely that additional in-depth interviews with SIS stakeholders in our study countries could produce clearer articulations of their perceived value and needs for soil data. However, prior research addressing decision support in African agriculture demonstrate that a **value model for soil data is often overlooked in development initiatives, and the perceived need for soil data among stakeholders is often poorly aligned with actual decision processes**. For example, in a survey of 110 key stakeholders in African agriculture, Clapp et al.[40] found that less than half could specify a decision need "of any kind related to their perceived data needs." Similarly, a review of 103 monitoring initiatives spanning agriculture, environment, and public health found "a recurrent problem with many measurement initiatives is that they are designed with the assumption that the data generated will be transformed into information [...] However often there is little evidence, including from this review, that this assumption is actually met."[41]

These prior research findings are reinforced by our data and observations. We found that soil data stakeholders embarking on SIS design may have some familiarity with SIS functionality and/or use cases in other countries and strive to build their own SIS to replicate those situations, even if soil data needs and capacities in their own country may be quite different. One interviewee in country B, for instance, noted that the SIS in their country had been first conceived as an effort to re-create a system that had been previously developed in another country, omitting mention of any particular use case or decision process ongoing in country B that could benefit from soil data.

Other examples point toward aspirations for the SIS being misaligned with the realities of users' lives. Supporting smallholder farmers to make better soil management decisions is a goal well worthy of support and investment, and was cited as an underlying motivation by SIS developers in several countries in our Archetypes 1 and 2. In some Archetype 4 countries, with SIS that have achieved the later stages of applying soil information and data and information serving, farmers themselves use the SIS data to make better soil management decisions. However, as noted by one interviewee, targeting smallholder farmers themselves as SIS users in Archetype 1 and 2 countries would entail substantial capacity-building and training efforts:

> *[...] aiming the SIS at small scale farmers [is never going to work] because most don't have a smartphone, not to mention the [basic data literacy] to be able to interact with the SIS. [...] Even for larger scale commercial farmers, you would need such an education and sensitization program behind it, that it just doesn't make sense.*

Support for farmers can and should remain an underlying motivation for SIS development, but bringing soil data and information into the hands of farmers requires recognizing and working within the constraints imposed by capacity gaps such as data literacy or smartphone access. With

40 Clapp, A., DauSchmidt, N., Millar, M., Hubbard, D. & Shepherd, K., 2013. A Survey and Analysis of the Data Requirements for Stakeholders in African Agriculture. World Agroforestry Centre.

41 Shepherd KD, Farrow A, Ringler C, Gassner A, Jarvis A. 2013. Review of the Evidence on Indicators, Metrics and Monitoring Systems. Commissioned by the UK Department for International Development (DFID). Nairobi: World Agroforestry Centre. http://r4d.dfid.gov.uk/output/192446/default.aspx

low economic capacity, farmers also have low (but not zero) willingness to pay for information.[42,43] Data needs to be interpreted into appropriate user-friendly products. Even then, co-investment will likely be needed to enable farmer-level usage of soil data.

Together, our data and previous research underscore the continued need for better assessment of the value of soil data for users' specific needs and decision processes. While our study scope did not include an econometric analysis of national soil data, our interviews point toward patterns in how interviewees perceive the value and utility of soil data across several contexts. In archetype 1 and 2 countries, one of the applications was targeted fertilizer recommendations, which interviewees suggested benefit the government by reducing its burden of subsidy payments and freeing up funds for other uses by moving away from blanket fertilizer recommendations. In archetype 3, a target user group for soil data and information products is agricultural extension workers, who aid farmer decision-making toward improved efficiency and yields. Increased yields benefit not only the individual farmer's livelihood, but also regional and national agricultural economies. In archetype 4 countries, data from the SIS are applied in the management of water resources, design of carbon sequestration crediting and markets, farm-level sustainability credential programs, and support for agribusiness. Interviewees in archetype 4 perceive these applications of soil data to contribute to economic benefits for farmers, the government, and the public by increasing the efficiency of policies and programs for agricultural and natural resource management:

> *There hasn't been an effort to put a dollar value to [the benefits of the SIS]. What we do know is that soil data has saved lives, [through applications like] predicting valley fever and [support for] clean water.*

As Clapp et al.[40] note: "The habit of collecting data for the sake of having data is a practice that should be discouraged in view of limited resources." While we do not deny the benefits of improving fertilizer recommendations, supporting data-driven agricultural advisory, and management of a range of natural resources, what appears to be a persistent gap is the **evidence-based linkage of soil data with the actual decisions** that need to be taken by stakeholders who work in these domains. Generalized approaches and tools exist to guide such a process, which could be readily applied in the context of SIS development initiatives. For example, Shepherd et al.[44] developed Stochastic Impact Evaluation to assess the value of information and its role in decision models, with example applications in land restoration initiatives.

This and similar decision analysis approaches can help SIS donors, implementers, and users build rational and evidence-based arguments for investing in certain aspects of soil data and information and not others. Such decisions are key to determining the technical requirements and approaches for each component of the soil information workflow. For example, data supporting decision-making in regional watershed management may be suitable at a relatively lower spatial resolution than data needed for soil fertility management at farm scale, which translates into different requirements for spatial sampling schemes and soil properties measured, potentially different standards of data quality, and differing costs involved in implementing the data collection.

Defining use cases for SISs are pivotal for addressing agricultural transformation, food security,

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42 Abebe, F., Zuo, A., Ann Wheeler, S., Bjornlund, H., van Rooyen, A., Pittock, J., Mdemu, M., Chilundo, M., 2020. Irrigators' willingness to pay for the adoption of soil moisture monitoring tools in South-Eastern Africa. International Journal of Water Resources Development 36, S246–S267. https://doi.org/10.1080/07900627.2020.1755956

43 Martey, E., Etwire, P.M., Adombilla, R., Abebrese, S.O., 2023. Information constraint and farmers' willingness to pay for an irrigation scheduling tool. Agricultural Water Management 276, 108043. https://doi.org/10.1016/j.agwat.2022.108043

44 Shepherd K D, Whitney C W, Luedeling E. 2021. A decision analysis framework for development planning and performance measurement: application to land restoration investments. ICRAF Working Paper no 324. World Agroforestry, Nairobi, Kenya. DOI. https://dx.doi.org/10.5716/WP21042.PDF

sustainable land management, and sustainable development in multiple sectors. Use cases describe the key applications for the SIS, key issues to be addressed, what soil information is needed and by whom. Appendix 7 provides a range of generalised use cases for SISs and builds on the work by ISRIC- World Soil Information in **Development options for a Soil Information Workflow and System**. The information provided is to support those involved in national SIS development to clearly define their use cases, which is a key activity in the **framework for sustainable national soil information systems**.

5. Conclusions and next steps

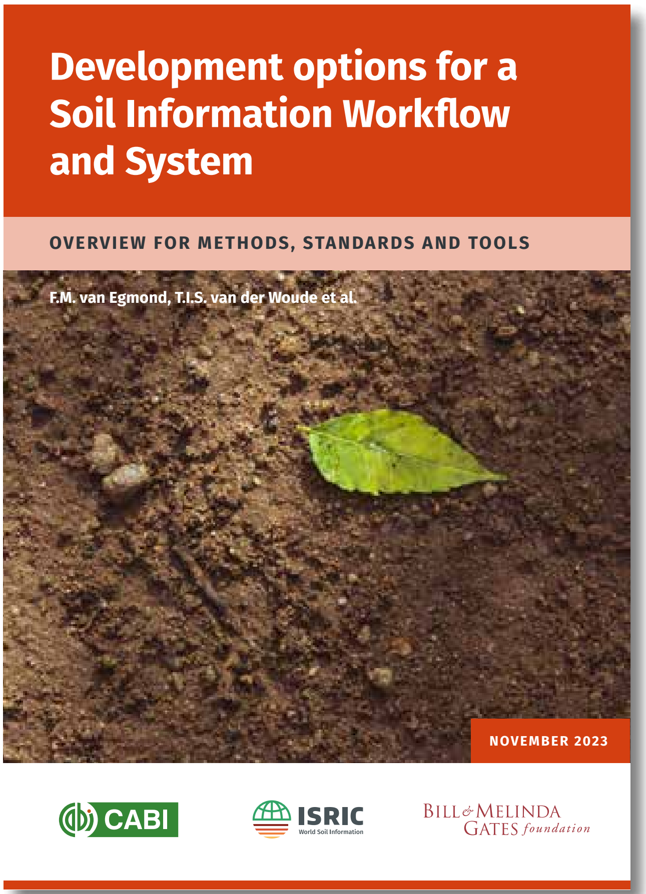
Our results, together with insights from prior research, highlight three considerations for planners and implementers of SIS:

1. Comprehensively assess potential soil data users, use cases, and the **decisions that potential users are taking** that could be improved using soil information. This can be approached through identifying the country's position among the archetypes identified in our analysis, and through adapting established decision analysis approaches to understand the value of soil information for each group of stakeholders in the context of the country's enabling environment.
2. **Identify and centralise existing and legacy soil data** in the country, digitize where needed, and develop interpretive aids that enable users to benefit from these data in the relatively short term.
3. Identify and support a **SIS champion** who can progressively facilitate buy-in and cooperation among stakeholders at various levels, from farmers to district-level planners to NGOs to the national government

There is no single formula to approach SIS development in a novel context, and the range of SIS cases in our dataset demonstrates several possible enabling environment configurations and technological options. In countries with sufficient funding resources, a supportive institutional environment, and the necessary technical capacities, it may be reasonable to plan a new SIS intervention from the ground up that aims to reach all stages of the SIW and that meets the needs of multiple sectors and user groups. However, even in the relatively well-resourced countries in archetype 4, SIS developers encountered challenges and stumbling blocks across social, institutional, political, financial, and technological domains, requiring flexibility and changes in strategy to continue.

The observations and insights generated in this work will be used by CABI and partners in subsequent workstreams of the ***Process Toward Strengthening National Soil Information Services*** project. Using the list of enabling environment components and criteria, the four SIS archetypes, and synthesis insights, our next steps include developing a generalized, reproducible SIS intervention framework that integrates both technological and socio-institutional considerations which emerged during these workstreams. The goal of that activity will be to develop and test an improved process-based approach for SIS intervention design and implementation in novel contexts. That generalized SIS intervention framework will then be tailored to selected African countries, based on a comprehensive review of their enabling environment components and criteria, a user assessment, and a resources and capacities assessment. These tailored versions will then be validated as "roadmaps" for improved SIS intervention design with soil data stakeholders, potential SIS developers, and potential investors.

Appendix 1: Workstream 2 report



Link for the Workstream 2 report **here**

Appendix 2: SIS Roles

Group of roles	Group definition	Example roles within group
Decision-makers	Individuals who determine high-level characteristics and positioning of the SIS: Goals, funding and resourcing, strategy, institutional home, partnerships	Approvers Motivators / champions SIS management
Developers	Individuals who refine and implement the vision for the SIS set by decision-makers. This includes design, operations, HR and IT resourcing, and data collectors / processors / analysts	Technical - system design / architecture Technical - soils data creators, processors, analysts Field data collectors, technicians, & operations planners Laboratory technicians & analysts
Integrators	Individuals who align the SIS with existing or emerging policy and/or best practices. This includes legal considerations, data licensing, and community engagement & marketing	Data licensing and FAIR / data sharing officers National soils and environmental policy experts / officers Communications officers
Users	Potential or actual users of data, information, and knowledge from the SIS	Extension Researchers In-country NGOs / development organizations [Others, varying based on SIS and use cases]

Appendix 3: Guide to interview topics and questions

Note for interviewer team: Italicized text is used throughout this document to indicate instructional notes, alternative questions, and other guidance for you. This text is not intended to be read aloud to the interviewee.

All text that is in standard, non-italicised and non-bold font *can be read aloud, and/or adapted to your own voice.*

[Optionally, start with a brief introduction of the SIS project; briefly introduce who is in the Zoom room; ***if they participated in a prior conversation with Aline, explain that this interview is a follow-up to work done previously by our colleagues****. Then move on to the following introductory remarks.]*

Thank you for agreeing to have a conversation with us about SIS and soils data in *[country]*. This interview is intended to be semi-structured, and we have 37 questions that will guide the topics we'd like to cover. We expect this conversation to require between 60 and 90 minutes.

Two of us *[indicate interviewers in the Zoom room]* will be asking questions, and the third will take notes *[indicate who is the note-taker].*

This interview will be audio-recorded. The recording of the conversation will be kept confidential within our small team at CABI and ISRIC, and will be used only to validate and fill gaps in the notes taken during our conversation. The purpose of this is to ensure we can fully capture all of the key points and information that you're sharing with us.

[If the interviewee was also interviewed by Aline / the UCD team, add:] Some of our questions may have been asked by our colleagues who spoke with you previously, and part of our effort now is to validate that information. In case there is any question that you prefer not to answer, you can let us know that you'd like to skip that question and we will move on.

Do you have any questions for us before we begin?

SECTION 1: OPENING QUESTIONS

Purpose of section: Establish rapport; prompt the interviewee to begin thinking about the SIS, their role, etc.; hear the "story" of it from their perspective, in an open-ended way.

We'd like to start our conversation by asking some very broad questions about *[the SIS].*

	Questions	Interviewee responses	Interviewer notes
1	First, can you tell me the "history" of this SIS, from your perspective -- when and how it was started, by whom, with what goal, etc.? Follow-up questions : 1. Who “owns” or is responsible for the SIS? [Individual or organization] 2. How long has it been under development? 3. How has the project, goals, or mandate changed over time? 4. Is the SIS currently operational and available? If not, what is the current situation and / or plans to make it operational?	M1: [type response to the main question here] F1: [type response to followup question 1 here] F2: [type response to followup question 2 here] [The person writing interviewee’s responses can use the above structure to organize according to the questions.] [The interviewee might speak more holistically about these questions, in which case this strict numbering of responses can be dropped. Capturing what is said accurately is more important than organizing responses according to the question numbering.]	*[Interviewer’s unstructured notes, observations]* *[Use only as needed / if useful to help keep track of the conversation. Can be messy]*
2	How would you describe your role in relation to this SIS? Follow-up questions: 1. What is your experience / background / role with national-scale soils data and/or SIS more generally?		
3	What is the role that [your organization] plays in the SIS? Follow-up questions: 1. What was the reason your organisation was established? 2. Is the original vision and mission of your organisation still actual or how has this changed over time? 3. How has the staff composition and competence at your organisation change over time? 4. How many people in your organisation are involved in the SIS?		
4	In [country], which institutions are most important in the space of soils, environment, data governance, etc?		

SECTION 2: INSTITUTIONAL SUPPORT AND CLARITY

Purpose of section: To understand (1) the institutional environment around the SIS, and (2) the past, current, and future commitment of partners.

Following on that last question, we'd like to know more about the institutional partnerships or collaborations that were involved in the development and implementation of the SIS.

	Questions	Interviewee responses	Interviewer notes
5	Can you explain a bit more about these partnerships in terms of their involvement with: A) funding? B) needs assessment? C) technical and data aspects? D) operational and administrative aspects? Follow up questions: 1. Are these partnerships still ongoing? 2. Is the branding of the SIS agreed upon by the project partners?		

SECTION 3: INITIAL AND LONG-TERM FUNDING

Purpose of section: To understand at a high level (1) the initial funding context for the SIS, (2) how the SIS is sustained financially, and (3) how the SIS is expected to be sustained financially into the future.

The next several questions have to do with the four areas we just discussed: funding, user needs, technical and data aspects, and operational and administrative issues. We'll start with a couple of questions about the funding of the SIS.

	Questions	Interviewee responses	Interviewer notes
6	You mentioned that [organization / institution] funded the SIS initially. *[If not answered previously, instead ask: Who funded the creation of the SIS?]* 1. Followup question: Are you able to tell us about the costs of developing and implementing the SIS? *[If they don't know, at the end of the interview, request a reference to any others they may know who could speak about this.]*		
7	Is the SIS (now or in the future) self-sustaining financially, or will it depend on additional and/or external funds? *[If not self-sustaining:]* Is there funding for maintaining, sustaining, and growing the SIS into the future? Follow-up questions: 1. How well did the actual budget align with the initial expected budget for developing the SIS? 2. *[If budget revisions were needed]* Which areas were most challenging in terms of maintaining the budget?		
8	Does the SIS follow a business model? If yes, can you explain how the model works?		

SECTION 4: SIS USERS AND USE CASES

Purpose of section: To understand (1) the specific use cases and needs of users of the SIS, (2) How well the interviewee understands the users of the SIS, (3) understand what the user groups are, and (4) understand the extent to which the SIS has been built with intention to meet the needs of its users.

Now we have some questions about the audiences and users of the SIS.

	Questions	Interviewee responses	Interviewer notes
9	Who is/are the primary audiences for the SIS? Follow-up question: 1. Is that the same group that are the actual primary users now?		
10	Is the SIS tailored to the needs of these different users? Followup questions: 1. If so, can you tell me how? 2. What were some of the design decisions made with the user in mind?		
11	Is there any tracking of the use of the SIS? Followup questions: 1. How? (website hits? Time spent on site? Data downloads?)		
12	Can you tell me about any feedback the SIS has received from users?		
13	What problems or needs did the creation of this SIS aim to solve? Followup questions: 1. Was a needs assessment performed before/during the development of the SIS?		
14	Can you tell us what the use cases are? How did the SIS developers / decision-makers approach understanding the use cases for the SIS? Followup questions: 1. Which use cases are most important? 2. Which are core and which are peripheral? 3. Are there unexpected use cases that have emerged since the SIS was first created?		
15	What types of data or information are needed to meet these use cases? *[followup to prompt interviewee to answer as detailed as possible]* Followup prompts (for example): 1. not “soil data”, but what type of soil data *[nutrient content, pH, soil depth, etc.]* 2. not “climate data” but what type of climate data *[rainfall, temperature, annual means or time series, real-time etc.]* 3. not” crop data” but what type of crop data *[yield for a specific crop, crop calendar, production statistics, etc.]*		

SECTION 5: INFORMATION AVAILABILITY AND ACCESSIBILITY WITHIN THE SIS

Purpose of section: to learn from the interviewee broadly what information is available in the SIS, and whether and how that information has been made accessible to users.

Now that we've discussed the use cases and users of the SIS, we'd also like to know more about how the SIS serves their needs.

	Questions	Interviewee responses	Interviewer notes
16	How does the SIS enable users to view and/or work with the soil information? Followup questions: 1. How can users interact with the data in your system? (e.g., download data directly, any reports that can be run at a website to answer questions) 2. What is the format of the data visualization available to users? (are there maps published on the internet?)		
17	How is the current system made available--website, server, etc? Followup questions: 1. Where / who hosts this?		
18	Are there synthesis products, derivatives, or other insights provided along with the soil data? Followup questions: 1. What are some of these?		
19	How has information or new knowledge from the SIS has been used to guide actions / outcomes?		

SECTION 6: DATA POLICIES & LICENSING

Purpose of section: to understand how data licensing and data sharing are approached in the system / context in which the SIS operates.

	Questions	Interviewee responses	Interviewer notes
20	Are data licensing and data sharing policies in place in this country / system? Followup questions: 1. Are additional national policies or legislation needed?		
21	How is governance of the SIS and its data organized? Followup questions: 1. What policies or practices are in place to make data in the SIS: a. Findable? b. Accessible? c. Interoperable? d. Re-usable?		

SECTION 7: SOIL AND ENVIRONMENTAL POLICIES

Purpose of section: To understand the country policy environment or factors that may affect the mandate for the SIS or how it is developed.

	Questions	Interviewee responses	Interviewer notes
22	Do you have environmental laws, policies, subsidies in your country that (also) relate to soils? *[Additional prompt if needed: for example, agricultural, water, degradation, (soil) contamination, etc.]* Followup question: 1. Does the SIS (or soil data) have a role in policy development in these areas?		

SECTION 8: BUSINESS CASES AND SIS SUSTAINABILITY

Purpose of section: To understand whether and how the SIS is or will continue to be justified into the future. Does the interviewee perceive that the benefits it provides will balance the costs to build and maintain it?

We understand that an important aspect of building a SIS is planning for how it will be sustained into the future. The next few questions address the business case of the SIS and its sustainability.

	Questions	Interviewee responses	Interviewer notes
23	Is the SIS useful for you, and/or for its users? Followup questions: 1. What are some of the unmet needs that you believe still require attention? 2. What are the barriers to achieving this?		
24	Is the SIS still actively acquiring/receiving new data? Followup questions: 1. How do you incorporate new data?		
25	Is the SIS intended to evolve? Followup questions: 1. How often is it updated and improved? 2. Who is involved in this aspect of the SIS's management?		
26	How would you describe the long-term benefits of the SIS and soil data for [the country]? Followup question: 1. What role do you think the SIS might have in decision-making in *[country]*?		
27	Can you share about any potential challenges or uncertainties you foresee in the ongoing sustainability of the SIS into the future?		

SECTION 9: STANDARDS AND DATA WORKFLOW FOR THE SIS

Purpose of section: To understand at a high level how data is generated, processed, and integrated into the SIS and its products; and lessons learned about this.

Related to its sustainability are some questions about the SIS's functionality and features that ensure it continues meeting the needs of its users.

	Questions	Interviewee responses	Interviewer notes
28	What types of data are included in the SIS? Followup questions: 1. Can you tell me about how the data are / were collected, processed, and incorporated into the SIS? 2. Which are the key organizations involved in this workflow?		
29	Are there metadata available for all datasets in the SIS? Followup questions: 1. How are standards for metadata implemented in the SIS?		
30	What was the process of determining which technologies are integrated and made functional within the SIS? *[Additional prompt if needed: for example, open source – proprietary, custom or off-the-shelf / standardized]*		

SECTION 10: TECHNICAL CAPACITY

Purpose of section: Understand the technical resourcing and capacity (1) needed and (2) available for building and sustaining the SIS.

	Questions	Interviewee responses	Interviewer notes
31	What is the current capacity in-country for the technical aspects of the SIS? *[Additional prompt if needed: For example, collecting (or analyzing / archiving / organizing / modelling / serving) data on soil?]*		
32	Which laboratories, institutes, or organizations have already been engaged in these aspects? Followup question: 1. Is the necessary equipment in place to host the SIS?		
33	What types of staff and expertise are needed to sustain the activities and development of the SIS? Followup questions: 1. Is there an IT department? 2. Is it in the ministry, adjacent ministry, or outsourced? 3. How well-resourced (staff and budget support) is the IT department? 4. How stable is it? Turnover? 5. Is the IT department capable of meeting the specific requirements of the SIS, or is there a need for capacity building and additional resources?		

SECTION 11: CENTRALIZED OR FEDERATED SYSTEM

Purpose of section: To understand whether and how the SIS is integrated with other systems, and how these integrations are achieved at technical and institutional levels.

	Questions	Interviewee responses	Interviewer notes
34	How are data from different sources aligned in the SIS? Followup questions: 1. Do you have one database/data location, or does the interface show data from multiple sources that are located at different locations?		
35	Is the architecture of the SIS centralised or federated? Followup questions: 1. Can you tell me a bit more about how this works?		

SECTION 12: SYNTHESIS AND CLOSING QUESTIONS

Purpose of section: To understand whether and how the SIS is integrated with other systems, and how these integrations are achieved at technical and institutional levels

We have a couple more questions to finish up our conversation. As part of our work, we're interested in understanding the 'enabling environment' for the SIS. This means broad factors in [country] that have either supported or limited the SIS in its development.

	Questions	Interviewee responses	Interviewer notes
36	What are key success factors in your SIS development? What are limiting factors or barriers in your SIS development?		
37	What are some of the most important lessons you have learned about establishing a SIS? Followup question: 1. Could you identify approaches that worked well or did not work well?		

That concludes the main questions that we wanted to cover with you.

Is there anyone else with a connection to [the SIS] who you think we should speak with? *[Can also use this opportunity to ask more specifically for people in certain roles, if interviewees are needed.]*

Is there anything further you want to add to our conversation?

[Wrap up the conversation, thank them, etc.]

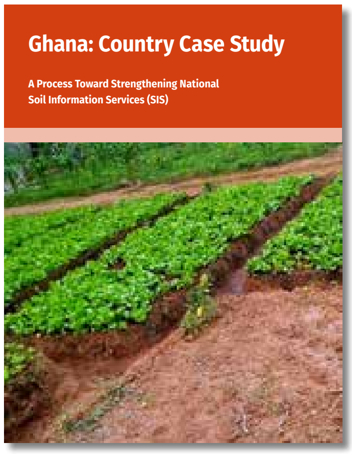
Appendix 4: Capacities and expertise

Soil Information Workflow stage	Capacities needed among SIS roles
User consideration	User assessment facilitators M&E specialists Champion, People Manager, Coordinator
Data collection	Soil survey logistical planners Field technicians Pedologists and soil taxonomists Quality assurance/quality control manager
Laboratory analysis	Laboratory technicians Pedologists and soil taxonomists Soil chemists & geomorphologists Remote sensing scientists QA/QC manager Statistician (uncertainty quantification, error handling
Soil archiving	Soil science generalists Digitizers of borings/samples Storage and preservation experts Librarians
Data organization	Data analysts Database designers / architects Data managers / administrators Data governance specialist Information technology & security engineer
Modeling and mapping	Soil classification and machine learning modelers Statisticians Spatial data scientists Soil science generalists and agronomists GIS analysts & cartographers
Applying soil information	Soil science generalists and agronomists Data scientists Decision tool designers UX designers Software developers Communications & policy specialists M&E specialists
Data and information serving	Data scientists UX developers Software developers Web developers Information technology & security engineer

Appendix 5: Country case studies

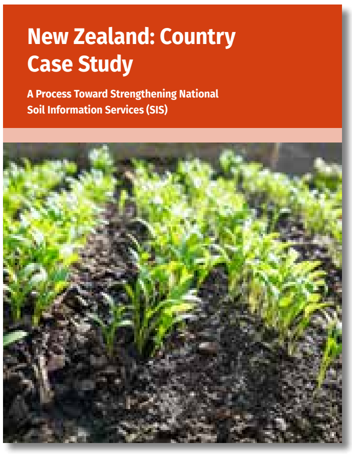
Click to view the Austrialia case study **here**

Click to view the Ethiopia case study **here**



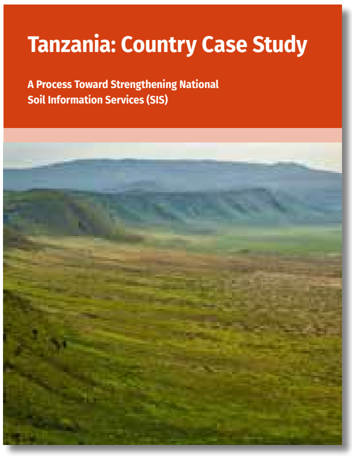
Click to view the Ghana case study **here**

Click to view the Lesotho case study **here**

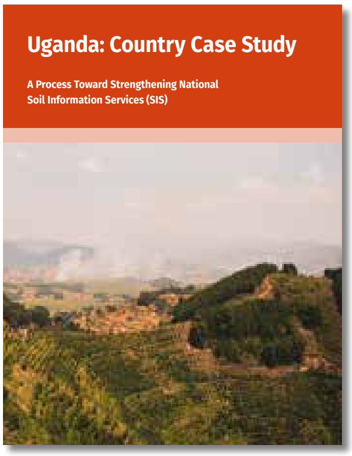


Click to view the New Zealand case study **here**

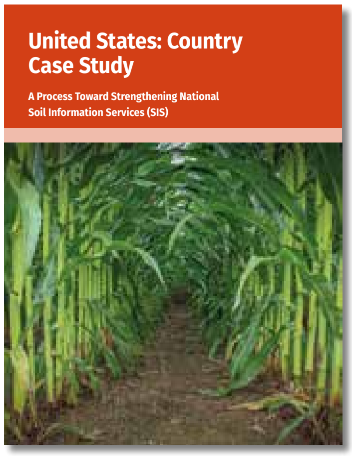
Click to view the Rwanda case study **here**



Click to view the Tanzania case study **here**



Click to view the Uganda case study **here**



Click to view the United States case study **here**

Appendix 6: Archetypes framework

Conditions

		Archetype 1: SIS is newly emerging		Archetype 2: SIS is approached as a discrete project			Archetype 3: SIS sustained by institutional coalition	Archetype 4: SIS is a function of the national government		
Enabling environment component	***Enabling environment criterion - condition***	***Country A***	***Country B***	***Country C***	***Country D***	***Country E***	***Country F***	***Country G***	***Country H***	***Country I***
Initial funding for the SIS	*Funding source for initial SIS effort*	Government; donor funding	Donor funding	Donor funding	Donor funding	Donor funding	Government; donor funding	Government	Government	Government
Institutional environment	*Presence of a SIS or soil data champion*	Yes - individual	Uncertain	Yes - individual	Uncertain	Yes - individual	Yes - institution(s)	Yes - institution(s)	Yes - institution(s)	Yes - institution(s)
	Current institutional host of the SIS	Government institute or ministry	Government institute or ministry	Government institute or ministry	Government institute or ministry	Government institute or ministry	Government institute or ministry	Government institute or ministry	Government	Government
Users, use cases, and beneficiaries	*Formal user or stakeholder needs assessment*	Uncertain	No	Uncertain	Uncertain	No	No	Yes	Yes	Yes
	Use cases that motivate(d) the SIS - named by interviewees	Fertilizer recommendations; soil nutrient management; acidity management	Fertilizer recommendations; soil erosion mitigation	Agricultural advisory services; land use planning; fertilizer recommendations	Acidity management; erosion management	Land use planning	Agricultural advisory services	Consolidation of legacy and new data; spatial land use planning; soil water management	Farm-level sustainability credentials; water resource management; land use planning; agricultural advisory; carbon credits / markets	Natural resources management; academic research; agribusiness
	User groups of the SIS - current and/or target	Government; researchers	Government; researchers	Government; academia; agricultural advisory; researchers	Government; students; research institutes	Government; external research institutes; academia	Government; agricultural advisory; external and internal research institutes	Regional government; agricultural advisory; landowners; private sector	Government; research institutes; academia; agricultural advisory; private sector	Government; research institutes; private sector; academia
Technical capacities and expertise	*Capacities existing internally for Data collection*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Capacities existing internally for Laboratory analysis	Yes - partial	Yes - partial	Yes - partial	Yes - partial	Yes - partial	Yes - partial	Yes	Yes	Yes
	Capacities existing internally for Data organization	No - needs capacity building	No - needs capacity building	Uncertain	No - needs capacity building	No - needs capacity building	Uncertain	Yes	Yes	Yes
	Capacities existing internally for Modeling and mapping	No - needs capacity building	Yes - partial	No - needs capacity building	No - needs capacity building	No - needs capacity building	Yes - partial	Yes	Yes	Yes
	Capacities existing internally for Applying soil information	Uncertain	No - needs capacity building	No - needs capacity building	Uncertain	No - needs capacity building	Yes - partial	Yes	Yes	Yes
	Capacities existing internally for Data and information serving	No - needs capacity building	No - needs capacity building	No - needs capacity building	No - needs capacity building	Yes - limited	Yes - partial	Yes	Yes	Yes
	Internal availability of scientific physical & material resources: laboratories, equipment, supplies	Yes	Yes	Yes - partial	Yes	Uncertain	Yes	Yes	Yes	Yes
	Capacity for local creation and retention of expertise needed to sustain a SIS	Yes - limited	Yes - limited	Yes - limited	Yes - partial	Yes - partial	Yes - partial	Yes - partial	Yes	Yes
Digital and computing infrastructure	*IT infrastructure and equipment to expand and grow the SIS from its current state*	No	Yes - partial	No	No	No	Yes - partial	Yes	Yes	Yes
	Internal availability of IT infrastructure and equipment: computers, software, servers	Yes - partial	Yes - partial	No	Yes	Yes	Yes	Yes	Yes	Yes
Business model and sustainability	*Capacities lacking internally to the SIS are filled by external partners or by hiring private sector contractors*	No	No	No	No	No	Yes	Yes	Yes	Yes

Outcomes

		Archetype 1: SIS is newly emerging		Archetype 2: SIS is approached as a discrete project			Archetype 3: SIS sustained by institutional coalition	Archetype 4: SIS is a function of the national government		
Enabling environment component	***Enabling environment criterion - outcome***	***Country A***	***Country B***	***Country C***	***Country D***	***Country E***	***Country F***	***Country G***	***Country H***	***Country I***
Business model and sustainability	***Continuity of the SIS / soil data efforts***	2016 (launch); 2018 (activities paused)	2020 (launch)	2013 (launch)	2017 (launch)	c. 1950 (legacy data); 2018 (launch)	2012 (launch)	1959 (legacy data); 1984 (early database); 2017 (relaunch)	c. 1998 (early SIS); 2021 (relaunch)	c. 1900 (legacy data); c. 1970 (early database); c. 1990 (relational database);
	Funding source for SIS operation & maintenance	Government; external partners	Government; external partners	Government; external partners	Government	Government	Government	Government; private investors	Government	Government
	Funding source for enhancements & additions	Uncertain (2024)	In active discussion (2024)	In active discussion (2024)	Government in-kind (data) contributions; project-based	Government in-kind (data) contributions; project-based	Project-based	Government; private investors	Government	Government
Institutional environment	***Institutional partners of the SIS***	Government	Government; external research institutes	Government; academia; internal research institutes	Government	Government	Government; external research institutes; external development partners	Government	Government	Government
Users, use cases, and beneficiaries	***Evidence of the SIS currently used to meet needs of any user groups or use cases***	Little available public information demonstrating usage	Little available public information demonstrating usage	Little available public information demonstrating usage	Yes - examples of usage described by SIS developers	Yes - examples of usage described by SIS developers	Yes - data are cited in publications, project materials, etc.	Yes - data are cited in publications, project materials, etc.	Yes - data are cited in publications, project materials, etc.	Yes - data are cited in publications, project materials, etc.
Data availability / accessibility	***Data currently accessible to users***	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Open-access types and formats of data	Raw data (download)	Soil properties; raw data (download); static raster (view and download)	Derived products; static raster (view and download)	Soil properties; interactive raster (view only)	Soil properties; interactive raster (view only)	Soil properties; interactive raster (view and download)	Soil properties; derived products; interactive raster & vector (view and download)	Soil properties; derived products; interactive raster & vector (view and download)	Soil properties; derived products; interactive raster & vector (view and download)
	Soil Information Workflow Components	Data collection Laboratory analysis Data organization Applying soil information (limited)	Data collection Laboratory analysis Data organization Applying soil information (limited)	Modeling and mapping	Modeling and mapping	Modeling and mapping	Applying soil information	Data and information serving	Data and information serving	Data and information serving
Data governance, policies, and licensing	***Policies or practices are in place to guide data access and use***	No explicit data governance	No explicit data governance	No explicit data governance	Data access is restricted	No explicit data governance	Data managed under a national data sharing policy	Open access; some data are under a pay model	Open access	Open access; some data available upon request, but requests are typically granted

Appendix 7: Soil Information System Use Cases

Use Case: **Precision farming and Sustainable Agriculture**

Key Issues to Address

- Fertiliser recommendations, soil fertility planning
- Crop suitability & yield potential
- Pest & disease management
- Sustainable farming
- Organic farming and sustainable farming certification
- Irrigation scheduling
- Food security studies

Key Applications of SIS

- Engage in end user decision making processes to ensure optimal use of soil information, by making the data and information available, fit for purpose and accessible, combined with raising awareness of stakeholders and users of its presence.
- Improve effectiveness and efficiency of agronomic practices, including fertilizer recommendations, irrigation, and organic matter management by adjusting them to the soils at a certain location, resulting in boosting of crop production, soil health and farm income.
- Enhance precision of water management for agriculture (irrigation, drainage, watershed management) in space, time, amount, resulting in cost savings for both the government and farmers.
- Enhance precision of fertilizer applications in space, time, amount and composition, resulting in cost savings for both the government and farmers.
- Provide advice on the soil fertility status and improvement of soil fertility (using spatial nutrient gap analysis based on yield response data).
- Identify specific soil constraints for crop production, including specific nutrient deficiencies, soil acidity, soil solidity/salinity, soil depth soil erosion risk, soil structural constraints, soil drainage, and soil carbon sequestration potential.
- Mapping of yield response to fertiliser.
- Empower farmers with the requisite knowledge to choose the best crops and farming strategies, based on the soil types and conditions.
- Support for organic farming practices through provision of relevant soil information on the need for organic amendments.
- Provide farmers with easy, accessible, and actionable soil information at a low cost to boost productivity, soil health and farm income.
- Enhance long-term sustainable soil management practices.
- Provide input data for food security modelling and analyses.

- Spatial targeting of fertiliser supply (types and quantities) to different regions within a country.
- Spatial targeting of carbon sequestration projects.
- Decision support tool for farmers on irrigation scheduling.

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Use Case: **Sustainable Land Management**

Key Issues to Address

- Land quality assessment
- Land evaluation and land use planning
- Fertility capability classification
- Civil engineering, infrastructure development (roads, engineering, building construction), and site investigations – pond siting, dam siting, septic tank siting
- Land reclamation, phytoremediation
- Land degradation assessment

Key Applications of SIS

- Provide information on current and possibly suitable land use and land management practices to assess and improve its suitability and therefore sustainability.
- Use adequate and/or best available soil information for land quality assessment, land evaluation and land use planning1 by various users.
- Use soil data to map Fertility Capability Classification for targeting interventions for sustainable agriculture.
- Protection of high potential land for agricultural use.
- Provide soil information for infrastructure development (roads, cables, bridges, buildings, dams, reservoirs, sceptic tanks, etc.) to improve location choice and design given the soil and water management characteristics of an area, and in doing so reduce risk and possibly realisation costs.
- Provide information on soil pollution and presence of waste dumps to assess its extent and to assess the suitability and projected costs of remediation techniques given the physical site conditions and pollution present.
- Assess degree and location of land degradation for intervention targeting and reporting to UNCCD.

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Use Case: **Soil Health and Quality**

Key Issues to Address

- Soil health assessments
- Soil quality assessments
- Soil threats assessments
- Soil drainage
- Soil pollution (heavy metals, microplastics, biocides)
- Reduce biodiversity loss
- Rangeland management
- Veterinary & livestock science – soil- and vector-transmitted diseases

Key Applications of SIS

- Assess soil health, soil quality and identify the presence and impacts of soil threats.
- Facilitate measures to mitigate soil threats and improve soil health.
- Help to create a regional or national soil monitoring programme and system for the various stakeholders (e.g. farmers) to:
- Monitor soil health, including biodiversity.
- Monitor soil threats.
- Identify and assess areas at risk of soil degradation due to climate and human pressure.
- Allow evaluation of mitigation and improvement measures.
- To assess progress towards climate change mitigation goals, soil health goals and soil potential productivity goals.
- Develop and evaluate soil or soil related policies.
- Help maintain long-term soil fertility and productivity.
- Provide information on soil pollution to assess its extent and to assess the suitability and projected costs of remediation techniques given the physical site conditions and pollution present.
- Participatory assessment of rangeland health.
- Temporal and spatial soil property and soil moisture monitoring to track potential for soil-transmitted, vector-borne, and zoonotic disease.

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Use Case: **Disaster Risk Management/Climate Change Adaptation and Mitigation**

Key Issues to Address

- Climate change (effect) modelling
- Carbon stock change assessments and carbon sequestration potential
- Disaster risk reduction

Key Applications of SIS

- Assess vulnerability of land to climate change impacts such as drought and floods.
- Use soil information in climate change adaptation strategies design and evaluation, such as adapted land use planning, increased drainage and water retention management, adaptations in crop and vegetation choices, etc.
- Assess greenhouse gas fluxes incl. hotspots from soils and design and evaluate mitigation strategies, e.g. reduced drainage of peatlands.
- Assess current soil organic carbon stocks and soil carbon sequestration potential.
- Identification of climate change related land degradation problems to policy makers to intervene by implementing low-cost policies and strategies.
- Use soil and other environmental data in disaster risk assessment and risk reduction strategies, for example by widening floodplains of rivers where possible, considering infiltration characteristics of soil.
- Landslide risk assessment.

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Use Case: **Soil and Water Conservation**

Key Issues to Address

- Soil conservation, erosion and sedimentation assessments
- Hydrological modelling & water resources management, flood risk prediction

Key Applications of SIS

- Contribute to managing freshwater resources, e.g. understanding aquifer recharge, runoff and sedimentation dynamics influenced by hydrophysical soil properties.
- Provide the soil data needed for actual and erosion risk assessment in an area. This will then allow to take appropriate erosion risk mitigation measures.
- Provide the underlaying soil hydrophysical data to facilitate local or watershed hydrological modelling for irrigation and water management, including an early warning system for droughts, risk and impact of floods, etc.
- Improved irrigation, drainage and erosion management at field, farm or watershed level by adjusting suggested measures to the actual and possibly future circumstances and hydrophysical characteristics of an area.

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Use Case: Policy and Decision Making

Key Issues to Address

- Soil and environmental laws
- Policies and land use acts
- Soil related policy making and evaluation

Key Applications of SIS

- Make informed decisions and develop and evaluate policies and legislation related to e.g. land use planning, soil health, sustainable soil management, soil fertility, climate change mitigation and adaptation, infrastructure, water quality, quantity and disaster management.
- Informed decision-making is facilitated by coordination among existing and future soil data projects and efforts towards or by providing a centralized soil data hub for a diverse range of users to equip stakeholders with accurate soil information to inform their decisions.
- Harmonised soil information across national borders can facilitate regional or continental policy development and evaluation to improve soil health, to strengthen and secure resilience against climate change, to allow continental food security decision making, concerted action against land degradation and biodiversity loss, etc. Because of its harmonised nature, discussion is expected to centre more on the policy and its effectiveness itself than on the quality and representativeness of the numbers per country.
- Improved reporting on national commitments to conventions and international agreement, including UNFCCC, UNCCD, UNCBD, African Convention on the Conservation of Nature and Natural Resources.

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Use Case: **Research and Development**

Key Issues to Address

- Soil science research
- Soil science education such as soil formation and soil variation at different spatial scales
- Utilising legacy or scattered soil data
- Pedotransfer functions
- Digital soil mapping
- Soil spectral calibration libraries
- Soil information standards
- Agronomy and horticulture
- Forestry - site suitability, impacts of management on sol health.
- Ecology – soil as habitat, restoration, agroecology, biodiversity
- Geography, Geology, Geomorphology, Hydrogeology, Hydrology & Earth sciences
- Biogeochemistry
- Archaeology
- Public health – malarial habitats, soil health-food health linkages, food safety, soil-transmitted diseases
- Space exploration

Key Applications of SIS

- Facilitate research in general by providing an overview of and access to, ideally, standardised and/or harmonised soil data.
    - Public health:
        - Monitoring landscape-level soil moisture to identify endemicity hotspots for vector-borne and soil-borne pathogens and disease.
        - Identification of areas with high soil particle aerosolization with potential contribution to air pollution.
        - Soil nutrient profiles may influence local or regional crop nutrient profiles, suggesting specific soil management or enrichment of food crop products.
    - For soil science research, such as on soil formation, soil chemistry, soil physics, the interaction between geology, geomorphology (landscape formation) and soil types and properties in space and time, etc.
    - For land evaluation, agronomy, forestry, horticulture, land use planning to understand the interaction between soil, climatic, moisture dynamics and characteristics and the (foreseen) vegetation and use of the land.
    - Development of soil spectral calibration libraries and digital soil property maps.
    - As input to dynamic process models to simulate current and future conditions and e.g. crop production, food security, land degradation, suitability, etc.

  - As input to statistical or machine learning models to improve soil mapping and maps, either continuous soil property maps or soil class or other maps.
  - To provide the ground truth data to improve soil and other mapping from space by remote sensing.
  - To facilitate assessment of and development of new agricultural technologies and practices.
  - As input to understand previous e.g. land settlement to evaluate the likeliness of archaeological findings.
  - To understand patterns of soil fertility variability on smallholder farms.
- Create an easily accessible digital repository of existing soil information.
- Safeguard existing (non-digital and digital) legacy and new soil data to facilitate research and other uses.
- Provide the data to make updated soil maps of an area, possibly specifically for a single purpose, or more generic.
- Provide materials for soil science and other soil related education.
- Provide and develop soil information standards for e.g. soil sampling, lab analysis, data storage and exchange.
- Give in depth understanding of e.g. soil nutrient cycles and other soil processes to guide adoption of strategies to maintain soil health.

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Use Case: **Economic and Social Benefits**

Key Issues to Address

- Higher yield of crops
- Improvement of human and livestock health
- Avoid conflict resulting from land degradation and a lack of food security
- Improvement of agriculture resilience and sustainable livelihoods under a changing climate
- Sustainable use of soil resources
- Defence – military application

Key Applications of SIS

- Contribute to higher and more reliable crop yields, better market opportunities, increased profitability, and improved livelihoods.
- Improvement of human health by e.g. improving crop nutrition, reducing exposure to chemicals, pesticides, and toxins in the food system.
- Provide accurate soil information to avoid or mitigate land degradation which can result in conflicts.
- Through better assessment of soil potential production versus actual production, facilitate decision making on mitigation of food security risks and improvement of regional or national food production.
- Reduced risk of engineering failure in building of roads, bridges, buildings, dams, and other infrastructure.
- Provide economic insights on the benefits of precise soil information, highlighting cost savings, such as better infrastructure construction planning resulting in reduced risk costs.
- Better land use planning resulting in reduced costs for climate change adaptation, especially in river basin, low lying areas or areas with a higher risk of drought.

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Appendix 8: Usage of global and continental soil information products

Global and continental soil information products, such as WoSIS and GLOSIS, are used to target continent-scale interventions. These information products may be used to address issues such as micronutrient supplementation programmes, intervention programmes on Podoconiosis (non-filarial elephantiasis), or targeting of fertilizer formulations and quantities by fertilizer companies. Soil data on, for example, Fe and Zn levels, may be used to identify potentially deficient areas. Mapping of volcanic soils may be used to determine risk factors for Podoconiosis. Continental mapping of soil macro- and micro-nutrient deficiencies can be used to guide companies' fertilizer supply strategies. Primary users of global and continental soil information products include international donors and development initiatives and fertilizer companies.

Usage of global and continental products

Global and continental soil information products are frequently used. As an indication, the latest WoSIS scientific paper was viewed close to 20,000 times since its publication in 2020, downloaded over 5,000 times and cited in 193 other publications as of late 2024. The latest SoilGrids scientific paper was viewed over 22,000 times since its publication in 2021, downloaded over 5,000 times and cited in 592 other publications. SoilGrids is available through multiple web portals (e.g. soilgrids.org, Google Earth Engine, others), and exact statistics are therefore difficult to retrieve. It has been used to 'gap-fill' countries for FAO-Global Soil Partnership (GSP) and UN Convention to Combat Desertification (UNCCD) maps and reporting.

The **iSDAsoil** digital soil properties map of Africa at 30-meter resolution provides maps for over 20 soil properties at two soil depths including uncertainty estimates. This open-source product has been widely used with 708,336 API calls made in 2023 alone and with published applications in agriculture, conservation, environment, public health, and livestock health. Including training points from other countries has shown to improve soil property estimates for a target country. The cloud-based workflow based on Google Earth provides a training resource for national digital soil mapping. National SIS can use the workflow to generate their own digital soil property maps and test the addition of their own training data and covariate data (e.g., soil taxonomic maps, geological maps).

Examples of use cases of global or continental soil map products

2024 INSII Survey Results

In early 2024 CABI and ISRIC collaborated on the implementation of a survey to be distributed among members of the International Network of Soil Information Institutions (INSII). Responses to the survey provide illustrative examples of the use cases and applications for global and/or continental soil information products. Examples drawn from the survey results, lightly edited for clarity, are provided below.

As a ministry of environment, I need to provide the Land Degradation Neutrality reporting for my country to the UNCCD. I do not have a national soil organic carbon map or representative and recent monitoring available. So I use a regional, continental or global product to provide me with the best estimate available to be able to fulfill my reporting duties. If I have some scattered recent soil organic carbon (SOC) data available, I might test which of the available maps (e.g. SoilGrids, iSDA SOC map, others) best matches my own data. Otherwise, I might judge the maps based on the reported uncertainty for my country and on the patterns that are visible on the map to see if they match my knowledge of the soils and landscapes in my country. I am satisfied when I recognise the patterns on the map, if I do not see artefacts of other used imagery and if the values on the map and their SOC patterns match the values and patterns of my own data within reasonable limits.

As a national INSII member, often a national soil institute, bureau of statistics or ministry of agriculture or environment, I am tasked to provide the national contribution to one of the GSP global products and SoilSTAT. I do not have national data that I can use. I can use continental or global products (e.g. SoilGrids, iSDA maps, others) to provide information about my country to FAO or other UN bodies (e.g. UNCCD). I will check whether the continental or global products reflect the patterns and values of the soil properties I expect based on my expert knowledge of my country. I am satisfied when the continental or global maps seem to reflect a reasonable estimate of the status of the soils in my country. If they do not, I will use this as an argument to discuss a national soil mapping or monitoring campaign with my government.

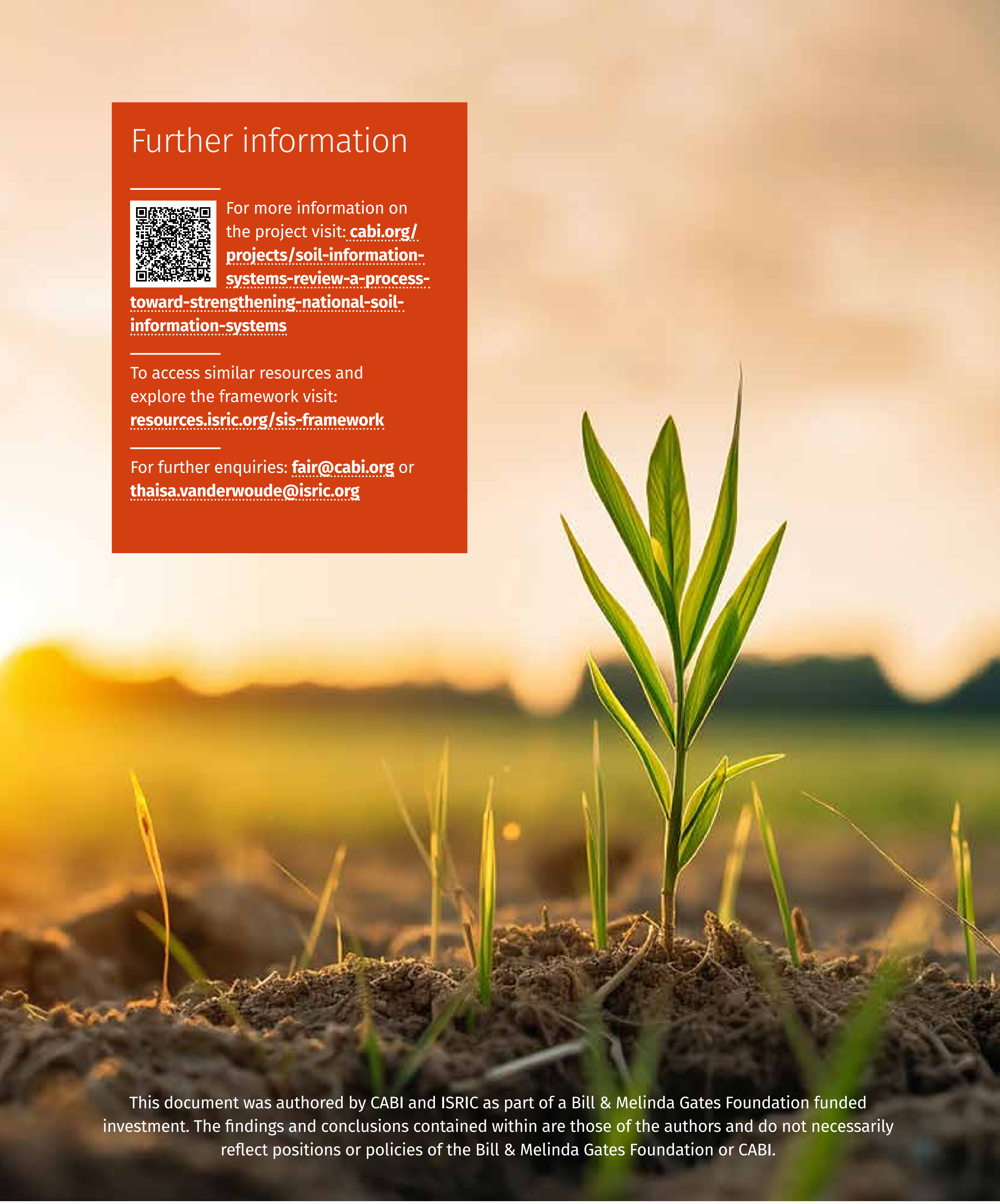
As a UN body (FAO, UNCCD, UNFCC, others), I would like to understand the status of the worlds soil resources and the trends that key soil properties show, to understand whether the policies and pledges of countries are working and if they are sufficient to reach the goals we agreed upon together. Such as the Paris Agreement, the Sustainable Development Goals, the current and potential productivity levels of soils to feed the world and contribute towards climate change mitigation goals. For this purpose, I need to have information about the soils in all countries that I operate in (all UN member countries), that is reliable, representative of the spatial patterns in a country, recent (with adequate timestamp), and accurate enough to observe relevant changes. Ideally this information is in the same unit of measure, collected with similar or adequate methodologies. If I only need statistics per country, I do not care about boundary effects. If I need maps to run my models, e.g. for climate change scenarios, I would like to have continuous maps that do not have artefacts, boundary effects (which makes me question the validity of the values on the map) and have a resolution that is fine enough to capture in country patterns, but coarse enough to allow me to run my models. I would like to source this information from countries themselves and if not possible from global or continental products that incorporate as much of the recent, reliable and available soil information (of countries and other entities) as possible.

I am satisfied if the provided soil information allows me to evaluate the adequacy of the current measures and the reachability of the goals we set with reasonable uncertainty.

Additional published examples

A country has invested in soil mid-infrared spectroscopy technology for rapid and high throughput analysis of a suite of soil properties. The soil survey department have collected 1,000 soil georeferenced samples in a new national sampling campaign but do not have resources to analyse the samples using conventional soil analysis methods. The country uses calibrations developed by the Global Spectral Calibration Library and Estimation Service (Shepherd et al, 2022) to provide approximate soil property estimates from the MIR soil spectra. They use these estimates to create a digital map of soil constraints for the country to guide interventions such as liming programmes and to prioritise soil conservation efforts. They analyse a 10% subset of the samples in their own laboratory to test the accuracy of the spectral estimates. They also submit a few hundred diverse samples to the estimation service for conventional and spectral analysis, both to assess their laboratory results and to localise the global spectral calibrations for their country. The localised and validated calibrations can then be used for making soil property estimates for any new samples taken.

International agricultural research centres wanted to get an overview of soil fertility constraints in rice fields in Africa and how they are affected by production systems and agro-ecological zones to better target their research. A soil survey of rice fields was conducted on 1628 farmers' fields at 34 sites and in 20 countries. Samples were analysed using soil infrared spectroscopy. Results are reported in Johnson et al., 2021.



Further information

For more information on the project visit: cabi.org/projects/soil-information-systems-review-a-process-toward-strengthening-national-soil-information-systems

To access similar resources and explore the framework visit: resources.isric.org/sis-framework

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