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Global soil spectroscopy assessment

Spectral soil data: needs and capacities

2020

GLOBAL SOIL PARTNERSHIP

2020 | Global Soil Spectroscopy Assessment

Spectral soil data: Needs and capacities

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ISRIC – World Soil Information

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Canada - University of Saskatchewan

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United States of America - Texas Tech University

United States of America – United States Department of Agriculture, Natural Resources Conservation Service

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Australia – Commonwealth Scientific and Industrial Research Organisation

Australia - University of New South Wales

Republic of Fiji - Department of Primary Industries Parks Water & Environment Tasmania

Republic of Fiji - Sugar Research Institute of Fiji

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Abbreviations and acronyms

FAO: Food and Agriculture Organisation of the United Nations

GLOSIS: Global Soil Information System

GLOSOLAN: Global Soil Laboratory Network

GSP: Global Soil Partnership

ICRAF: International Centre for Research in Agroforestry

ISO: International Organization for Standardization

ISRIC: International Soil Reference and Information Centre – World Soil Information

MIR: mid-infrared

NENA: Near East and North Africa

NIR: near infrared

PXRF: portable x-ray fluorescence

RESOLAN: Regional Soil Laboratory Network

SOP: standard operating procedure

SWIR: short-wave infrared

USDA: United States Department of Agriculture

VNIR: visible and near infrared

WG: working group

Key messages and outlook

The key messages emerging from an analysis of the results of this questionnaire (reported in Annex I) are that:

- The vast majority of participants to this survey want to start or improve measurement of soil properties using diffuse reflectance soil spectroscopy methods.
- Laboratories expect support on starting soil spectral measurements and on improvement of their current soil spectral measurements from GLOSOLAN and the RESOLANs, and they want to join the initiative.
- Laboratories measure VNIR and MIR ranges for diffuse reflectance soil spectroscopy; efforts should therefore focus on both.
- Most-used brands are Bruker and Agilent for MIR, and ASD and FOSS for VNIR.
- There is a clear demand for:
    - improvement of the quality of measurements and spectral modelling;
    - a standardized soil spectral calibration library;
    - harmonization of methods;
    - training and tools;
    - soil spectral data sharing; and
    - a community effort on all of this, led by GLOSOLAN.
- Sharing and using shared soil spectroscopy data is welcomed by most, although the ability to do so is not always present.
- Integration of soil spectral data in GLOSIS is welcomed by the vast majority of respondents.
- Soil spectral data sharing is preferred as both flat files and proprietary formats, through a web portal that allows querying of the data and/or makes data downloadable as zip files.
- Efforts should be prioritized within each region as current status and requirements vary.
- Respondents indicated their willingness to help, which supports the aim to continue building a community of practices on soil spectroscopy.

These key messages summarise the priorities for the work plan of GLOSOLAN and advise cooperation with GLOSIS.

1. Introduction

This survey was conducted by the Global Soil Laboratory Network (GLOSOLAN) of the Global Soil Partnership, FAO. GLOSOLAN was established in November 2017 with the purpose of building and strengthening the capacity of laboratories in soil analysis and to respond to the necessity for harmonizing soil analytical data. In April 2020, GLOSOLAN launched its initiative on soil spectroscopy[1] (additional information available here), an alternative to the use of wet chemistry for soil analysis. With the support of its partners, GLOSOLAN aims to build a globally-representative calibrated soil spectral calibration library (database) based on MIR spectra with accompanying accurate soil property reference data. The library will be paired with a freely available and easy-to-use soil property estimation service based on the evolving GLOSOLAN global MIR spectral calibration library. GLOSOLAN initiative on soil spectroscopy will focus on country capacity building and will support countries to contribute to both soil spectral calibration library and the soil property estimation service, by organizing training sessions, developing standards and protocols.

The GLOSOLAN work plan on soil spectroscopy was defined at the first plenary meeting on soil spectroscopy[2], which was organized on the online platform Zoom in September 2020. In order to support the discussion and set priorities for activities, all soil laboratories registered in GLOSOLAN and members of the IUSS Pedometrics WG email list were asked to complete an online survey on their capacities and needs for the use of soil spectroscopy. The survey was open from November 2019 to July 2020. The survey results are herewith reported and discussed.

1.1. Participation in the survey

The survey was completed by 97 laboratories and experts from 56 different countries. The list of countries responding the survey is herewith organized by regions:

- **Africa**:
  Total number of countries in the region: 48
  Total number of responding countries to the survey: 14
  Cameroon, Djibouti, Ethiopia, Ghana, Kenya, Lesotho, Madagascar, Niger, Nigeria, Senegal, South Africa, Togo, Uganda, Zimbabwe
- **Asia**:
  Total number of countries in the region: 25
  Total number of responding countries to the survey: 6
  Bhutan, India, Nepal, Pakistan, Philippines, Sri Lanka
- **Europe and Eurasia**:
  Total number of countries in the region: 42
  Total number of responding countries to the survey: 18
  Austria, Belgium, Czechia, Denmark, Estonia, France, Germany, Hungary, Kazakhstan, Netherlands, North Macedonia, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom
- **Latin America and the Caribbean:**
  Total number of countries in the region: 41
  Total number of responding countries to the survey: 8
  Argentina, Brazil, Colombia, Dominican Republic, Ecuador, Mexico, Nicaragua, Venezuela
- **Near East and North Africa:**

[1] http://www.fao.org/global-soil-partnership/glosolan/soil-analysis/dry-chemistry-spectroscopy/en/
[2] http://www.fao.org/global-soil-partnership/glosolan/soil-analysis/dry-chemistry-spectroscopy/presentations-1st-spectroscopy-2020/en/

Total number of countries in the region: 19
Total number of responding countries to the survey: 4
Iran, Iraq, Jordan, Sudan

- **North America:**
  Total number of countries in the region: 2
  Total number of responding countries to the survey: 2
  Canada, United States
- **Pacific:**
  Total number of countries in the region: 18
  Total number of responding countries to the survey: 4
  Australia, Fiji, New Caledonia, Samoa

The European and Eurasian region provided the largest number of feedbacks (see figure 1).

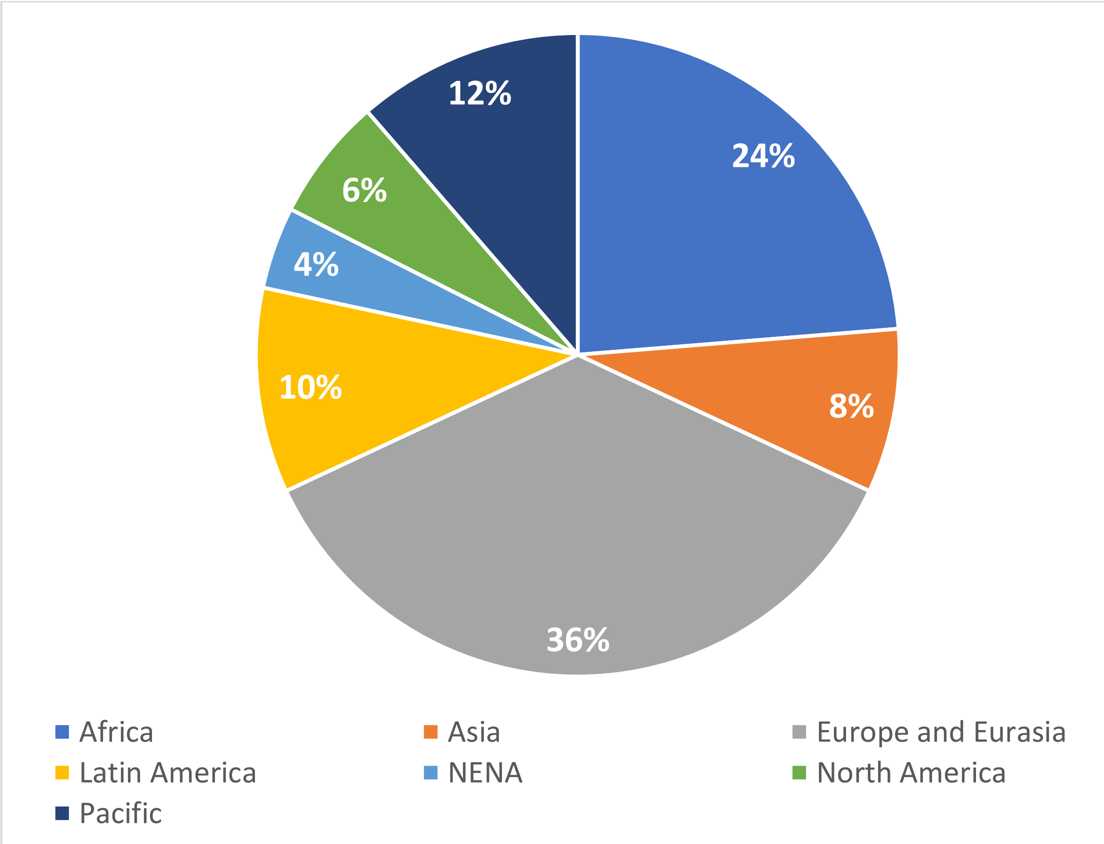


Figure 1 – Participation in the survey by region, expressed as a percentage of the total amount of answers collected.

1.2. Structure of the survey

The survey was available in three languages (English, French, and Spanish) and consisted of 36 questions, organized in four sections (see Annex I).

Section 1: The Global Soil Information System (GLOSIS) and Soil Spectral Data

- **Value of organizing the information in a distributed infrastructure and possibility to use it**: the objective here was to retrieve opinions on how the soil spectra data should be organized (more specifically about the option to incorporate it into the Global Soil Information System – GLOSIS).

Section 2: Laboratories and Procedures

- **Number of soil samples analysed every year**: the objective here was to learn the analytical capacity of laboratories.
- **Soil properties analysed**: this question enquired what soil parameters are most commonly analysed by laboratories, as this can focus the efforts for spectral models and proficiency tests.
- **Measurement of soil spectral properties:** to assess how many laboratories do measure spectral properties of soil samples in their performances, how many do not, and how many do not know about spectral properties.
- **Interest in measuring soil spectral properties**: this question surveyed the interest of laboratories in adopting this technique, according to the national context.
- **Drawbacks on the use of soil spectroscopy:** the main challenges in measuring spectral properties of soil samples were enquired.
- **Possible assets in the perspective of adopting soil spectroscopy measurements:** the objective here was to learn about what might help laboratories to start such measurements.
- **Expected support from GLOSOLAN and RESOLAN:** this question was asked to learn what are the expectations from laboratories about the support that the global and regional soil laboratory networks may provide so the networks can prioritize activities to what is considered necessary.
- **Potential clients in the country**: the objective here was to get information on the presence of potential users that ask for spectrally-derived soil data, and what the objectives are of such clients. This can indicate the potential for a viable business model.
- **Instruments used**: This question was asked to get information on which are the most used instruments (type and brand) to measure spectral properties of soil. Since GLOSOLAN is working on standard operating procedures for soil spectral measurements and on supporting soil laboratories in equipment purchasing, such information might be used to prioritize the SOP development and to guide the personnel towards the choice of instruments that are more widely used (whose manufacturer may then provide a wider and better assistance).
- **Spectral region analysed:** the question aimed to collect information on the spectral region most commonly measured by laboratories to prioritize the WG work.
- **Laboratory procedure followed:** this question aimed to get information on the use of more common or lab-specific SOPs by laboratories use for spectral measurements to inform the harmonization of SOPs.
- **Main difficulties experienced in the measurement:** this was asked to collect information on the main challenges faced by laboratories in the process of performing spectral measurements. This helps to define priorities and work plan activities.
- **Main difficulties experienced in the data processing:** this was asked to collect information on the main challenges faced by laboratories in the process of processing the data and supplying the spectrally-derived soil data.
- **Potential support from GLOSOLAN:** the information provided by laboratories will help GLOSOLAN to prioritize the work in the WG (especially in terms of trainings).
- **Adoption of a Laboratory Information Management System (LIMS):** this question aimed to get information on the development and application of LIMS by laboratories to organize and manage their data.
- **Potential support from RESOLAN:** the information provided by laboratories might suggest how to downscale the GLOSOLAN work plan on spectroscopy, allowing the Regional Soil Laboratory Networks to implement activities locally.
- **Additional inputs:** laboratories were invited to provide extra points of discussion on the topic of spectral measurement, in addition to those covered by the previous questions.

Section 3: Spectral Data Provisioning

- **Spectra data sharing — willingness**: this question was asked to assess if it is worthwhile to start working on developing a platform (library) where laboratories can share their spectral data.
- **Spectra data sharing — capability**: this question was asked to get information on the actual capabilities of laboratories to share their own spectral data (e.g., if it is allowed by their institutions/countries or if the infrastructure is present).
- **Data provisioning — access:** the question aims to collect the preferences of laboratories on how the data should be provisioned (query-based web portal, web service, downloading in .zip format, other).
- **Data provisioning — format:** the question aimed to collect the preferences of laboratories regarding the format in which the data should be provisioned (flat table, instrument-generated file types, database, etc.)
- **Organization of flat tables:** this question enquired whether measured data, metadata, and spectral data should be organized in the same flat table or separately.
- **Modelling software:** this was asked to collect information on what type of software is used for data modelling to prioritize work on those if required.
- **Soil properties provisioned:** the question aimed to collect all soil characteristics that laboratories are most interested in; for instance, to inform future proficiency testing and spectral modelling.
- **Need of provision resampled:** the information provided by laboratories will help GLOSOLAN/GLOSIS to focus the way in which MIR ad VNIR data should be provided and subsequent tools.
- **Current spectral data provision:** this question was asked to gain information on how spectral data are provided by those laboratories that already do it. This can give an overview of the current best practices.

Section 4: Spectral Data Analysis

- **Preferences on data modelling:** this question was asked to get information on the modality laboratories prefer to model the data: in the cloud or locally.
- **Code and tools support**: this question enquired whether laboratories might be interested to receive technical support in terms of code and/or tools.
- **Platform suitability:** the questions here regard any special request to make a platform more suitable for usage by laboratories; for instance, visualisation.
- **Testing a beta web-based platform:** laboratories were asked to express their willingness to eventually test this type of platform.
- **Usefulness of a best practice manual:** this was asked to know whether laboratories would see benefits in using a best practice manual for spectral measurements and modelling, e.g., reporting wavelength ranges and pre-processing and modelling methods, set-up of instrumentation, data storage, quality assessment and control, hosting of data, etc.
- **Suggestions for handling calibration transfer:** this question aimed to get possibly new ideas on how to harmonize spectra that were measured using different instruments or different wavelength resolutions to allow joint use for modelling.
- **Type of metadata:** this question aimed to retrieve information on which metadata the laboratories consider relevant to receive or provide together with soil spectral data.
- **Offering support:** laboratories were asked if they might provide technical support to the project, such as technical expertise, tools, or datasets.
- **Interest in joining the work:** Participants were asked about their interest in joining the efforts of the GLOSOLAN Working Group on Soil Spectroscopy, under the framework of the Global Soil Partnership.

2. Results and discussions

Results are presented and discussed as per the four thematic sections previously identified (section 0).

2.1. The Global Soil Information System (GLOSIS) and soil spectral data

As shown in figure 2, the large majority of survey participants (88 percent) expressed a favourable feedback on the proposal of incorporating soil spectral data in GLOSIS, which is being developed in the framework of the Global Soil Partnership Pillar 4. The outcomes of this question indicate that most users agree on the establishment of a federated system in which databases from different owners (who will keep control of their own data) will be linked, forming a network of databases that can then be accessed through a common portal. This will represent a powerful tool to improve soil information systems because they will be maintained and added to by the data owners themselves, thereby growing the repository and its use. It also provides ample opportunities in capacity-building and efficiency since developed trainings and tools can be shared and used among its members. Still, 6 percent of the respondents foresee the benefit of this tool but will not use it, while 1 percent of survey participants will it only once available. In addition to it, 5 percent of responding laboratories do not see any added value from the creation of such system (whose 2 percent would not use it and 3 percent might consult it).

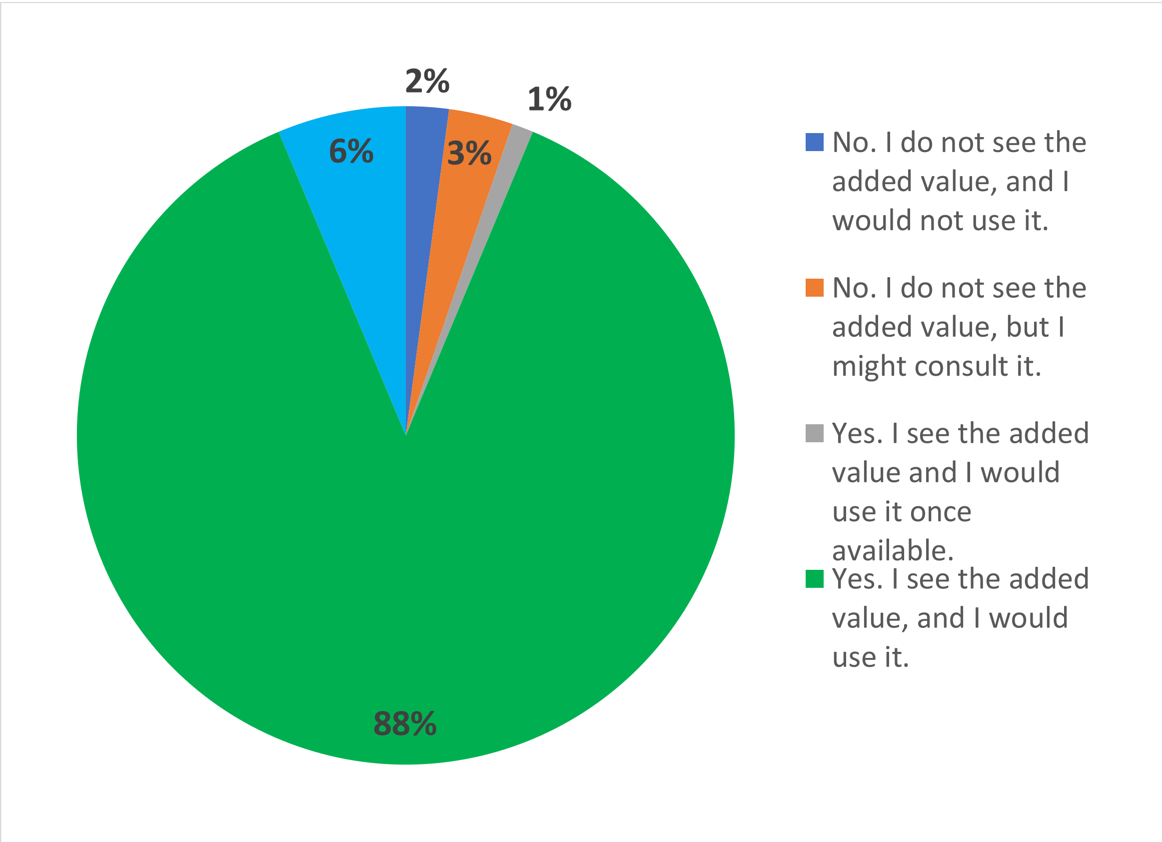


Figure 2 – Graph showing how laboratories judge the establishment of a distributed infrastructure and its potential adoption.

2.2. Laboratories and procedures

2.2.1. General

The second part of the questionnaire aimed to retrieve indicative information on the capacity, size, priorities, and interests of soil laboratories and on their applications of soil spectroscopy. Firstly, laboratories were asked to provide an estimation on how many samples they analyse every year (figure 3). Fifty percent of participants handle less than 1 000 samples per year (more in details: 9 percent process less than 200 samples per year, 24 percent analyse between 200 and 500 samples per year, and 17 percent manage between 500 and 1 000 samples per year). The other half of survey participants reported to analyse more than 1 000 samples per year, with 20 percent of the laboratories handling between 1 000 and 2 000 samples per year, 17 percent analyse between 2 000 and 5 000 samples per year, and 13 percent of the responding institutions deal with more than 5 000 samples on annual basis.

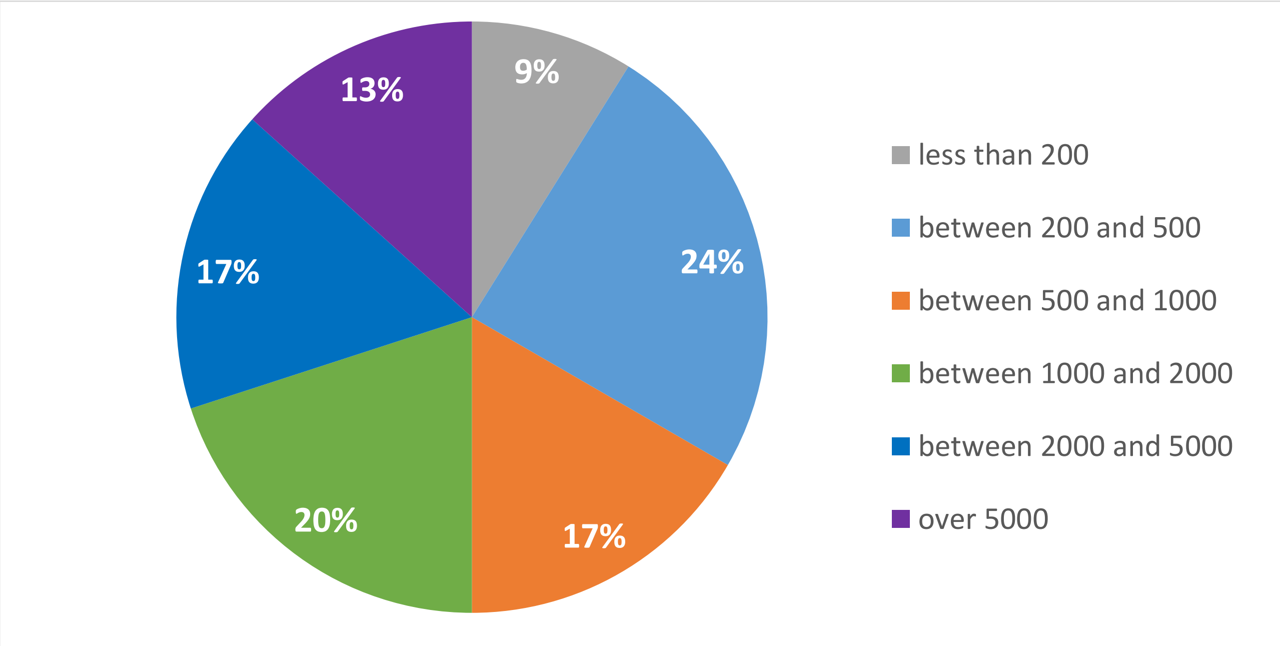


Figure 3 - Number of soil samples analysed every year by the laboratories that answered the survey.

Secondly, laboratories also were asked to provide information on what type of analysis they perform. Results revealed that almost all laboratories perform soil chemical, physical and soil organic matter analysis, while only few of them perform soil biological and other testing as well. Figure 4 shows what type of soil parameters are analysed by laboratories, and in what percentage.

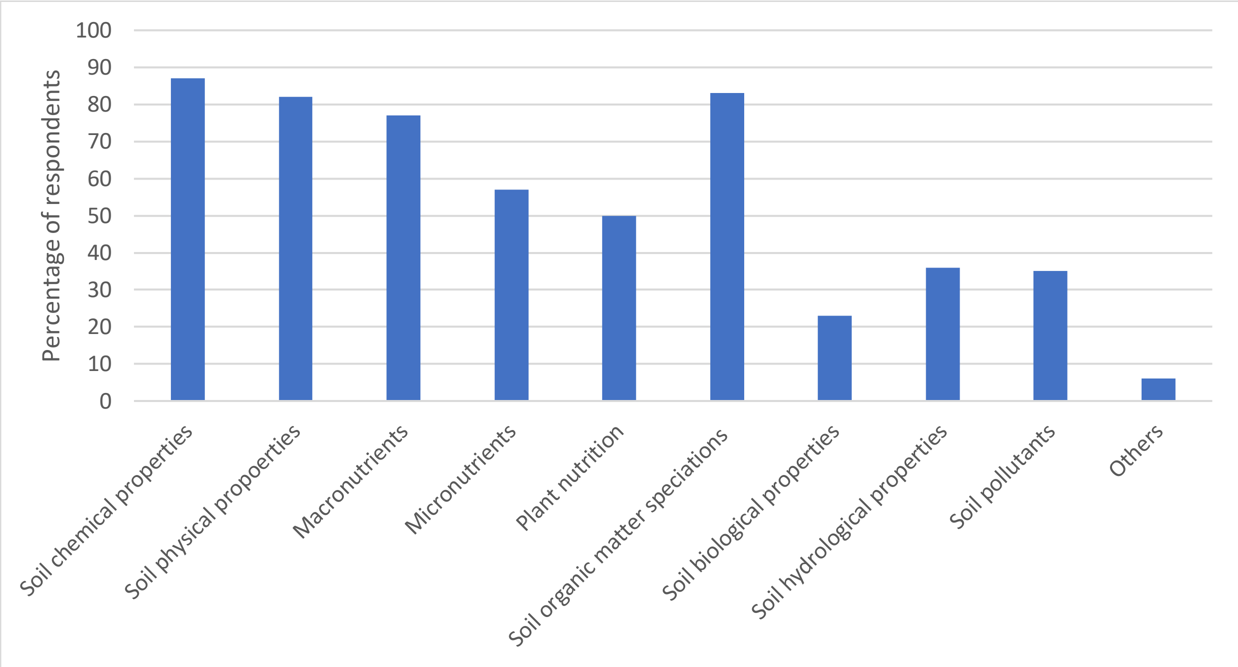


Figure 4 - Percentage of laboratories responding to the survey on the different soil parameters they analyse.
Note: "Others" refers to: Chloride, Sulphate, ^{137}Cs, ^{210}Pb, ^{7}Be, mineralogy, salinity, $CaCO_3$, $CaSO_4$, soil enzyme activities.

The current use of soil spectroscopy was asked as well. The majority, 57 percent of the laboratories, answered that they do measure spectral properties of soil samples, while 39 percent of them do not, and 1 percent perform spectral analysis only for some samples. Moreover, 3 percent of the respondents did not know what spectral properties are, confirming that efforts in awareness raising on the potential application of this technique are still necessary. Since the survey was sent out to many more labs who did not respond, we likely can assume that this percentage is higher. Results showed also that the regions where spectral measurements are more adopted are North America, the Pacific, and Europe and Eurasia. Still, this technique is used by less than 25 percent of the laboratories in NENA, Latin America, and Asia. The survey answers collected from the African region reported that 55 percent of laboratories perform spectral measurements.

2.2.2. Laboratories not performing spectral measurements

The second part of this section focused on the context and challenges related to the application of spectral analysis by soil laboratories. For the entries that answered they do not (yet) measure spectral data for soil, a few questions were posed to provide more information on why they do not perform spectral measurements. The first question was whether laboratories are interested in this type of technology, revealing that a very large majority (92 percent) would like to measure soil spectral properties. Five percent of respondents reported a lack of interest in soil spectroscopy due to the scarce national demand. Some other laboratories (3 percent) specified that the limitations of this technology in their country are caused by the shortage of calibration services.

These laboratories were also asked to list the main drawbacks encountered in measuring spectral properties in soil samples, together with some suggestions on how to best support laboratories in facing such challenges. The collected information is reported in table 1 and can help in prioritizing the work of the WG. The biggest drawbacks are the lack of the right equipment (73 percent), training (37 percent), procedures (10 percent), and other reasons such as lacking a business case, calibration data, staff.

When asked how GLOSOLAN or their RESOLAN can help them, 35 percent indicated that they would welcome help to get equipment, 49 percent indicated that support by means of capacity building would be appreciated, also help in benchmarking, calibration data and mobilising funds is welcome. Participants to the survey specified that they expect GLOSOLAN and the RESOLANs to play an active role in implementing some of the solutions that were listed (see table 3). Moreover, some highlighted the great potential of the GLOSIS platform in linking databases in a global perspective.

Table 1 - Main challenges faced in starting to perform spectral measurements of soil samples, with inputs on potential solutions.

Main drawbacks (in order of importance)	**Potential solutions (organized according to the list of drawbacks)**
• Lack of equipment • Acquire sufficient technical knowledge • The need for procedures to follow • The need for a better calibration and a developed spectral calibration library • Maintenance of the instruments and availability of consumables • Low confidence on the accuracy of the data, compared with the conventional analysis • Shorten the measurement time	• Sustain laboratories in purchasing the right equipment (also to include more spectral ranges) • Organization of trainings • Harmonize standard operating procedures • Development of an open-source spectral calibration library • Support in financial resources mobilization • Provide reference data and samples

In order to better understand the context in which soil laboratories decide to perform soil spectral measurements or not, the main objectives of their clients were investigated. The recognized areas of interest are listed here in order of number of responses:

- Digital soil mapping
- National soil survey
- Soil health and soil quality
- General farm management
- Soil monitoring
- Soil fertility advise
- Carbon sequestration for climate mitigation
- Soil pollution

2.2.3. Laboratories that perform spectral measurements on soil

For laboratories that already perform spectral measurements, the challenges and needs are likely to be different than for labs that do not yet perform them. Their answers related to spectral measurements are specified here.

To better understand the current use of various available instruments and to help prioritize the development of spectral measurement SOPs and trainings, it was asked what type of instrument is used for the spectral measurements (in terms of both type and model). Information collected is reported in figure 5. Results show that a wide range of Bruker systems are used for MIR measurements alongside some Agilent systems. ASD is used a lot for VNIR measurements alongside some FOSS lab instruments. A range of field and other instruments also are used by the laboratories, together with the worktop instruments or standalone.

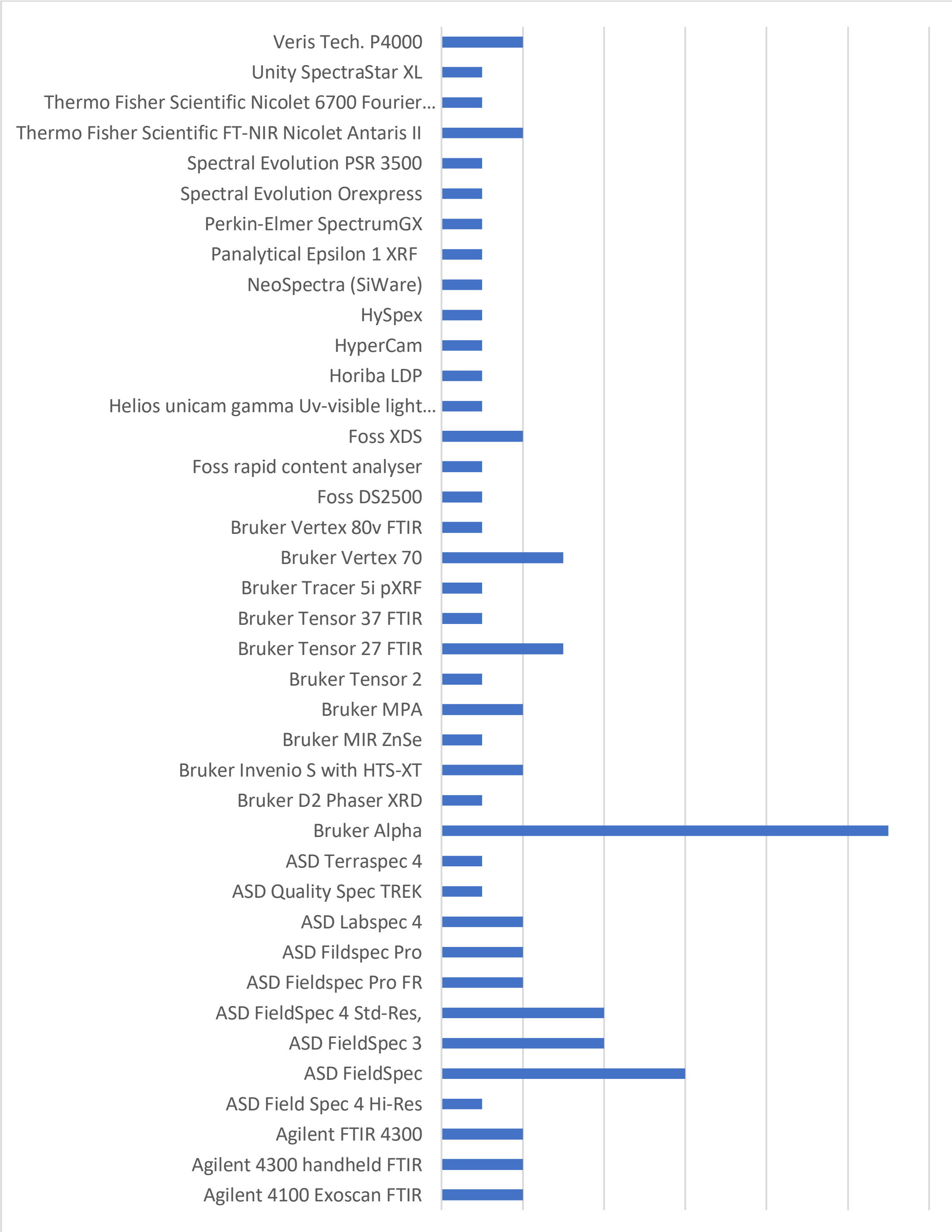


Figure 5 – Instruments used by laboratories that answered the survey to perform spectral measurements. Note: the length of the horizontal bars indicate the adoption of each model. Still, some of the listed instruments are not diffuse reflectance MIR or VNIR targeted, indicating it is very important to be as precise as possible in communication.

The spectral region measured by laboratories was investigated as well, prescribing answers related to diffuse reflectance ranges (Annex 1). Answers (reported in figure 6) indicated that the VNIR (400–2 500 nm) is the most commonly measured spectral region (66 percent of laboratories reported to measure it), closely followed by MIR with 56 percent. Less respondents indicated to (only) measure specific parts of the NIR (780-2 500 nm) range, such as SWIR (900–1 700 nm). This can be because it is relatively narrow and more specific.

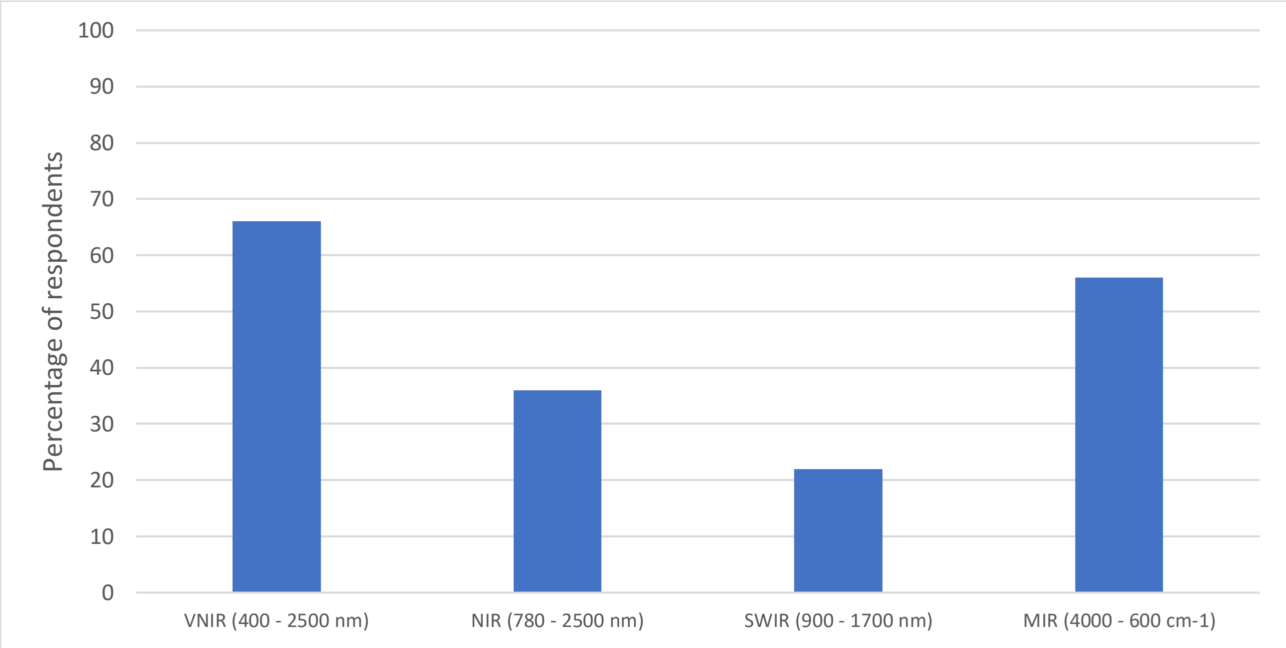


Figure 6 – Spectral regions measured by laboratories responding to the survey, in percentages.

Laboratories also were asked to provide information on which procedures they follow when performing spectral measurements (figure 7). Results reveal that there is, as expected, a need to harmonize the SOPs for spectral measurements. As in most cases (62 percent) laboratories use SOPs they developed themselves, leading to potential problems when results from different laboratories are compared. Some laboratories adopt international procedures, such as the one from ICRAF (followed by 16 percent of responding laboratories), or from Ben Dor (2013) and USDA (both followed by 6 percent of responding laboratories). In addition to the Wetterlind procedure for VNIR measurement (followed by 2 percent of respondents), laboratories reported adoptions of other procedures (8 percent of the total answers), such as those from CSIRO Australia, the University of Hohenheim (Germany), Nobel *et al.* (2019), and Okalebo *et al.* (2002). It should be noted that some of the procedures are quite similar already, although not the same (for instance, ICRAF and USDA).

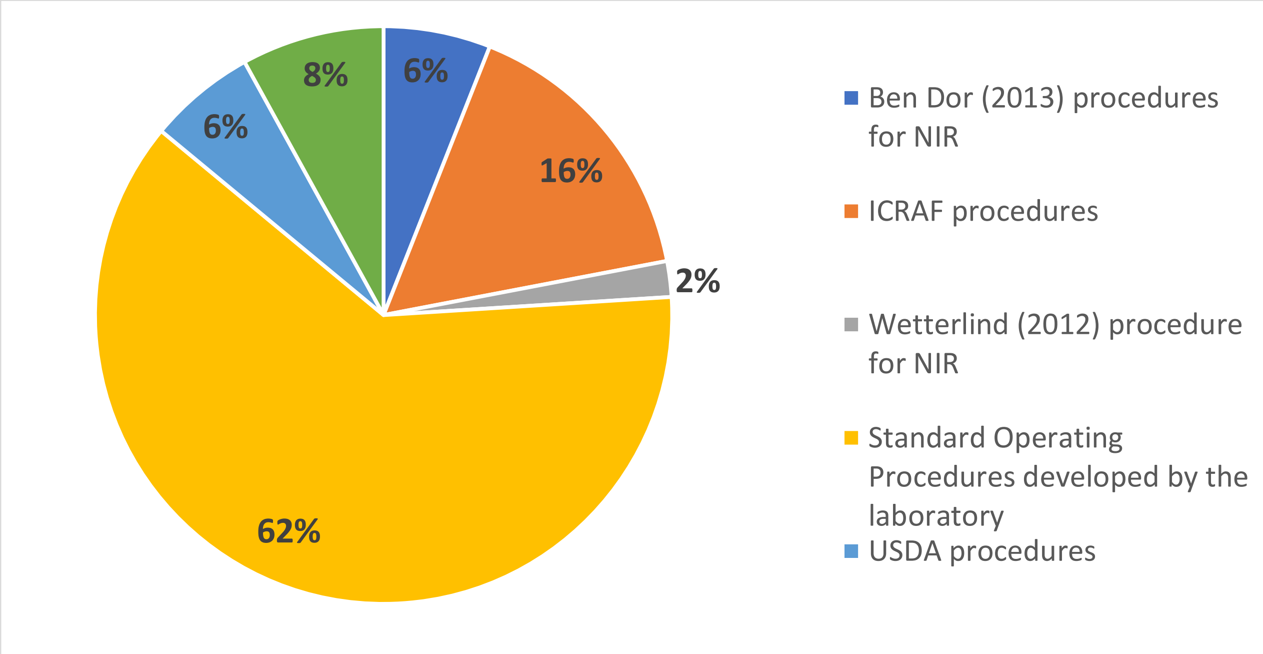


Figure 7 - Laboratory procedures followed for spectral measurements.

According to the information collected, building a spectral calibration library seems to be the main challenge faced by laboratories during the measurements (figure 8), confirming the necessity of developing a common library, accessible by all soil laboratories within the network (confirmed by 41 percent of respondents). In addition to that, other difficulties concern the sample preparation, getting properly trained staff members, and performing quality checks. On the other hand, operation of instruments was reported as a minor problem.

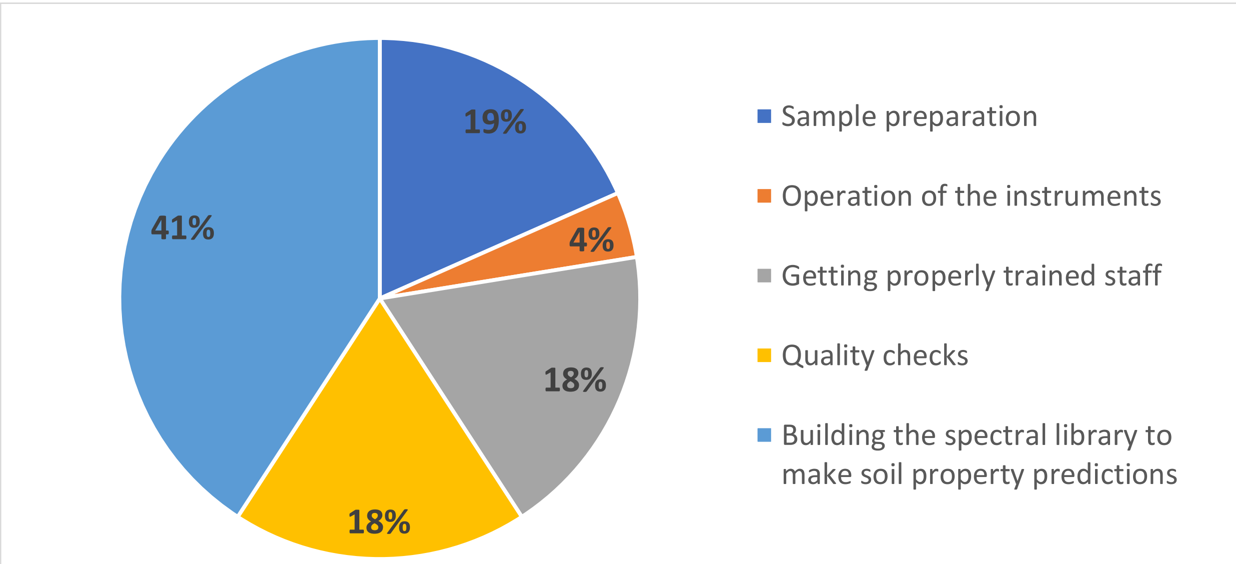


Figure 8 – Main challenges faced by laboratories during the soil spectral measurements.

The difficulties experienced by laboratories were investigated also with regard to the data processing and in supplying the spectrally-derived soil data. The challenges identified in the survey are reported in figure 9. Performing quality checks on the spectra and judging the result were identified to be the main challenges (31 percent, respectively). Still, 21 percent of the laboratories that answered the survey noted difficulties in building the spectral model.

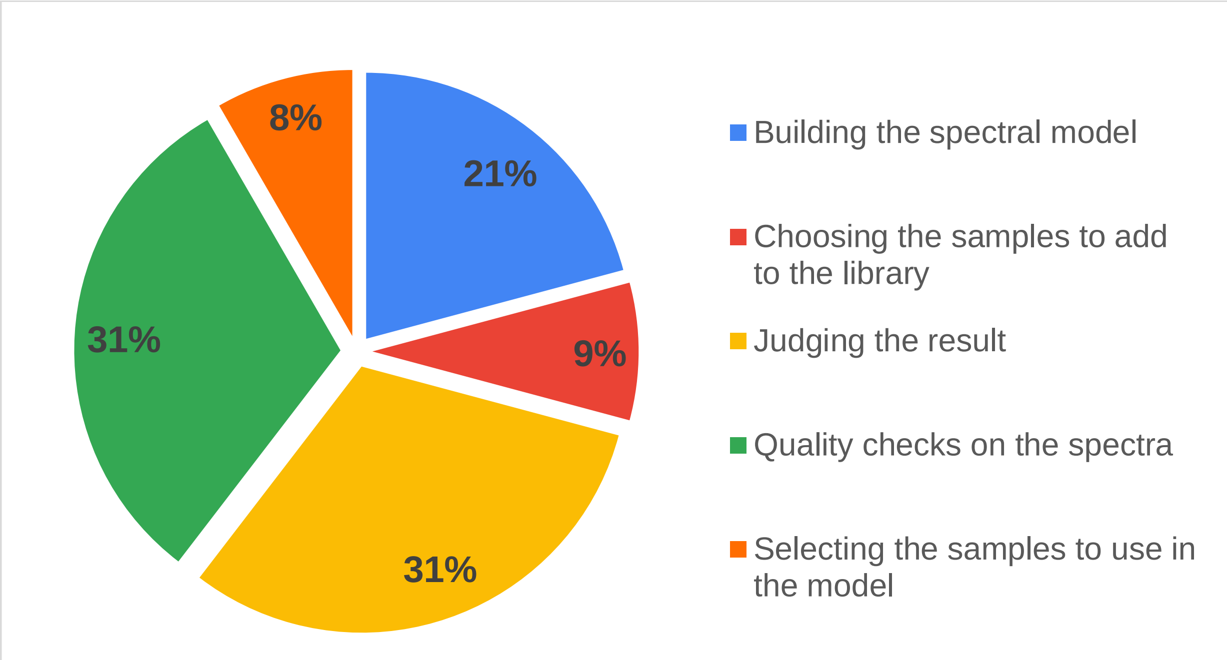


Figure 9 - Main challenges faced by laboratories after the spectral measurement, in relation to data processing and supplying the spectrally-derived soil data.

Also on this topic, laboratories were asked to provide some inputs on possible solutions to overcome these challenges. Among the contributions received, most laboratories (72 percent) agree that benefits might come from developing a strategy that should include: (i) supporting the laboratories with more tools for quality control, (ii) standardization of the reference samples, and (iii) building a standardized spectral calibration library (Figure 10).

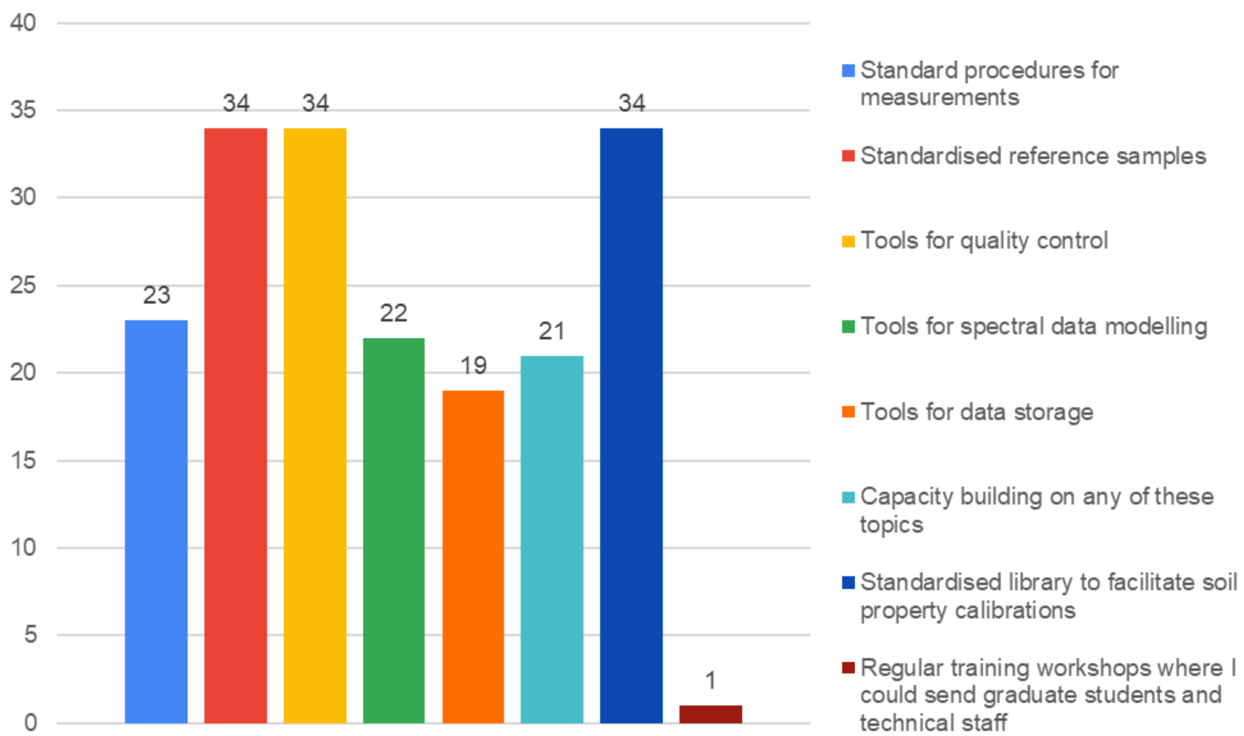


Figure 10 - Main solutions proposed by laboratories to improve the spectral measurements.

The topic of data management was investigated in more depth by asking laboratories whether they adopted a Laboratory Information Management System (LIMS) to store the measured data. Results showed that more than two-third of soil laboratories which answered the survey (72 percent) needed assistance and training to develop their own LIMS, as they did not have one.

In order to develop an adequate work plan to properly support laboratories in dealing with these challenges, participants to the survey were asked to provide their opinion on how GLOSOLAN can assist them. The collected inputs are reported in table 2 and highlight the key role GLOSOLAN might play in improving the spectral performance of laboratories.

Table 2 - Areas of interventions where GLOSOLAN might support the laboratories.

Areas of interventions	**Outcomes**
Harmonize and promote SOPs on soil spectroscopy (including sample pre-treatment and instrument calibration)	Harmonized procedures for soil spectral measurement and analysis
Build a global spectral calibration library (easily accessible)	Support soil spectral information exchange and provide high quality spectral calibration datasets
Organize trainings and PTs	Technical support and better laboratory performance
Facilitate benchmarking or easy calibration transfer by reference samples	Enhanced comparability of spectral data obtained with different equipment
Knowledge and experience sharing	Community of Practice on soil spectroscopy
Provide tools and data, data storage, quality checks, LIMS	Easier and efficient workflows
Facilitate the application of models combining (VN)IR and PXRF elemental or other data (later on)	Further improve spectral predictions

Since the application of soil spectral measurement should rely on a market demand, the presence and type of potential clients for spectrally-derived soil data in each country was investigated. The clients' main areas of interest are listed here in order of number of responses:

- National soil survey
- Digital soil mapping
- Soil health and soil quality
- Soil fertility advise
- Soil monitoring
- General farm management
- Carbon sequestration for climate mitigation
- Soil pollution

2.3. Spectral data provisioning

This part of the survey first focused on the willingness of soil laboratories to share spectral data (including reference and metadata) and their actual capability to do that. A vast majority (91 percent) of the respondents stated that they would like to share spectral data. However, only 70 percent of the respondents are capable to share spectral and reference data and metadata. Impediments can be due to technical, financial, or data policy aspects.

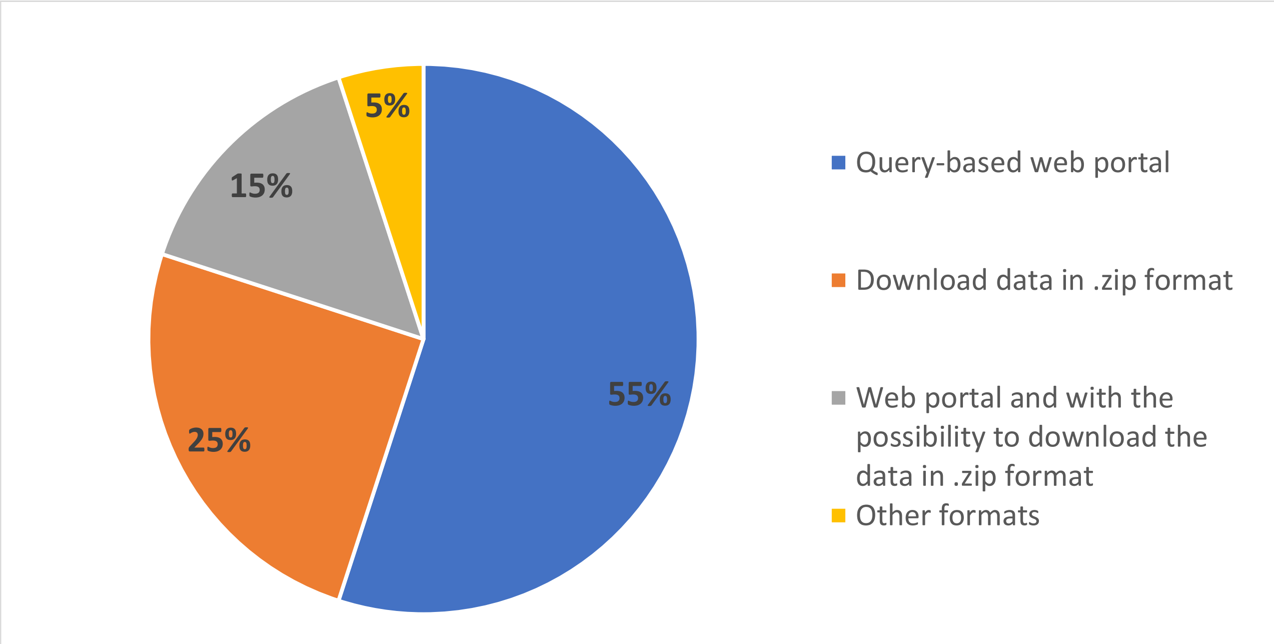


Figure 11 – In what way the data should be provisioned, according to the preferences of laboratories that joined the survey.

To guide the development process of spectral data provisioning services, respondents were asked their preferred or most user-friendly access to data. As shown in figure 11, the majority of answers (55 percent) proposed the use of a query-based web portal, possibly with tools for online processing. Others (25 percent) preferred to download data in .zip format, while 15 percent of participants preferred to combine the two ways by exploring the online portal with the possibility to download the data in .zip format. A few contributors proposed to make data available in other ways, such as in JSON. In general, participants stressed the importance of providing some type of control on who can download the data, and for what purposes. The preferences on file format for spectral data provisioning are reported in figure 12.

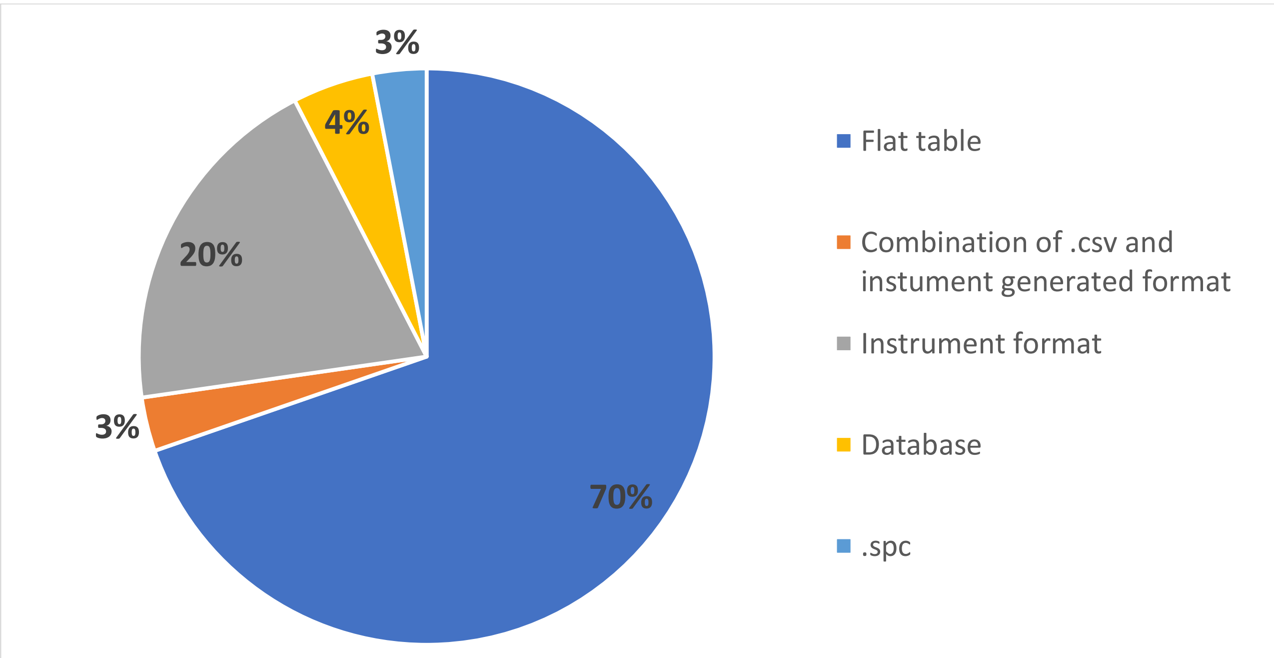


Figure 12 – Answers of what type of format the laboratories prefer the data to be provisioned.

In this regard, 70 percent of laboratories reported to prefer provisioning data as a flat table (possibly in .csv format), while 20 percent would prefer the format generated from the instrument. The remaining 10 percent of participants opted for database, .spc files, or a combination of flat tables and instrument-generated data. In case of flat tables, the survey revealed that laboratories have no preferences on reporting measured data, metadata, and spectral data in the same table or in separated ones (48 against 52 percent).

The investigation focused also on which modelling environment laboratories use for spectral modelling (prediction of soil properties from spectra). As shown in figure 13, results showed that most participants (about 60 percent) rely on open-source software (mostly R software) while 23 percent of them use proprietary software, this is in line with the data format results. Still, some of the respondents (17 percent) reported to not perform any data modelling.

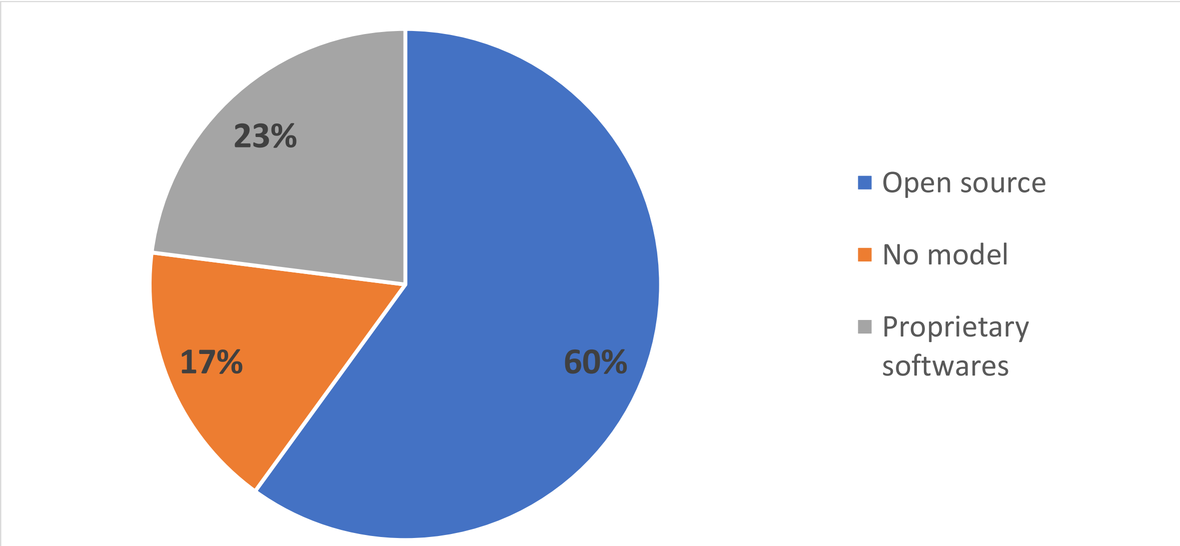


Figure 13 - Modelling program preferences expressed by laboratories in the survey.

To better understand the requirement for harmonization of spectral data storage and serving, survey participants were asked to express their opinion on the need to provision resampled spectral data, such as smoothed lower resolution information, in addition to the raw background-corrected data for MIR (on absorbance) and for VNIR (on reflectance). Responses highlighted that 65 percent of participants do not have a strong demand for this. Still, 35 percent of respondents reported that resampled data should be included in the provisioning service of GLOSOLAN and GLOSIS.

Finally, as last question on this topic, it was inquired how many soil laboratories already provision spectral data, and how, by describing method, format, units, and tools. In this regard, the majority of laboratories (80 percent) do not provision spectral data yet. Nevertheless, those laboratories that serve spectral data showed a wide variety of methods. While most laboratories share the data simply via email upon request within the institute or with partners, some report the use of web services or having a network of partners or a national spectral calibration library.

2.4. Spectral data analysis

The last section of the survey focused on where and how laboratories analyse spectral data. We found that the majority of laboratories preferred to model spectral data locally (about 75 percent of responses), while only the 25 percent of laboratories perform this procedure online, in the cloud. Laboratories were asked to provide an opinion on the type of support that may bring an improvement in the analysis. The feedback received (reported in figure 14), showed that most of respondents would appreciate the option to use code and tools to model data. Still, 20 percent of the answers received showed that laboratories preferred to perform the spectral data analysis by themselves.

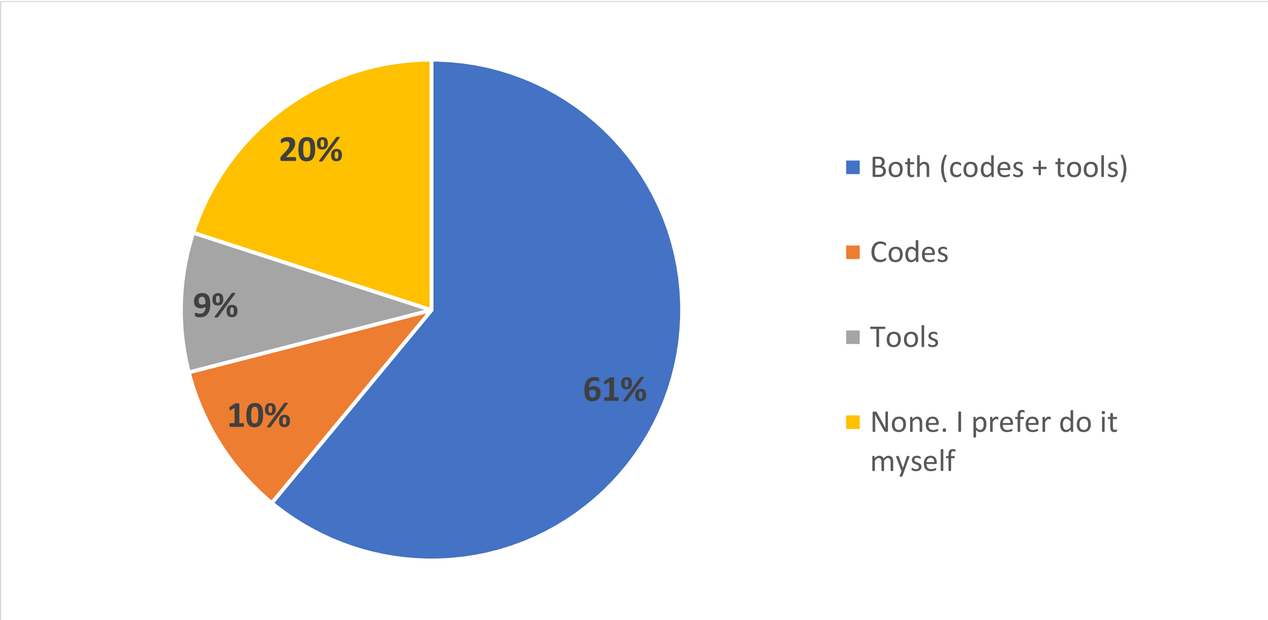


Figure 14 - Feedback on the possibility to provide laboratories with codes and tools to perform spectral soil analysis.

In view of the plans to develop an online platform to analyse spectral data, participants were asked to provide input on the accessibility and functionality of such a tool, focusing on how it may become more suitable for their purposes. Forty-five percent of participants mentioned the importance to develop a platform that is easy to use, with a Graphic User Interface (GUI) that allows a functional visualization of the information reported (figure 15). Some inputs received referred to the importance of visualizing soil properties along with spectral data, with the possibility to handle large datasets. Thirty-five percent of respondents stressed the role of querying functionality, and the need to include tools for data processing, data modelling, calibration and prediction linked to a global spectral calibration library and prediction service. Other inputs received valued the possibility to add georeferencing tools and the need to provide a function to export data in an exchange format.

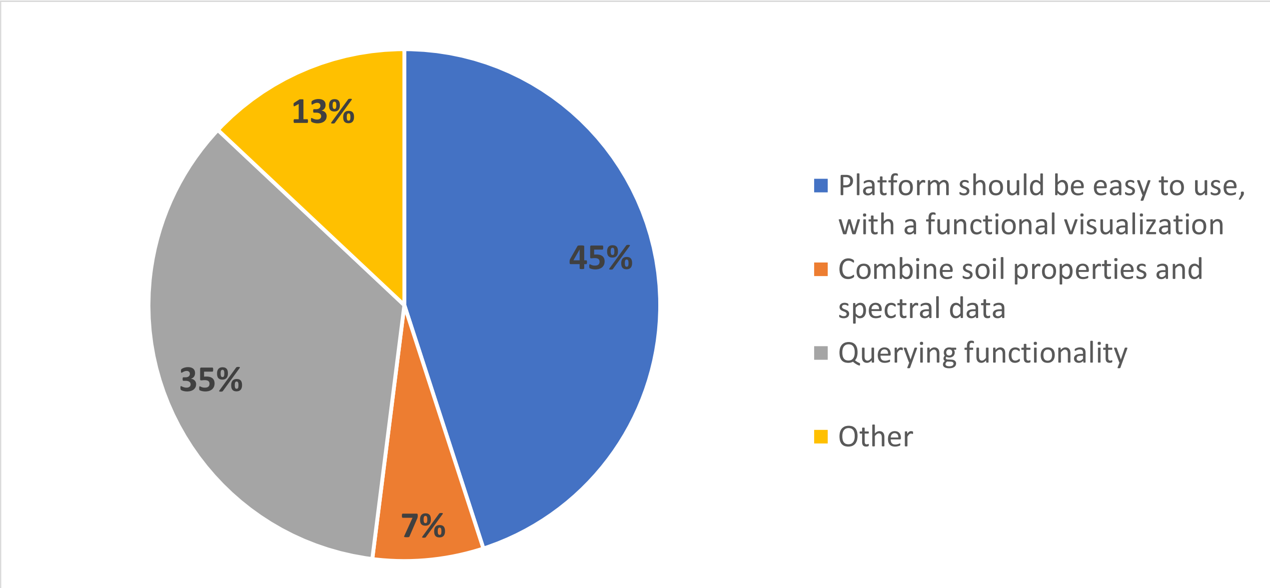


Figure 15 – Graph reporting the requests brought by the participants on how to make a platform more suitable for their purposes.

Furthermore, the majority of laboratories (60 percent) stated to be available to test a beta web-based platform, once it will be available. About 38 percent of respondents answered that they might be available, while only in the 2 percent of answers a negative feedback was collected.

As supporting documents (such as a best practice manual/cookbook) represented an asset for users in other initiatives implemented by GSP, survey participants were asked to provide an opinion on the use of this type of document on spectral data modelling. Almost 80 percent of laboratories reported that a manual recommending for instance wavelength ranges and pre-processing methods would be useful, while 20 percent of them answered that this type of document might be useful. Two responses reported not to be interested.

Considering the variety of spectral wavelengths and resolution that can be measured and instruments and sample preparations that can be used, calibration transfer plays a major role in spectral data analysis. For this reason, the survey asked also for suggestions on this matter. The main contributions are reported in the following list:

- Use transformation algorithms, once the dataset is standardized
- Distribute samples to be used as reference materials
- Adopt SOP already developed (such as Ben-Dor *et al.*, 2013)
- Test data derived from mixed instruments after aligning into the same spectral region. One input received suggested to develop transfer models by grouping soil samples on soil type basis.

Laboratories were asked to provide feedback also on the type of metadata that should be stored or received together with the soil spectral data. According to the suggestions received, the metadata should include:

- Pedological information of the sample: soil chemical, physical and biological properties, soil type, parent material
- Sampling details: sampling strategy, sampling depth, sampling date, sample pre-treatment procedure(s).
- Georeferenced dataset reporting the coordinates and information on the location where the soil samples analysed come from (altitude, land use, vegetation cover, climate, etc.)

- Information on the instruments used: brand, model, device configuration, original resolution, original range, scan date, software used to record the spectra, operator, instrument serial, gain (if applicable), temperature (if applicable), device test results, etc.

Considering the preliminary stage and voluntary nature of the project, the survey also asked the main topics in which participants may contribute. Answers received on this topic are summarized in figure 16.

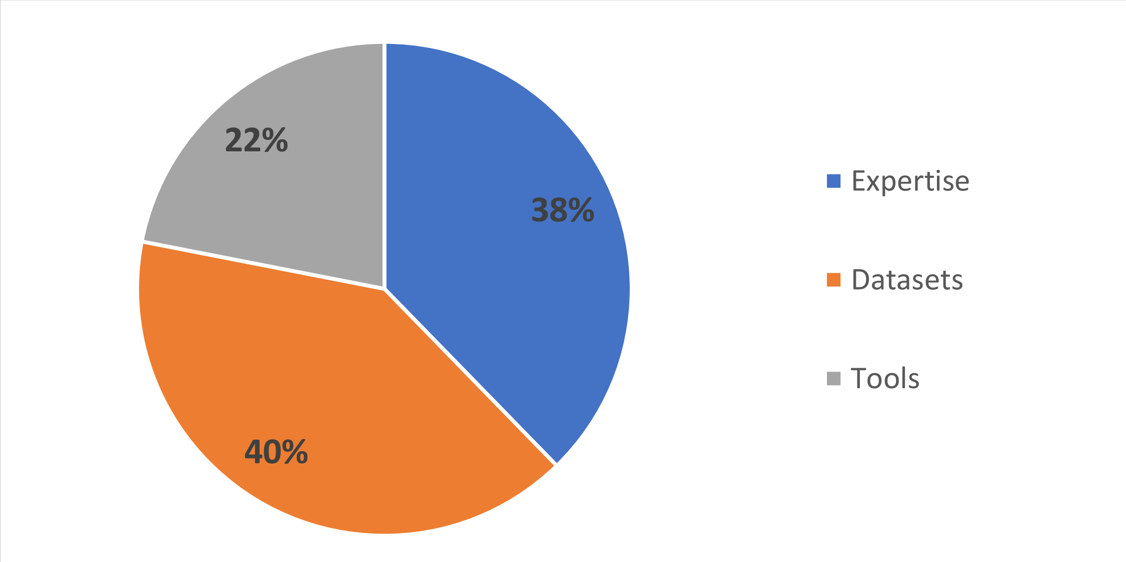


Figure 16 - The potential contribution from survey participants to the project, in terms of expertise, information (datasets), and tools.

Finally, as last question of the survey, participants were asked to express their interest in joining the effort to develop a global spectral calibration library under the leadership of the GLOSOLAN Working Group on Spectroscopy. The answers submitted revealed that a great majority of laboratories (90 percent of respondents) wished to be involved in the project, while 10 percent of them stated to not be interested in it.

2.5. Main areas of interventions

Figure 17 summarizes the main needs expressed by laboratories concerning soil spectral analysis. From a global perspective, there is a clear need to support laboratories in retrieving standardized reference samples, building a spectral calibration library, harmonize SOPs for spectral measurements, support quality improvement and capacity building and tools in general. These are the challenges that the GLOSOLAN work plan on spectroscopy should be based on, in order to provide laboratories with efficient tools aimed to address their main needs.

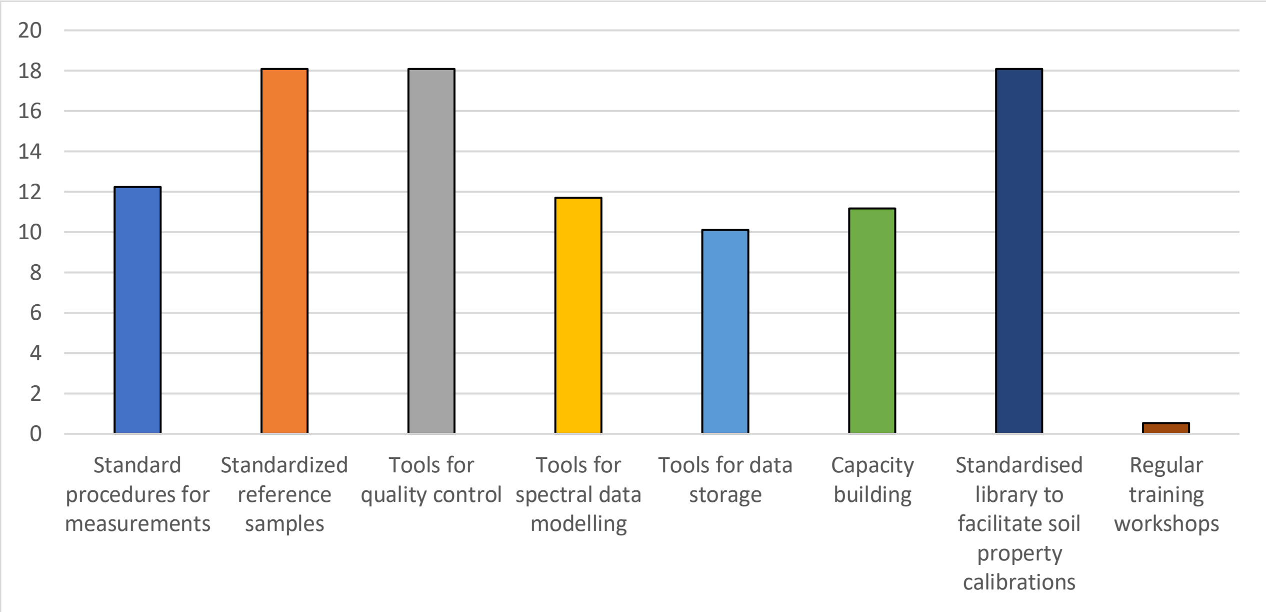


Figure 17 – Laboratories main requirements to improve their spectral measurements, expressed in percentages of the total answers to the survey.

3. Conclusions

The information collected in the survey on the capabilities and needs for collecting and managing soil spectral data provide an overview of the current expertise, capabilities, needs and priority areas for labs that want to start or improve their spectral measurements and modelling, both for MIR and VNIR regions.

Laboratories operating in all regions that do not perform spectral measurements yet identified the lack of equipment as main drawback in adopting spectral measurements, followed by (lack of) training and procedures. However, only half of these, 35 percent would welcome support in obtaining instruments. More (49 percent) indicated that training would be quite welcome along with other support. Labs that already perform spectral measurements indicated challenges with respect to building a spectral calibration library, quality checks, sample preparation, and in the modelling stage judging the result, quality checks on the spectra and building the spectral model itself.

However, different obstacles were reported by laboratories in each region. The main needs of the laboratories from the different regions have been collected and reported in table 3, together with their main drawbacks.

Table 3 - Regional major drawbacks for measuring spectral properties of soil samples and main needs.

Region	Major drawbacks for measuring spectral properties of soil samples	Main needs concerning spectral measurement
Africa	- Equipment - Insufficient knowledge - Data processing	- Standardized calibration library to facilitate soil property calibrations - Standardized reference samples - Tools for quality control - Tools for spectral data modelling - Capacity building
Asia	- Equipment - Insufficient of knowledge - Lack of accuracy (compared to wet chemistry)	- Standardized reference samples, Tools for spectral data modelling - Developing more valid predictive model through own local data
Europe and Eurasia	- Equipment - Insufficient knowledge - Calibration - No standardized procedures to follow	- Tools for quality control - Standardized calibration library to facilitate soil property calibrations - Standardized reference samples - SOPs
NENA	- Equipment - Time required for the measurement	- SOPs - Standardized reference samples - Tools for quality control - Tools for spectral data modelling - Tools for data storage - Capacity building - Standardized calibration library to facilitate soil property calibrations
North America	- Equipment - Calibration	- SOPs - Standardized reference samples - Tools for quality control - Capacity building
Latin America	- Equipment - Calibration - No standardized procedures to follow	- Tools for quality control - Standardized calibration library to facilitate soil property calibrations - SOPs
Pacific	- Equipment - No standardized procedures to follow - Insufficient knowledge	- Standardized reference samples - Tools for quality control - Standardized calibration library to facilitate soil property calibrations - Tools for data storage

In general, the survey revealed clear areas of intervention. Firstly, there is a need to raise awareness on the potential application of soil spectroscopy as an alternative for wet chemistry. In addition to that, laboratories (both those already performing spectral analysis and those that do not yet) expressed the need of community and technical support to properly implement soil spectroscopy measurements, as there is a strong demand from clients in many countries. This includes standard operating procedures, tools for quality checks, training, standardized reference samples, spectral model building and performance.

A successful soil spectroscopy set-up requires the implementation of an online (open source) spectral calibration library and the establishment of a user-friendly web platform to allow for data provisioning and processing, with the option to download and model data. A link with GLOSIS is strongly welcomed.

The efforts within the GLOSOLAN initiative on soil spectroscopy should aim to support laboratories in improving or building their analytical performance on soil spectroscopy. Laboratories clearly expressed their availability to join efforts and to contribute to this initiative under the guidance of both GLOSOLAN and GLOSIS.

Annex I. Spectral soil data: needs and capacities questionnaire

Thank you for your willingness to fill in this questionnaire. It is intended to gather insight into the needs and capacities of GLOSOLAN and the wider soil-sensing community.

With your contribution, we hope to:

1. Acquire an overview of the capacities, needs, and goals of soil laboratories worldwide with respect to spectral soil data; and
2. Determine if serving spectral data in a more structured, cooperative, and coordinated way would be useful for laboratories and other users. If so, we hope to understand how to address the needs of potential users and suppliers of data.

The questionnaire consists of four parts:
Part 1. The Global Soil Information System (GLOSIS) and Soil Spectral Data
Part 2. Laboratories and Procedures
Part 3. Spectral Data Provisioning
Part 4. Spectral Data Analysis
Although we welcome you to fill in all of the questions, you can also choose to answer only parts.

Glossary:

- Spectrum/spectra: visible, near- and mid-infrared reflectance or absorbance spectra
- Spectral calibration library: dataset where soil samples have been measured with both conventional and spectral laboratory methods
- Spectrally-derived soil data: soil property estimates derived from new spectral measurements using a spectral calibration library and statistical, machine-learning data models
- LIMS: Laboratory Information Management System (laboratory database software)
- Provisioning: sharing data with others, usually online

This survey takes less than 15 minutes to complete.

The Global Soil Partnership thanks you in advance for your precious time and contribution. If you have any questions, please contact GLOSOLAN Coordinator Ms. Lucrezia Caon at lucrezia.caon@fao.org.

General information
The information gathered in this section will only be used within the context of this questionnaire. It will allow us to more effectively design follow-up activities, such as targeted capacity building and technical (product) development. It will be distributed only to the lead of the GLOSOLAN Spectroscopy Working Group. It will not be used for any other purpose.
Name and last name______________
Email address______________
Laboratory/institution______________
Country______________

Part 1. The Global Soil Information System (GLOSIS) and Soil Spectral Data

We propose to incorporate soil spectral data in GLOSIS, the Global Soil Information System, which is currently being built in Pillar 4 of the Global Soil Partnership. GLOSIS will be a federated system. Data owners will keep their own database (and therefore control) but will be able to link to a network of databases. The network will provide tools and training and thereby help improve the data owner's national, local, or lab soil information system. GLOSIS will adhere to GLOSOLAN results and common lab practices for reference data. The system will facilitate quality control and a standardized data structure that enables plug-ins for high quality spectral predictions and for national reporting.

- Do you see added value in a distributed infrastructure as described here, and would you use it once available?
    - Yes. I see the added value, and I would use it.
    - Yes. I see the added value, but I would not use it.
    - No. I do not see the added value, and I would not use it.
    - No. I do not see the added value, but I might consult it.

Part 2a. Laboratories and Procedures

This section is meant for laboratories that operate wet chemistry, dry chemistry, or both.

- How many soil samples do you process on average every year?
    - less than 200
    - between 200 and 500
    - between 500 and 1 000
    - between a 1 000 and 2 000
    - between 2 000 and 5 000
    - over 5 000
- What soil properties are you (most) interested in at your lab? Check all that apply.
    - Soil physical properties (clay, silt, sand, median grainsize, bulk density)
    - Soil chemical properties (CEC, pH, EC, exchangeable bases, etc.)
    - Macronutrients (N, P, K, etc.)
    - Micronutrients (B, S, Zn, Cu, etc.)
    - Plant nutrition (exchangeable nutrient fractions)
    - Soil organic matter speciations (organic matter, organic carbon, total carbon, inorganic carbon, etc.)
    - Soil biological properties (bacteria and fungi quantity and speciation, nematodes, etc.)
    - Soil hydrological properties (water retention, saturated hydraulic conductivity, infiltration capacity, etc.)
    - Soil pollutants (Pb, Zn, Cu, PAHs, organic substances, PFAS, etc.)
    - Other:
- Do you measure spectral properties of soil samples in your lab?
    - Yes
    - No
    - I do not know what spectral properties are

Part 2b. Laboratories and Procedures

- Would you like to measure spectral properties of soil samples in your lab?
  - Yes.
  - No. I do not trust this technology.
  - No. There is not enough local and national interest in this type of measurements.
  - No, because we do not have calibrations for my country.
  - No: other.
- What are your biggest drawbacks for measuring spectral properties of soil samples in your lab?
- What would most help you to start these measurements?
- How can GLOSOLAN or your Regional Soil Laboratory Network help you on this?
- Do you have potential clients in your country for spectrally-derived soil data, and what are their objectives? Check all that apply.
  - Yes: general farm management
  - Yes: soil fertility advise
  - Yes: (national) soil survey
  - Yes: digital soil mapping
  - Yes: soil monitoring
  - Yes: carbon sequestration for climate mitigation
  - Yes: soil health/soil quality
  - Yes: soil pollution
  - Yes: other
  - No

Part 2c. Laboratories and Procedures

- Which instrument do you use to measure spectral properties of soil (brand and type)?
- What spectral region do you measure? Check all that apply.
  - VNIR (400 – 2 500 nm)
  - NIR (780 – 2 500 nm)
  - SWIR (900 – 1 700 nm)
  - MIR (4 000 - 600 cm-1)
  - Other
- Which lab procedures do you currently follow for spectral measurements?
  - ICRAF procedures
  - USDA procedures
  - Wetterlind (2012) procedure for NIR
  - Ben Dor (2013) procedures for NIR
  - Standard Operating Procedures developed by my own lab
  - Other
- What are the main difficulties that you experience in performing these measurements?
  - Sample preparation
  - Operation of the instruments
  - Getting properly trained staff
  - Quality checks
  - Building the spectral library to make soil property predictions

    - Other
- What are the main difficulties that you experience in processing the data and supplying the spectral derived soil data?
    - Quality checks on the spectra
    - Choosing the samples to add to the library
    - Selecting the samples to use in the model
    - Building the spectral model
    - Judging the result
- What would most help you to improve these measurements? Check all that apply.
    - Standard procedures for measurements
    - Standardised reference samples
    - Tools for quality control
    - Tools for spectral data modelling
    - Tools for data storage
    - Capacity building on any of these topics
    - Standardised library to facilitate soil property calibrations
    - Other
- Do you have a LIMS (Laboratory Information Management System)?
    - Yes
    - No
- How can GLOSOLAN or your local Regional Soil Laboratory Network help you?
- Do you have potential clients in your country for spectral derived soil data, and what is their objective? Check all that apply.
    - Yes: general farm management
    - Yes: soil fertility advice
    - Yes: (national) soil survey
    - Yes: soil monitoring
    - Yes: carbon sequestration for climate mitigation
    - Yes: soil health/soil quality
    - Yes: soil pollution
    - Yes: other
    - No
- Is there anything else regarding measuring spectra in the lab that is not addressed yet and you would like to share with us?

Part 3. Spectral Data Provisioning

- Would you like to share spectral data, including reference and metadata?
    - Yes
    - No
- Can you share spectral data, including reference and metadata?
    - Yes
    - No

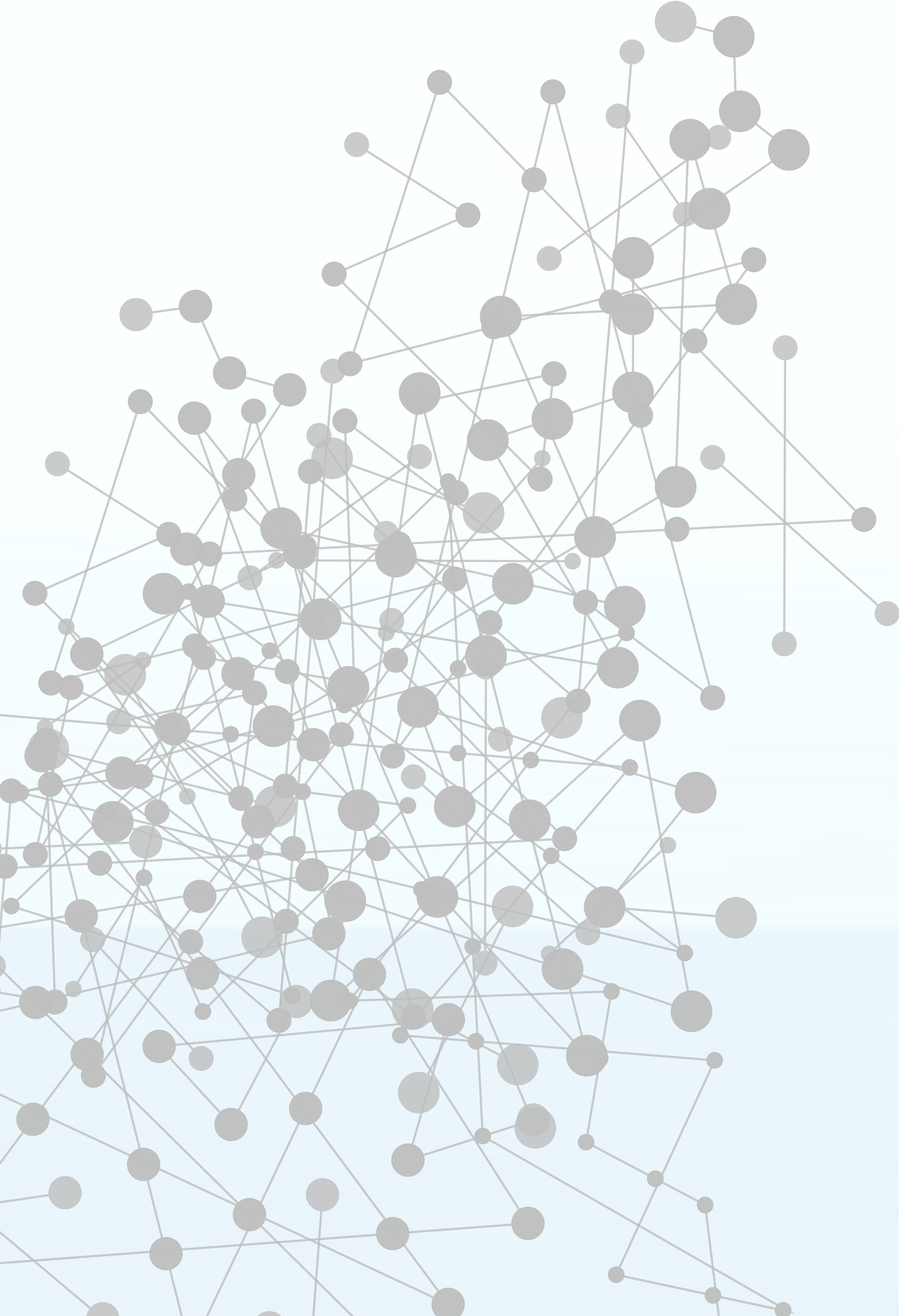
- In what way would you like the data to be provisioned? For example, by a query-based web portal or a webservice (OGC wfs, website); by downloading in zip format; or other (please specify)?
- In which format(s) would you like spectral data to be provisioned? For example, flat table (csv, ASCII, RData), instrument-generated file types (OPUS, etc.), *.spc files, database, etc.
- For flat tables, would you prefer reference (measured) data, metadata, and spectral data to be provisioned in separate tables or in one single table?
    - Separate tables
    - One single table
    - Other:
- Do you model in open source (R, etc.) or in proprietary software? Which modelling program(s) do you use?
- What soil properties/characteristics are of interest to you? Please provide an exhaustive list with prioritization.
- The current GLOSOLAN/GLOSIS plan is to serve raw background-corrected absorbance data for MIR and raw background-corrected reflectance data for VNIR. Is there a strong need to provision resampled (smoothed, lower resolution) data?
    - Yes
    - No
- Are you currently providing spectral data? If so, how? Please describe method, format, units, and tools. Please include a link if possible.

Part 4. Spectral Data Analysis

- Do you prefer modelling in the cloud or locally?
    - Cloud
    - Locally
- Would you appreciate code or tools to model the data?
    - Code
    - Tools
    - Both
    - I do it myself
- What special requests do you have to make a platform more suitable for your purposes (for example visualization, querying functionality, etc.)?
- Are you willing to test a beta web-based platform when the time comes?
    - Yes
    - No
    - Maybe
- Do you think a "cookbook" type, best practices manual for modelling data would be useful? Such a manual might, for example, recommend wavelength ranges and pre-processing methods.
    - Yes
    - No
    - Maybe
- Do you have suggestions for handling calibration transfer (between different optical benches/manufacturers)? Please describe.

- What metadata would you want to store or receive with soil spectral data?
- Do you have expertise, tools, or datasets that could be useful for this project? Check all that apply.
    - Expertise
    - Datasets
    - Tools
- Do you want to join this effort led by the Global Soil Partnership and in particular the GLOSOLAN Spectroscopy Working Group?
    - Yes, please
    - No, thanks

Thanks for taking this survey. Your contribution is very much appreciated!



The Global Soil Partnership (GSP) is a globally recognized mechanism established in 2012. Our mission is to position soils in the Global Agenda through collective action. Our key objectives are to promote Sustainable Soil Management (SSM) and improve soil governance to guarantee healthy and productive soils, and support the provision of essential ecosystem services towards food security and improved nutrition, climate change adaptation and mitigation, and sustainable development.

GLOSOLAN
GLOBAL SOIL LABORATORY NETWORK

GLOSOLAN is a Global Soil Laboratory Network which aims to harmonize soil analysis methods and data so that soil information is comparable and interpretable across laboratories, countries and regions. Established in 2017, it facilitates networking and capacity development through cooperation and information sharing between soil laboratories with different levels of experience. Joining GLOSOLAN is a unique opportunity to invest in quality soil laboratory data for a sustainable and food secure world.

Thanks to the financial support of

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