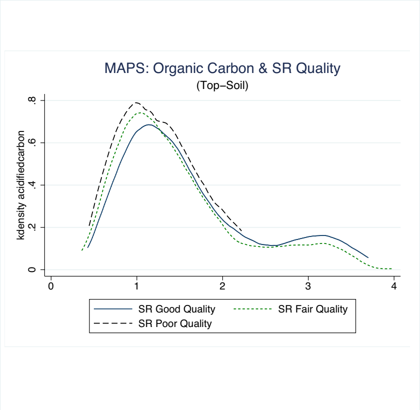


LSMS GUIDEBOOK
October 2017

Spectral Soil Analysis & Household Surveys

A Guidebook for Integration

Sydney Gourlay, Ermias Aynekulu, Calogero Carletto, and Keith Shepherd

LSMS Living Standards Measurement Study

World Agroforestry Centre

THE WORLD BANK
IBRD • IDA

LSMS GUIDEBOOK
October 2017

Spectral Soil Analysis & Household Surveys

A Guidebook for Integration

Sydney Gourlay
World Bank

Ermias Aynekulu
World Agroforestry Centre

Calogero Carletto
World Bank

Keith Shepherd
World Agroforestry Centre

ABOUT LSMS

The Living Standards Measurement Study (LSMS), a survey program housed within the World Bank's Development Data Group, provides technical assistance to national statistical offices in the design and implementation of multi-topic household surveys. Since its inception in the early 1980s, the LSMS program has worked with dozens of statistical offices around the world, generating high-quality data, developing innovative technologies and improved survey methodologies, and building technical capacity. The LSMS team also provides technical support across the World Bank in the design and implementation of household surveys and in the measurement and monitoring of poverty.

ABOUT THIS SERIES

The LSMS Guidebook Series offers information on best practices related to survey design and implementation. While the Guidebooks differ in scope, length, and style, they share a common objective: to provide statistical agencies, researchers, and practitioners with rigorous yet practical guidance on a range of issues related to designing and fielding high-quality household surveys. The Series aims to achieve this goal by drawing on the experience accumulated from decades of LSMS survey implementation, the expertise of LSMS staff and other surveys experts, and new research using LSMS data and methodological validation studies.

Living Standards Measurement Study (LSMS)
World Bank
Development Data Group (DECDG)
lsms@worldbank.org
www.worldbank.org/lsms
data.worldbank.org

Cover images: Gourlay, S., ICRAF
Cover design and layout: Deirdre Launt

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

AfSIS	Africa Soil Information Service
AgSS	Agricultural Sample Survey (Ethiopia)
CAPI	computer-assisted personal interviewing
CR	compass and rope area measurement, also referred to as traversing
CSA	Central Statistical Agency of Ethiopia
DSM	digital soil mapping
EA	enumeration area
FAO	Food and Agriculture Organization of the United Nations
GPS	global positioning system
Ha	hectare
ICRAF	World Agroforestry Centre
IR	infrared spectroscopy
LASER	Land and Soil Experimental Research study, Ethiopia
LDSF	Land Degradation Surveillance Framework
LSMS	Living Standards Measurement Study
LSMS-ISA	Living Standards Measurement Study – Integrated Surveys on Agriculture
MAPS	Methodological Experiment on Measuring Maize Productivity, Variety, and Soil Fertility, Uganda
MIR	mid-infrared diffuse reflectance spectroscopy
NIR	near-infrared diffuse reflectance spectroscopy
SR	self-reported, also referred to as farmer-reported
SSA	spectral soil analysis
TXRF	total x-ray fluorescence spectroscopy
UBOS	Uganda Bureau of Statistics
UN	United Nations
UNEP	United Nations Environment Programme
XRD	x-ray powder diffraction spectroscopy

ACKNOWLEDGMENTS

This document was made possible by generous funding from UK Aid. The authors would like to thank Alemayehu Ambel, Wilbert Vundru Drazi, Talip Kilic, Simone Pieralli, Asmelash Haile Tsegay, and Alberto Zezza for their inputs during fieldwork implementation and preparation and review of this Guidebook. Fieldwork for the methodological experiments was executed in partnership with the Central Statistical Agency of Ethiopia and the Uganda Bureau of Statistics. Our greatest appreciation goes to these partners for their dedication to these studies. This Guidebook has large areas of overlap with a companion research paper (Gourlay et al., 2017), which has a specific emphasis on the analysis of the data from the above-mentioned methodological experiment in Ethiopia.

Data from the Land and Soil Experimental Research (LASER) study is available for download now from the Living Standards Measurement Study (LSMS) website, as are other national LSMS Integrated Surveys on Agriculture (ISAs) and methodological experiment data. Find them here: www.worldbank.org/lsms

EXECUTIVE SUMMARY

This Guidebook is intended to be a reference for survey practitioners looking for guidance on integrating soil health testing in household and farm surveys. The role of soil in agrarian societies is unquestionable, yet the complex nature of soil makes it much more challenging to measure than agricultural inputs such as fertilizers or pesticides. Historically, household surveys either include subjective questions of farmer assessment or rely on national-level soil maps to control for land quality, if anything at all. Recent scientific advances in laboratory soil analysis—via spectral soil testing—have opened the door to more rapid, cost-effective objective measurement of soil health in household surveys. This Guidebook explores the nascent possibility of integrating plot-level soil testing in household surveys through a presentation of results comparing various soil assessment methods and a step-by-step guide for practical implementation.

In partnership with the World Agroforestry Centre (ICRAF), the Living Standards Measurement Study of the World Bank's Development Data Group set out to validate (1) the feasibility of implementing spectral soil analysis in household surveys, and (2) the value of subjective farmer assessments of soil quality compared with objective measures in order to determine the need for objective soil analysis, specifically in low-income, smallholder agricultural contexts. These objectives were met by implementing two methodological validation studies, one in Ethiopia and one in Uganda. In both studies, plot-level soil samples were collected following identical international best-practice field protocols and analyzed using wet chemistry and spectral analysis methods at ICRAF's Soil-Plant Spectral Diagnostics Laboratory. Additionally, plot managers were administered a series of subjective questions that are often used to gauge soil health in national household surveys. These studies resulted in two uniquely rich datasets that allow for comparison of subjective indicators of soil quality against laboratory results. Both laboratory and subjective results can also be compared with publicly available geospatial data, as all plots were georeferenced.

How do subjective assessments of soil health compare to laboratory measures?

The results from the two methodological studies suggest that farmer assessments of soil health inadequately capture the overall state of soil quality and fail to untangle the complexities enough to inform specific policy decisions. Subjective questions aim to capture soil health through soil color, texture, type, and farmer-reported overall soil quality.[1] In both studies, soil color is consistently correlated with key soil properties, such as organic carbon content, with black soils having greater health than soils reported as white, light, or red. Soil texture, collected in a categorical manner, is also found to be a significant predictor of organic carbon content, with reportedly coarse soils having lower carbon content than those reported as fine, which is in line with expectations that sandier soils hold fewer nutrients.

Results on farmer assessments of overall soil quality are less reassuring, however. Farmers' ability to assess overall soil quality, as measured by both organic carbon content and a variety of soil quality indices, varies by study. In Ethiopia, the organic carbon content in soils reported as "good" is only marginally higher (and with marginal statistical significance) than in soils reported as "poor." There is no significant difference between the mean carbon content in plots reported as "good" and "fair" in Ethiopia, although a significant difference is observed in Uganda. Analysis using household fixed effects in Ethiopia suggests that respondents do not rank plots appropriately even within households, at least in terms of the overall soil quality. The strength of the relationship between the subjective overall soil quality and laboratory results vary by study, raising doubt about the reliability of subjective assessment.

While subjective assessments have the benefit of cost and time efficiency, and in turn lower rates of missing data, they suffer from a weak correlation with objective measures as well as a lack of variation within households. In households that cultivated more than one plot, more than 63 percent of households reported the same soil quality, more than 67 percent reported the same soil color, and more than 64 percent reported the same texture on all plots in both the Ethiopia and Uganda studies. This pattern persists even in Ethiopia, where the average number of plots cultivated is very high. For example, of households that cultivated eight plots, nearly 70 percent reported the same soil color on all plots. The lack of variation may be due to truly similar soil properties, the lack of effort or knowledge on the part of the respondent, or simply the inability of the

1 The terms soil fertility, soil health, and soil quality are used interchangeably throughout the Guidebook.

coarse categorical variables to capture gradations in soil properties. While the convenience of subjective soil assessments is tempting, the unreliable relationship with objectively measured data and the lack of intrahousehold variation may limit the usefulness of the data, even in informing decisions at a regional or national scale.

Soils can exhibit a wide range of variation across sample studies, within enumeration areas, and even within households, depending on the context. A comparison of plot-level soil testing and geospatial data from the Africa Soil Information Service (AfSIS) suggests that the geospatial data fail to capture the degree of variation in key soil properties, namely organic carbon, in enumeration areas with high variation. On the whole, the correlation between the plot-level methodological data and the AfSIS carbon content is 0.59 in Ethiopia and 0.56 in Uganda. In both studies, the mean carbon content reported by AfSIS is higher than that observed in the plot-level soil analysis. This implies that integrating spectral-based methods in household surveys can reduce uncertainties in assessing soil quality, and hence, improve smallholder agricultural statistics.

Practical guidance for spectral soil analysis in household surveys

Soil testing at the plot level in conjunction with a household survey is largely unexplored territory. The knowledge gained in the implementation of the two methodological validation studies, together with ICRAF's operational and analytical expertise related to soil sampling and analysis, drives the content of this Guidebook. First, detailed, step-by-step guidance on planning and implementing a household survey with a component on soil sample collection and analysis is provided. Instructions on implementation include all topics from training to shipment to the laboratory, including considerations for sampling, equipment and training needs, specific in-field protocols, and soil-processing requirements. A section on laboratory analysis familiarizes the practitioner with what one can expect from the laboratory and how to best prepare for the final output.

The experience of the two studies suggests that integrating spectral soil analysis with household surveys is feasible, given the proper budget and timeframe. The ease of implementation can be increased with a few simple steps, such as using barcode labeling or using local infrastructure for soil sample processing. Collecting samples will increase the amount of time enumerators spend with a given household but potentially not to a debilitating degree. Soil sampling took approximately 40 minutes per plot on average in Ethiopia and 24 minutes per plot in Uganda. It is important to budget for extra fieldwork time and fuel, however, as the soil samples must be delivered to the laboratory within five to seven days of collection to prevent organic matter from decomposing when soils are wet.

Given the emerging nature of this type of research, and the complexities of soil quality measurement, we encourage further validation of such projects, particularly under soil conditions different from those presented here.

KEY GUIDEBOOK HIGHLIGHTS AND RECOMMENDATIONS

- Soil spectroscopy has made it feasible to integrate soil monitoring into household surveys. Such methodological improvements in smallholder agricultural statistics inform decision making.
- Soil sample collection took approximately 40 minutes per plot in Ethiopia and 24 minutes per plot in Uganda, including a set of enumerator observations on soil texture and other properties.
- Farmer-reported soil color and texture consistently predict organic carbon content, but with limited strength.
- The relationship between farmer assessments of overall soil quality and objectively measured indicators varies by study, suggesting a lack of consistency in the ability of the subjective survey questions to capture the true state of the soil.
- Subjective indicators exhibit little intrahousehold variation:
    - In each study, more than 63 percent of households cultivating more than one plot report the same overall quality on all plots.
    - In each study, more than 67 percent of households cultivating more than one plot report the same soil color on all plots.

Part 1 - Background and Definitions

Soil is a key input in agricultural production and analysis. This Guidebook offers practical guidance for integrating spectral soil analysis into household survey operations, particularly in low-income, smallholder farmer contexts. It is geared toward survey practitioners and includes guidance on what to consider in evaluating competing methods for measuring soil health, the trade-offs incurred when relying on subjective soil assessments, and how to implement soil sample collection in the field. The recommendations are based on purposely designed methodological validation studies on integrating soil monitoring via spectral soil analysis into household surveys by the Living Standards Measurement Study of the World Bank, the World Agroforestry Centre, the Statistical Agency of Ethiopia, and the Uganda Bureau of Statistics.

INTRODUCTION

Renewed interest in raising agricultural productivity to meet food security needs and increasing the resilience of agricultural systems in low- and middle-income countries, especially in sub-Saharan Africa, makes understanding soil health constraints and trends ever more important. Measuring and monitoring soil health are fundamental to developing a sound knowledge of problems and solutions for sustainable crop production and land management (Sanchez et al., 2009; Takousting et al., 2016). Much of the current analysis on agricultural productivity is hampered by the lack of consistent, good-quality data on soil health and how it is changing under past and current management. Direct systematic measurement of soil health as part of household-level data collection has rarely been attempted owing to the high costs of soil sampling and analysis. This Guidebook explores the nascent possibility of integrating plot-level spectral soil testing into household surveys, while also analyzing the measurement error associated with current approaches, subjective assessment, and geospatial modeled outputs.

Linking soil health information to socioeconomic household survey data provides an important opportunity for enhancing our understanding of trends in soil health and their impact on crop productivity among smallholders, as well as the coping mechanisms adopted by farmers faced with deteriorating soil conditions. The new systematic surveillance frameworks for consistent monitoring of soil and land health have been developed based on digital sensing technology. In particular, new rapid low-cost technology for assessing soil characteristics using infrared spectroscopy has made soil health characterization feasible in large studies (Shepherd & Walsh, 2002, 2007). These techniques are now being supplemented by other light-based techniques using laser and x-ray spectroscopy and applied to sampling schemes in large areas of sub-Saharan Africa under the AfSIS project (Hengl et al., 2015).

Soil health information is of interest to many different audiences and for different purposes. The ideal measurement scheme would be tuned to the exact purpose and context for which it is required. It is rarely feasible, however, to develop and refine methods for every situation. Hence this Guidebook describes a procedure based on that recently implemented in two methodological experiments and suitable for a systematic measurement of soil health as part of household-level data collection. This procedure provides a general sense of survey design requirements and implementation considerations and may be modified to fit specific study objectives and data needs. The results of the studies also illustrate the benefit of including objective measurement of soil health in household surveys with an agricultural focus. The target users of this Guidebook include survey practitioners, technical staff of relevant government agencies and research institutes, and researchers interested in micro-level analyses in which household and plot-level data are necessary, as are integrated data on household behavior, socioeconomic characteristics, and agricultural practices.

The World Bank Living Standards Measurement Study–Integrated Surveys on Agriculture (LSMS-ISA) initiative includes multitopic, national panel household surveys with a strong focus on agriculture that are implemented in numerous countries in sub-Saharan Africa. As part of this initiative, and with funding from UK Aid, the World Bank LSMS team implemented the Minding the (Agricultural) Data Gap methodological research program aimed at improving the quality and relevance of agricultural statistics. The methodological research activities span seven topics: (1) land area measurement, (2) soil fertility, (3) rainfall, (4) labor inputs, (5) skill measurement, (6) production of continuous and extended-harvest crops, and (7) computer-assisted personal interviewing for agricultural data. This Guidebook is based on the soil fertility component of the project, which evaluated both the feasibility of integrating soil-quality analysis into household socioeconomic data collection operations and the local knowledge of farmers in assessing their soil quality.

This document is anchored in the Ethiopia Land and Soil Experimental Research (LASER) study and the Uganda Methodological Experiment on Measuring Maize Productivity, Variety, and Soil Fertility (MAPS), implemented respectively by the Ethiopia Central Statistical Agency (CSA) and the Uganda Bureau of Statistics (UBOS), under a partnership between the World Bank LSMS and the World Agroforestry Centre (ICRAF). Fieldwork consisted of implementing a variety of subjective farmer-estimated indicators of soil quality as well as conventional and spectral soil analysis, resulting in unique plot-level datasets. By comparing subjective and objective measures of soil properties, the data allow for analysis of the impacts of relying on subjective farmer estimates of soil quality for policy-based decision making. The results from the two methodological studies suggest that farmer assessments of soil health inadequately capture the overall state of soil quality and fail to untangle the complexities sufficiently to inform specific policy decisions.

This Guidebook uses the protocols, experiences, and lessons learned from the Ethiopia LASER and Uganda MAPS studies to provide a step-by-step guide to integrating soil collection and analysis into household surveys. It focuses on household survey operations in low-income countries and implementation challenges that are often encountered in these contexts, but protocols are also relevant in higher-income contexts. Wherever possible, implementation steps and strategies are generalized to the fundamental requirements and complemented by the specific approach used in the two studies. The soil sampling and measurements implemented in the studies, and in this Guidebook, were derived from AfSIS protocols and adapted to fit sampling from agricultural plots.

The Guidebook begins with a review of the uses of soil health measurements from household surveys and a discussion of basic concepts, definitions, and methodological options in measuring soil quality (Part I). Part II presents an assessment of the performance of the various methods. In this section, the key results from LASER and MAPS are presented, including an assessment of the comparative performance of the subjective and objective methods and a brief comparison of plot-level soil analysis with publicly available geospatial soil data. The objective laboratory analysis and subjective farmer assessments of soil health are analyzed in terms of accuracy, cost, time, feasibility of implementation in large scale surveys, and sensitivity to problems in survey implementation. Part III tackles the specifics of integrating spectral soil analysis into household surveys, including a step-by-step guide to collecting soil samples from agricultural plots and key considerations for soil processing and analysis, particularly those relevant for survey practitioners engaging with soil laboratory analysis. A summary of main messages is provided in the concluding chapter, which also highlights areas where further validation work is needed, including the use of in-field tools.

BOX 1 — KEY SOIL PROPERTIES AND THEIR ROLE IN AGRICULTURAL PRODUCTION

The information in this box draws heavily from the FAO Soils Portal (http://www.fao.org/soils-portal/soil-survey/soil-properties).

Soil properties are divided into three main categories: physical, chemical, and biological. The primary focus of this document is on physical and chemical properties, which are analyzed through spectral soil analysis.

Key physical properties:

- Texture: Determined by the components of sand, silt, and clay, each of which is based on the granularity of the soil. Texture can affect other soil properties such as soil nutrient content and water-holding capacity.
- Soil structure: A function of the soil texture that affects plant root growth, water movement, and resistance to erosion.
- Color: Generally determined by organic matter content and degree of oxidation. May be used as a qualitative indicator of organic, salt, and carbonate content, though not necessarily a strong predictor of exact soil properties.
- Other physical properties include depth, consistency, porosity, density, and water characteristics. Refer to the FAO Soils Portal for more detail (http://www.fao.org/soils-portal).

Key chemical properties:

- pH: A measure of acidity, ranging from 3.5 (acidic) to 9.5 (alkaline) in soils. There is an optimal level for each crop, with most crops performing best with a pH of 6.5.
- Cation exchange capacity (CEC): An indicator of the maximum quantity of cations the soil can hold. A higher CEC implies greater fertility and nutrient retention capacity.
- Organic carbon: Improves physical soil properties, CEC, and water-holding capacity. Organic carbon also prevents nutrient leaching and enables mineral availability to plants. Soil organic matter is primarily made up of organic carbon and holds most of the soil nutrients. Additionally, organic carbon stabilizes soil pH levels. A greater organic carbon content implies greater soil health.
- Nitrogen: Nitrogen is critical to plant growth. Plant-available nitrogen comes in the form of the cation ammonium or the anion nitrate. Raw organic nitrogen in the soil is not readily available to plants directly.
- Micro- and macronutrients: Macronutrients are critical for plant development, and a high quantity is needed (nitrogen, phosphorus, potassium, calcium, sulfur, and magnesium). Micronutrients are needed but in smaller quantities (boron, chlorine, manganese, iron, zinc, copper, molybdenum, nickel, and cobalt).

Key biological properties:

- Soil biota, including flora (plants), fauna (animals), and microorganisms: Perform functions that contribute to the soil's development, structure, and productivity.
- Soil flora: Aids in soil structure and porosity and in supplying soil organic matter via shoot and root residue.
- Soil fauna: Work as soil engineers, initiating breakdown of dead plant and animal material, ingesting and processing large amounts of soil, burrowing pores for water and air movement, mixing soil layers, and increasing aggregation.

2. USES OF OBJECTIVE SOIL HEALTH MEASURES FROM HOUSEHOLD SURVEYS

Detailed and spatially disaggregated soil data, when integrated with data on farming practices, can inform our understanding of the effects of household-specific soil management strategies and the most appropriate strategies to encourage going forward. The data can assist in targeting agricultural interventions regarding optimal crop selection, fertilizer selection and application rate, and the potential for the use of micronutrient-enriched or otherwise improved seeds.

Soil health is at the root of agricultural production. As the pressures on agriculture increase with growing populations and changing climates, understanding the details of soil properties is essential in designing and implementing appropriate soil management practices. The complexity of soil and its interaction with crops means that there is no blanket soil management practice (refer to Box 1 for a description of properties). Rather, decisions must be made with respect to site-specific conditions. Integrating plot-level soil analysis into household surveys that collect household- or plot-specific data on farming practices and socioeconomic structure allows for the analysis of when, where, and by whom the appropriate farming practices are employed, given plot-specific soil conditions. Such information can be used to improve extension services, target specific groups of farmers, and identify primary constraints in improving productivity. Detailed soil data with high spatial resolution, such as at the plot level, can inform numerous forward-looking decisions such as optimal crop or variety for the conditions and optimal fertilizer use (including type and application rate). These data can also serve to monitor soil health over time, as well as assist with the adaptation of agriculture to climate change. As Lal (2009) clearly states, with respect to climate change, "adaptation is crucial to survival."

Collecting detailed data on soil health, including micronutrient levels, at the household level has the potential to benefit human health. Deficiencies of micronutrients, such as in iron, zinc, and vitamin A, afflict populations worldwide (Tulchinsky, 2010). Insufficient intake of key micronutrients, especially during early childhood, can have severe implications for health and human capital outcomes. Relatively recent advancements have been made to bridge the gap between micronutrient poor soils and micronutrient content in plants themselves. Welch and Graham (2004) and Lal (2009) have demonstrated the potential of biofortification of micronutrients in the seeds of staple crops to improve nutritional outcomes. Because plants require micronutrients for growth, enriching seeds with micronutrients that the soil lacks could result in increased crop yield and resistance to disease, thereby increasing the abundance of food, while also improving its nutritional value. Bouis (2003) argues that these improvements in production may result in high uptake by farmers. Better yet, he makes a case that enriching staple crops with micronutrients is one of the more cost-effective nutritional solutions available. Collecting data on micronutrient levels in soils at the household level, as through spectral soil analysis, would help target such seed biofortification programs by identifying where soils are micronutrient poor and which nutrients in particular they lack.

In addition to these potential uses of detailed soil data, perhaps the most frequent use of soil data is in agricultural productivity analysis. Including accurate soil health measures in production functions is a key step toward controlling for the unobserved plot-level heterogeneity that is often claimed to determine both outcomes and key explanatory variables and that could result in biased coefficient estimates. As will be illustrated in the following sections, farmer-reported measures of soil health are not effective controls in agricultural productivity analysis. Similarly, using national-level soil maps may not capture the same level of variation across space as plot-level soil analysis, but this issue is largely left for future validation.

3. CONCEPTS AND DEFINITIONS

Holding, parcel, field, and plot are concepts with internationally accepted statistical definitions. Soil fertility testing in household surveys can take place at any of these levels. The objectives of the survey and the variation in soils in the study area should be considered when deciding at which level to collect soil samples.

Any measurement effort must start with a clear definition of the objectives and what exactly needs to be measured to reach said objectives.[2] Before turning to methods, therefore, this section briefly reviews concepts and definitions that are relevant when designing a survey involving the measurement of the quality of agricultural land.

In agricultural surveys and censuses the primary statistical unit is the agricultural holding, whereas in population-based

2 This section draws heavily on FAO (2005).

surveys it is generally the household. According to FAO (2005, p. 21):

> An **agricultural holding** is an economic unit of agricultural production under single management comprising all livestock kept and all land used wholly or partly for agricultural production purposes, without regard to title, legal form, or size. Single management may be exercised by an individual or household, jointly by two or more individuals or households, by a clan or tribe, or by a juridical person such as a corporation, cooperative, or government agency. The holding's land may consist of one or more parcels, located in one or more separate areas or in one or more territorial or administrative divisions, providing the parcels share the same production means, such as labor, farm buildings, machinery. or draught animals.

According to the "housekeeping-concept" adopted by the United Nations (2008, p. 100):

> The concept of **household** is based on the arrangements made by persons, individually or in groups, for providing themselves with food and other essentials for living. A household may be either (a) a one-person household, that is to say, a person who makes provision for his or her own food and other essentials for living without combining with any other person to form a multi-person household or (b) a multi-person household, that is to say, a group of two or more persons living together who make common provision for food and other essentials for living. The persons in the group may pool their resources and may have a common budget; they may be related or unrelated persons or constitute a combination of persons both related and unrelated.

The definitions used in household surveys generally relate pretty closely to these international standards, although one should be aware of existing differences across countries, and of the implications of differences in definitions for the resulting statistics, which may be particularly large for certain groups in the population (Grosh & Glewwe, 2000; Beaman & Dillon, 2012; Randall & Coast, 2015).

In agricultural surveys, the holdings may pertain to the household sector or to the nonhousehold sector (e.g., corporate farms). This Guidebook focuses specifically on the household sector. While definitions of the household may vary from survey to survey, there is generally fairly strong correspondence between agricultural holdings and households with own-account agriculture. Two main exceptions occur: (1) when two or more units make up a household (which may mean sharing meals or sleeping under the same roof) but manage land or livestock separately, or (2) when a household operates land or livestock jointly with another household or group of households (FAO, 2005). Some countries opt for adopting criteria in agricultural surveys whereby the agricultural and household holdings coincide. Chapter 3 in FAO (2005) describes in detail the advantages and issues implied by different options in defining the primary statistical unit.

While not all agricultural holdings have land, most normally do. According to the FAO (2005, p. 81):

> A holding is divided into parcels, where a parcel is any piece of land, of one land tenure type, entirely surrounded by other land, water, road, forest, or other features not forming part of the holding or forming part of the holding under a different land tenure type. A parcel may consist of one or more plots or plots adjacent to each other. The concept of a parcel used in the agricultural census may not be consistent with that used in cadastral work. The reference period is a point of time, usually the day of enumeration. A distinction should be made between a parcel, a field, and a plot. A field is a piece of land in a parcel separated from the rest of the parcel by easily recognizable demarcation lines, such as paths, cadastral boundarieboundary, and/or hedges. A field may consist of one or more plots, where a plot is a part or whole of a field on which a specific crop or crop mixture is cultivated.

There are at least three reasons why survey designers need to have these definitions in mind when planning a survey. First, it is important to convey these concepts clearly and consistently to enumerators and respondents (as well as to data users) if data are to be collected and used consistently. Second, it is necessary at the survey design stage to consider the information that needs to be collected at each level. This depends on a number of factors, including the planned use of the data (e.g., what types of analyses are going to be conducted at farm versus plot level), the way that enumerators are best able to conduct the interviews, and the way respondents are best able to answer the questions. Third, the adoption of internationally agreed definitions is bound to increase the international comparability of the data being collected. As an example of good practice in adhering to international definitions, Annex 1 reproduces the guidance provided by the Uganda Bureau of Statistics to enumerators in the implementation of its National Panel Survey. The definition of the measurement level must be explicitly stated before commencement of the survey, as local definitions may vary across countries.

In deciding the level at which to conduct soil testing, survey designers should consider the objectives of the survey, the type of analytical uses that are envisaged for the data, and the expected variation of soil within the sample area. If the study area includes little variation in soil type and quality, as observed in national soil maps, for example, it may be sufficient to draw from only one parcel or plot per household. However, if high variation is expected and/or the primary objective is plot-level productivity analysis, soil sampling from more than one plot per household may be the preferred approach. Similarly, surveys aimed at analyzing gender dimensions of agricultural productivity and resource distribution would benefit greatly from plot-level measurements.

4. METHODOLOGICAL OPTIONS IN MEASURING SOIL HEALTH

Soil fertility is a highly complex subject, rendering its measurement challenging and expensive. Household surveys have often relied on subjective assessments of soil quality because that method is inexpensive. However, recent advances in technology have made the use of spectral analysis more affordable, rapid, and accurate, increasing its potential for use in household surveys.

4.1 SUBJECTIVE ASSESSMENT

In a household survey setting, collecting data on subjective indicators of soil health is undoubtedly the most inexpensive method. Rather than spend time visiting agricultural plots to measure soil quality, household surveys often ask respondents directly for their assessment of the soil through one or more questions. These questions often aim at capturing the overall soil quality level (in a categorical manner) as well as key soil quality indicators, such as soil color and texture. Additional questions may be asked about the incidence of erosion, any erosion management techniques in practice, and the use of organic and chemical inputs. Data on farming practices such as tillage, crop rotation, and the use of cover crops may also be included. An example of a subjective soil module can be found in Annex 2.

One might assume that respondents who spend ample time working on the land would be able to assess the health of the soil with reasonable accuracy. Soil health, however, is a highly complex subject, and this assumption can be misguided, as illustrated below. Several factors are worth considering when deciding whether to use subjective assessments.

First, given the utility of plot-level data for agricultural productivity analysis, subjective assessments of soil health should be provided at the plot level rather than farm level, where relevant.

Second, the corresponding plot manager, or one of the plot managers in case of joint management, should ideally answer for each plot, which raises the possibility of interviewing multiple respondents per household. Because the appropriate respondent(s) may not be available to answer questions during the time that the survey team or the enumerator will be visiting the associated enumeration area (EA), the use of proxy respondents will be one of the factors mediating the reliability of the information sought.

Third, whether interviewing one or more respondents per household, the benchmark or reference point used by the respondent(s) as part of the subjective assessment matters. In rural areas where mobility is limited, a respondent's reference is only the soil in and around his or her farm. This person's assessment of soil quality will, therefore, be relative to the soil he or she observes nearby. In areas with little variation in soil properties, it may prove difficult for farmers to determine whether an agricultural plot has good, average, or poor soil. More broadly, as with most subjective assessments, the answers provided by the respondents are expected to be correlated with their observable as well as unobservable attributes.

Fourth, it may not be clear to respondents that the intention is to isolate the quality of the soil itself and not other plot characteristics or production outcomes. Findings by Tittonell et al. (2008) suggest that farmers have a "holistic" view of soils; rather than assessing the soil properties explicitly, they often incorporate other components such as overall agricultural productivity and likelihood of crop theft, for example.

Despite these difficulties, the negligible cost of including subjective assessment of soil health as part of a household survey makes it an attractive proposition. Because subjective assessment does not require traveling to the agricultural plot itself, the resulting data will suffer from a lower rate of item nonresponse compared with methods that require plot visitation. However, the convenience of collecting subjective assessments of soil quality may come at the cost of data quality and granularity. This issue will be reviewed in Part II.

4.2 LABORATORY ANALYSIS

Objective measurement of soil properties, through laboratory testing, is preferable to subjective assessment in several ways. Laboratory analysis bypasses the subjective nature of farmer estimates, eliminating bias due to farmer characteristics. Objective measurement also allows for a much more detailed view of soil quality, reporting levels of a multitude of individual elements and nutrients, thus increasing the scope of application of the data. The advantages of laboratory analysis do not come without cost, however. Below, the primary options in laboratory soil analysis—conventional wet chemistry and soil spectroscopy—are described, as are their advantages and disadvantages.

4.2.1 CONVENTIONAL SOIL ANALYSIS

Accepted as the gold standard in soil testing, conventional soil analysis sets the benchmark for accuracy. It does, however, come with significant costs and implementation requirements that limit the scale up of the method into large-scale household surveys. Conventional soil analysis includes traditional wet chemistry methods for soil nutrient extraction, as well as basic physical analysis such as measurement of water-holding capacity. There are several approaches to nutrient extraction in conventional wet chemistry; among the most common is the Mehlich 3 extractant method. The Mehlich 3 method estimates levels of plant-available micro- and macronutrients (Mehlich, 1984).

Conventional analysis is widely accepted as accurate, but it is time intensive, costly, and destructive, and it is occasionally difficult to get reproducible results. The wet chemistry component involves mixing the soil sample with an extractant solution, such as Mehlich 3, destroying the sample and preventing any further analysis of it. The destructive nature of conventional soil testing, therefore, eliminates the repeatability of analysis. This weakness is addressed in the following section on spectral analysis.

The conventional soil analysis methods require intense manual intervention and therefore take a relatively long time to complete. On average, conventional testing takes a full day to analyze about 40 samples. Related to time requirements, and most important for scalability, is cost. The full suite of conventional wet chemistry testing can cost approximately US$60 per sample.

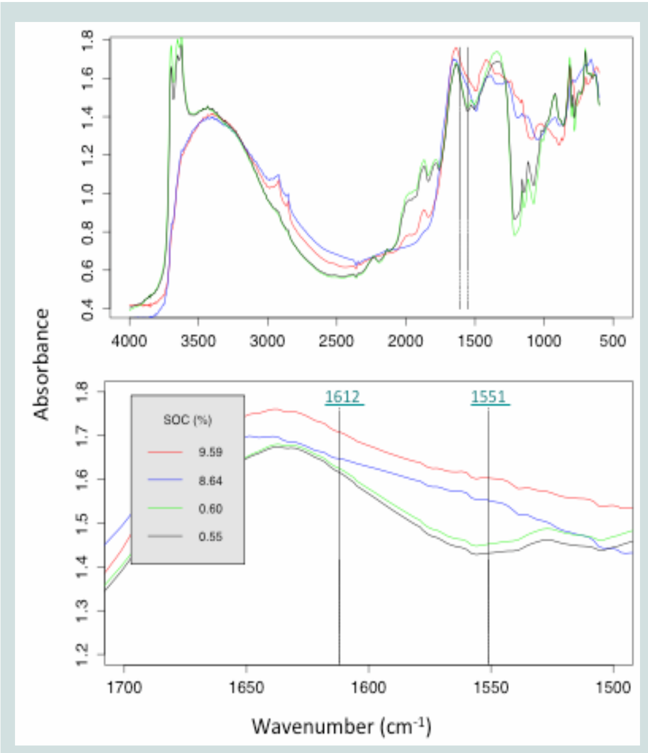
4.2.2 SPECTRAL ANALYSIS: SOIL SPECTROSCOPY FOR PREDICTING SOIL PROPERTIES

Spectral soil analysis, or soil spectroscopy, offers a relatively rapid, low-cost, nondestructive alternative to conventional soil testing. While still relying on conventional analysis for reference measures, soil spectroscopy minimizes costs by predicting soil property measurements from the conventional analysis results of a small subsample (10–25 percent of the full sample) to the full sample using spectral signatures.

Soil spectroscopy uses the simplicity of light—the interaction of electromagnetic radiation with matter—to characterize the physical and biochemical composition of a soil sample. Light is shone on a soil sample, and the reflected light, after interaction with the sample, is collected at different wavelengths by a detector. The resulting pattern of reflected or absorbed light at different wavelengths is referred to as a spectrum. Infrared spectral signatures (visible-near-infrared, near infrared, or mid-infrared) detect molecular vibrations that respond to the mineral and organic composition of soil or plant materials. Spectral signatures thus provide both an integrated signal of functional properties as well as the ability to predict a number of conventionally measured soil properties (Nocita et al., 2015). See Figure 1 for an example of a spectral signature.

Infrared spectroscopy (IR) is now routinely used for analyses of a wide range of materials in laboratory and process control applications in agriculture, food and feed technology, geology, and biomedicine (Shepherd & Walsh, 2007). The mid infrared (MIR, 2.5-25 μm) wavelength region was investigated for nondestructive analyses of soils and can potentially be usefully applied to predict a number of important soil physical, chemical, and biological properties, including soil texture, mineral composition, organic carbon and water content (hydration, hygroscopic, and free pore water), iron form and amount, carbonates, soluble salts, and aggregate and particle size distribution (Shepherd & Walsh, 2004). Importantly, these properties also largely determine the capacity of soils to perform various production, environmental, and engineering functions. IR enables soil-sampling density (samples per unit area) to be greatly increased with little increase

Figure 1 — Example of soil spectral signatures of four samples from the Ethiopia LASER study with different levels of soil organic carbon.



Source: Authors' calculations.

in analytical costs. Depending on the equipment used, up to 400 samples can be analyzed per day, with an approximate cost of US$5 per infrared sample.

The AfSIS uses spectral diagnostics, including IR, total x-ray fluorescence spectroscopy (TXRF), x-ray diffraction spectroscopy (XRD), and laser diffraction particle size analysis (LDPSA) techniques to measure soil functional properties on tens of thousands of georeferenced soil samples in a consistent way at a continental scale. The low-cost, high-throughput spectroscopy methods are being used both as a front-line screening technique for development of pedotransfer functions and for the direct development of indicators of soil functional properties (Minasny & Hartemink, 2011). This has been facilitated by recently developed analytical protocols, including modern laboratory infrastructure at the World Agroforestry Centre (ICRAF) Soil-Plant Spectral Diagnostics Laboratory. The AfSIS approach is being adopted in Ethiopia (Ethiopian Soil Information Service [EthioSIS]), Ghana (Ghana Soil Information Service [GhaSIS]), Nigeria (Nigeria Soil Information Service [NiSIS], Tanzania (Tanzania Soil Information Service [TanSIS]), and elsewhere. Large-scale efforts commenced in Ethiopia in 2012 under the EthioSIS project implemented by the Ethiopian Agricultural Transformation Agency (www.ata.gov.et). The national soil-mapping project includes intensive use of soil spectrometry, among other techniques.

Soil spectroscopy estimates of soil properties may not be as accurate as reference soil analyses (wet chemistry), although an examination of the predictive power of spectroscopy in Part III suggests very little concern. Spectroscopy can, however, improve soil resource assessments, as more samples can be analyzed for a given budget (Nocita et al., 2015).

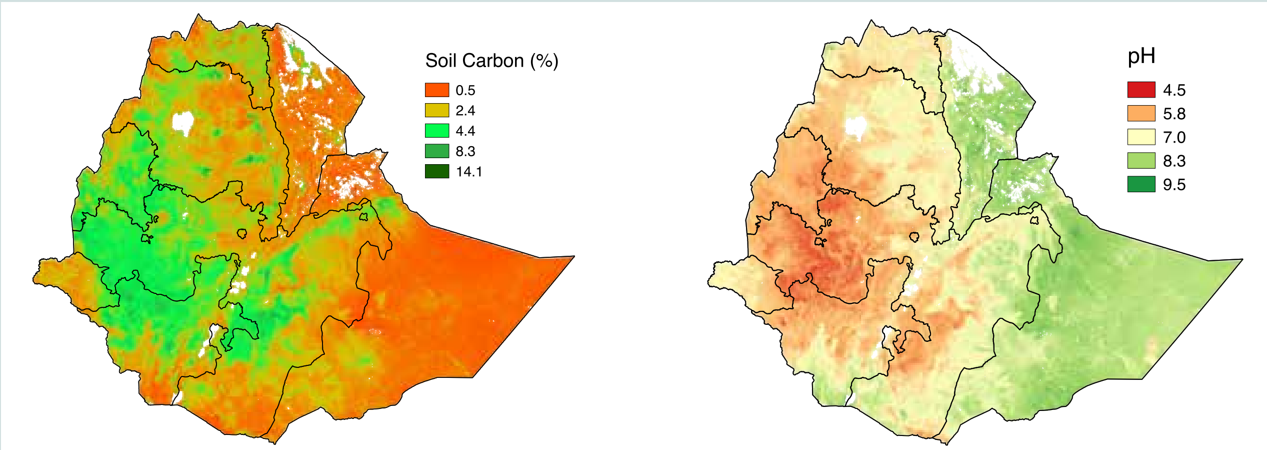
In addition to offering a lower per-sample cost, the cost-effectiveness of spectral analysis can increase as the base of reference samples for a given area increases. That is, although spectroscopy relies on a subsample of conventional soil analysis results (requiring a survey to also implement a small number of conventional tests), if these already exist for the region from a previous study, the existing results can be used again, bypassing the need to conduct any conventional analysis. The library of conventional testing results is continuously growing, improving future spectral prediction models and reducing the need for new measurement efforts.

While lab-based soil analyses provide high-quality results, some projects may find it too expensive to continually monitor soil health this way at a larger scale (Aynekulu et al., 2011). The implementation of soil analyses in the field by means of portable spectroscopy could allow assessment of soil health using a larger number of sampling locations compared with that offered by lab-based methods. Portable spectroscopy is less accurate, however, than lab-based methods, owing to environmental factors present during the in-situ measurement, such as soil moisture, ambient light, temperature, and condition of the soil surface, which partly mask the absorption features of some soil properties (Ji et al., 2014).

4.3 REMOTE SENSING & DIGITAL SOIL MAPPING

National or regional digital soil maps offer a potential solution for integrating soil characteristics with agricultural household survey data, particularly when agricultural plots are georeferenced. Improvements in technology have increased both the quantity and quality of geospatial soil data available to the public (for free or for purchase). Digital soil mapping (DSM)

Figure 2 — Soil Organic Carbon (%, left) and pH (right) Maps of Ethiopia



Source: Hengl et al., 2015

is the creation of a geographically referenced soil database generated at a given resolution by using field and laboratory observation methods coupled with environmental data. One example of the application of DSM is the mapping of soil properties across Africa at 250-meter resolution by Hengl et al. (2015) using the field data collected by the AfSIS project and other covariates, including legacy data (e.g., from the existing ISRIC-WISE and SOTER databases)[3]. Figure 2 shows a sample image of the 250-m resolution maps for soil organic carbon and pH in Ethiopia. The EthioSIS project, briefly discussed above, will result in a digital soil map of Ethiopia that is expected to be completed imminently. The project uses remote sensing technology, conventional wet chemistry methods, and soil spectroscopy to produce a grid-based, national-level digital soil map. The project, although not yet complete at the national level, has already shown great success in identifying nutrient deficiencies so that farmers can adjust fertilizing blends accordingly (Ethiopian ATA, 2017).

Digital soil maps may offer maps of individual soil properties, such as that illustrated in Figure 2, or aggregate measures of soil health. The Harmonized World Soil Database, for example, provides a global map of soil quality broken down into categorical terms according to the Global Agro-ecological Zones Assessment for Agriculture, in addition to individual soil parameters (Fischer et al., 2008).

Soil maps derived from satellite imagery and other covariates like terrain and climate, sentinel site analysis, or a combination of the two vary tremendously in resolution. While using existing soil maps can potentially cut down on survey costs compared with plot-level soil testing through spectral or conventional methods, there are trade-offs in geographic resolution that ought to be considered.

4.4 FUTURE POSSIBILITIES

The future for rapid, low-cost soil health testing is bright. The rate of technological advancement suggests that handheld devices will be able to estimate key soil properties in the field in the relatively near future. Most of the current handheld devices focus on a few soil parameters, like soil organic carbon, but as of yet there is no comprehensive method like the lab-based soil spectrometer. Aitkenhead et al. (2016), for instance, developed a mobile phone application to estimate soil organic matter. Additional research is underway by the United States Department of Agriculture to design a mobile phone application that could estimate soil properties based on soil color read through the application (Herrick et al., 2013). There is potential for the Alpha spectrometer, with analytical capabilities comparable to the laboratory spectrometer, to be customized for in-field use, yet consistency in soil preparation, soil moisture, ambient light, and soil surface conditions pose challenges in accurately estimating soil properties in situ (Wenjun et al., 2014). The proposed methods could significantly increase the scalability of soil testing in household surveys but would first need to undergo extensive validation.

3 ISRIC-WISE: International Soil Reference and Information Centre - World Inventory of Soil Emission Potentials; SOTER: Soil and Terrain.

Part II – An Assessment of Methodological Options in Measuring Soil Quality

5. THE LSMS METHODOLOGICAL VALIDATION PROGRAM

The LSMS, ICRAF, CSA, and UBOS collaborated to carry out validation studies in Ethiopia and Uganda, in which plot-level soil samples were analyzed through spectral soil testing alongside farmer assessment of soil quality.

The value of collecting detailed, high-quality, spatially disaggregated soil data and integrating those data with household surveys has been largely supported by the literature. The means by which these data should be collected, however, is less explored. Household surveys, when they do collect soil data, often do so by subjective means. The benefits of implementing subjective farmer assessments of soil quality over objective methods are twofold: (1) low cost; including questions on soil quality in an existing questionnaire instrument comes with a negligible cost and time for implementation; and (2) low item nonresponse in the resulting data. However, the value of the data collected by these subjective means must be validated against objective measures in order to assess the trade-offs between these benefits and potential data quality costs.

To address the gaps in the literature on soil data collection methods and integration in household surveys, the LSMS has prioritized soil health measurement in its research agenda. The remainder of this Guidebook is based on methodological validation studies in Ethiopia and Uganda. These studies set out to test the traditionally relied-upon farmer assessments of soil quality against the gold-standard method (conventional analysis) and the more plausible alternative in objective measurement, spectral soil analysis. The methods are reviewed with an eye not only to accuracy and cost, but also to ease of implementation and potential for scale-up. The questions on subjective assessment were selected from national LSMS-ISA surveys and supplemented by enumerator observation of specific properties. Farmer assessments were made at the dwelling rather than upon direct observation of the plot, in order to gauge the value of the questions in large-scale surveys where plot visitation is prohibitive. Conventional and spectral soil analyses were completed by ICRAF. The studies are briefly described in Box 2.[4]

In what follows, the results of each of the soil testing methods are presented independently, and the accuracy of subjective indicators of soil quality are in turn compared with the objective measures derived from the laboratory analysis. The laboratory results are subsequently compared with a single national-level soil map to potentially illustrate the value of plot-level soil analysis over existing geospatial datasets.

6. FARMERS' SUBJECTIVE ASSESSMENT

Before the collection of physical soil samples, a series of subjective plot-level questions was administered to the self-identified "best-informed" household member on each cultivated plot.[5] These questions ranged from "what is the soil quality of your crop field?" with a categorical coded response to questions on soil color and texture. In MAPS, respondents were asked about the overall quality of the plot in addition to the overall quality of the soil specifically. On 74 percent of the plots, soil was listed as one of the top three criteria for evaluating the quality of a plot. Box 3 elaborates on the top three criteria respondents use to rate their plots. An excerpt from the LASER questionnaire is available in Annex 2. It is worth noting that the subjective questions were administered at the dwelling, not upon direct respondent observation of the soils, as these studies were aimed at assessing farmer

4 The analysis that follows is presented in greater analytical detail in the companion research paper to this Guidebook, which focuses only on the Ethiopia data (Gourlay et al., 2017).

5 In MAPS, farmers were asked subjective soil questions only about plots on which maize was planted.

BOX 2 – DESCRIPTION OF THE METHODOLOGICAL EXPERIMENTS IN ETHIOPIA AND UGANDA

The dataset for **Ethiopia** comes from the **Land and Soil Experimental Research (LASER) study.** The LASER study involved methodological validation of plot area measurement, soil fertility testing, and measurement of maize production. Soil testing was conducted on up to two randomly selected plots per household. The questionnaires were administered using computer-assisted personal interviewing (CAPI). Professional enumerators were hired based on past performance with the Central Statistical Agency and previous experience with CAPI (meaning some degree of familiarity with the technology). Soil sampling was conducted from September to December 2013 (post-planting) in three zones of the Oromia region in Ethiopia (Borena, East Wellega, and West Arsi). In total, 85 enumeration areas (EAs) were randomly selected using the Central Statistical Agency of Ethiopia's Agricultural Sample Survey (AgSS) as the sampling frame. Within each EA, 12 households were randomly selected from the AgSS household listing completed in September 2013. Partners in the study include the Central Statistical Agency of Ethiopia, the World Agroforestry Centre (ICRAF), and the World Bank. Spectral soil analysis was conducted at ICRAF's Soil-Plant Spectral Diagnostics Laboratory in Nairobi, Kenya. Soil processing was completed at three locations: Awassa Agricultural Research Center, Ambo University, and Yabello Pastoral and Dryland Agricultural Research Center.

The dataset for **Uganda** comes from the **Methodological Experiment on Measuring Maize Productivity, Variety, and Soil Fertility (MAPS) study.** The MAPS study involved soil fertility testing, DNA fingerprinting of maize leaf and grain samples for variety identification, and measurement of maize productivity through crop-cutting and high-resolution satellite imagery-based remote sensing. The sample consists of maize plots only, with one plot randomly selected per household. Plot selection was random but stratified on cropping pattern (pure stand versus intercropped). The questionnaires were administered using CAPI and Survey Solutions software. Professional enumerators were hired based on past performance with the Uganda Bureau of Statistics. Soil sampling was conducted from April to June 2015 (post-planting) in four districts of Uganda's Eastern region, known for maize production (Serere, Sironko, Iganga, and Mayuge). In total, 75 EAs were randomly selected using the 2014 Census frame. Sironko and Serere each include 15 EAs, while Iganga and Mayuge have 45 EAs total. Within each EA, 12 households were randomly selected (with 6 pure stand and 6 intercropped maize-growing households where possible). Partners in the study include the Uganda Bureau of Statistics (UBOS), ICRAF, and the World Bank. Spectral soil analysis was conducted at ICRAF's Soil-Plant Spectral Diagnostics Laboratory in Nairobi, Kenya. Soil processing was conducted by laboratory technicians from the National Agricultural Research Organization (NARO) at the National Forest Research Institute of Uganda in Kampala.

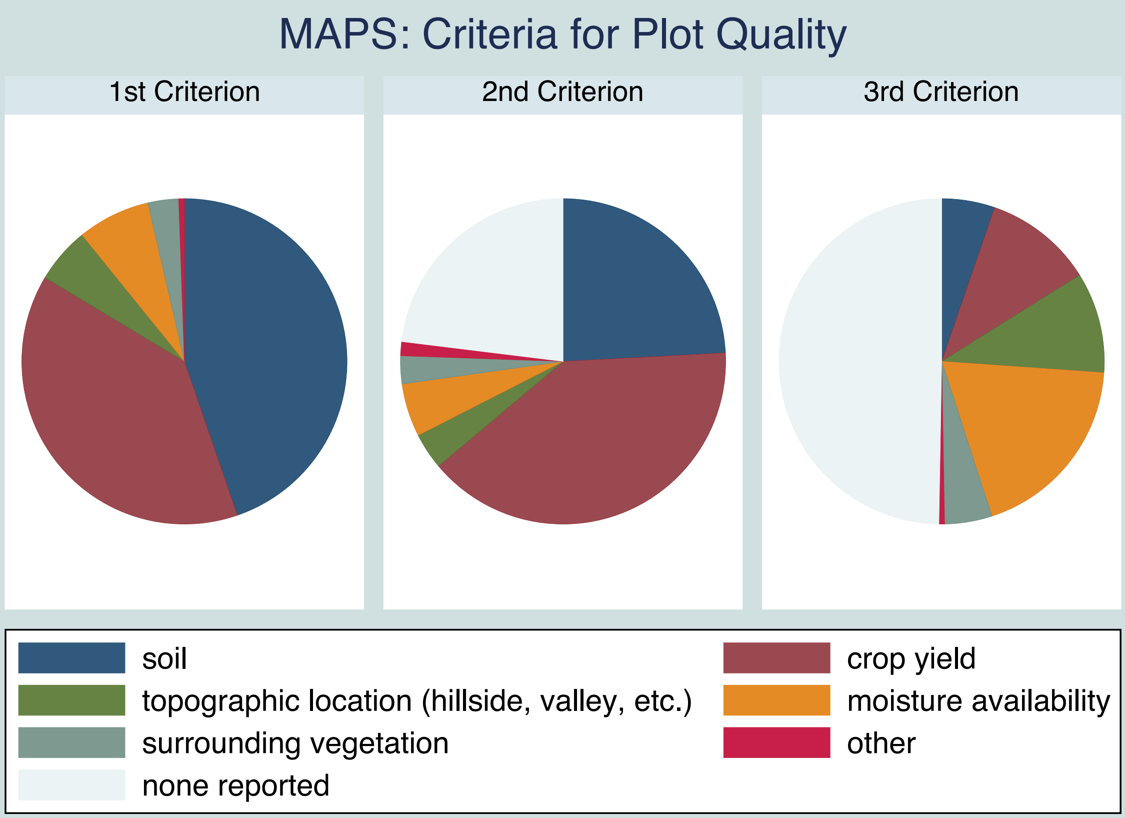
In both studies, subjective plot-level soil assessment was conducted at the dwelling before visiting the selected plots for soil sample collection. The respondent was the self-identified most-knowledgeable household member for that particular plot (usually the plot manager). Enumerators were instructed not to influence the farmer's assessment. Fieldwork protocols required that soil samples were delivered to soil-processing labs within five to seven days of collection in order to prevent decomposition of organic matter (which can occur when soils are wet or damp). Subsamples of the soils collected in the LASER and MAPS studies are stored at ICRAF for future use.

knowledge for larger-scale surveys that may not allow for visitation of each plot.

While subjective assessments of soil quality are both cost- and time-efficient, the quality of the data has not been validated. Also of concern is the ability of subjective questions to capture the necessary level of detail and intrahousehold variation. Summary statistics of the subjective questions included in the LASER and MAPS studies are found in Table 1. In each study, very few plots reportedly had "poor" soil quality (5 percent in LASER, 8 percent in MAPS), and the remainder of plots were allocated nearly evenly across "good" and "fair" quality categories. Figure 3 suggests that farmers use soil color and texture as key indicators of soil quality. Dark and fine-textured soils were often categorized as good, while red and course-textured soils were often categorized as poor. This result agrees with Karltun et al. (2013), who found that crop yield, indicator plants, soil softness, and soil color were useful indicators that farmers use to judge soil quality in Ethiopia. More specific questions, such as those on soil color and texture, appear to capture more variation, at

BOX 3 — HOW DO FARMERS JUDGE PLOT QUALITY?

Learning from the lessons of LASER, the MAPS study introduced a question geared towards understanding how respondents rate the quality of their plots. What criteria do they use? The pie charts below break down the top three criteria used by respondents when rating the quality of their plots as "good", "fair", or "poor". Soil was indicated as one of the top three criteria on over 74% of plots.



least across the full sample.[6] The data from the surveys supported by the LSMS-ISA also suggest that at a national scale, soil texture often offers more variation than overall soil quality estimates (see Figure 4, panels A and B).

6 Evidence from both studies suggests that some respondents may not be able to differentiate between soil type and color. In those observations in which soil type was indicated as "other, specify," the respondent indicated a color as the other type.

Table 1 — Subjective Soil Assessment Summary

	LASER		MAPS	
Number *	1677	100%	892	100%
Soil Quality				
Good	708	42%	399	45%
Fair	886	53%	423	47%
Poor	83	5%	70	8%
Soil Color				
Black	638	38%	426	48%
Red	760	45%	62	7%
White/Light Grey	264	16%	98	11%
Yellow	15	1%	●	●
Brown	●	●	299	34%
Other	●	●	7	1%
Soil Type				
Sandy	359	21%	233	26%
Clay	901	54%	80	9%
Loam/Mix of Sand and Clay	351	21%	559	63%
Other	66	4%	20	2%
Soil Texture				
Very Fine	56	3%	41	5%
Fine	869	52%	468	52%
Between Coarse and Fine	586	35%	307	34%
Coarse	158	9%	72	8%
Very Coarse	8	0.5%	4	0.4%
Incidence of:				
Erosion	266	16%	304	34%
Erosion Controls	654	39%	248	28%
Crop Rotation	1127	67%	630	71%
Zero Till	93	6%	15	2%
Organic Fertilizer °	297	18%	85	10%
Inorganic Fertilizer	425	25%	138	15.5%

* Includes households with at least one soil sample.

° Organic fertilizer includes manure and compost for MAPS

● Category not applicable for respective study; question response categories altered across studies based on discussion with local field staff

Source: Authors' calculations.

Figure 3

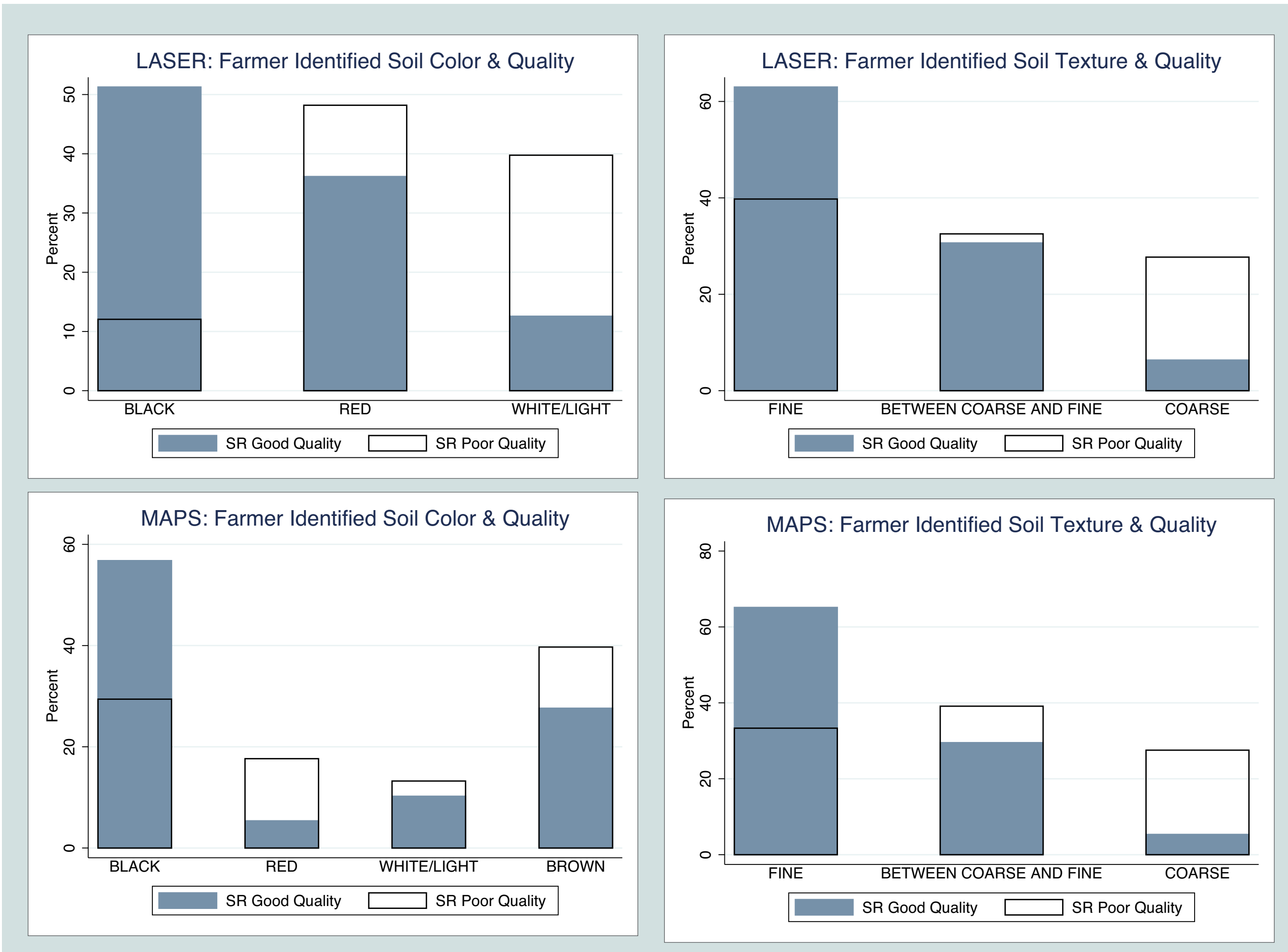
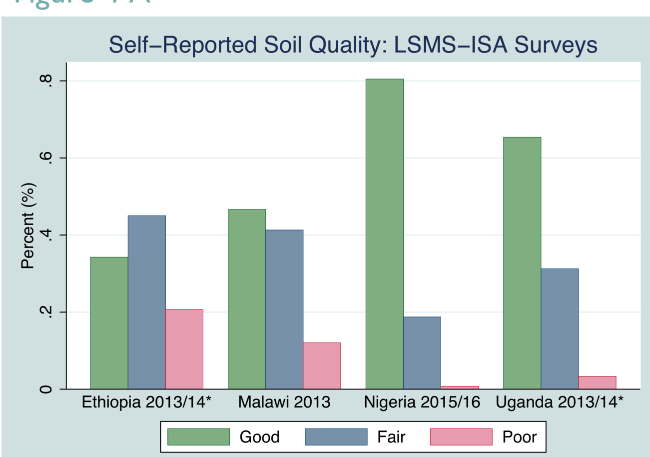
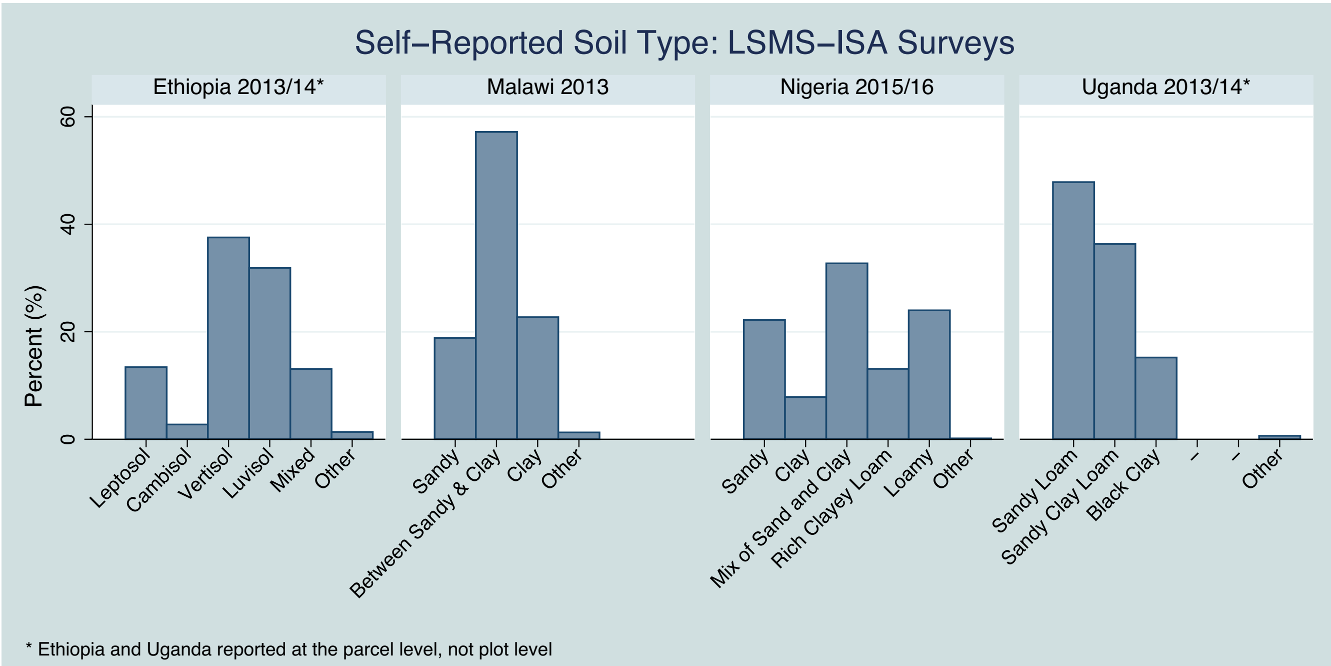


Figure 4 A



* Ethopia and Uganda reported at the parcel level, not plot level

Figure 4 B



Descriptive analysis on intrahousehold variation, however, reveals a slightly different story. Table 2 attempts to describe the intrahousehold variation captured by each subjective indicator by reporting the percentage of households reporting the same indicator for all cultivated plots (excluding those that cultivate only one plot). Based on this approach, the overall soil quality variable has the most intrahousehold variation. This is not a particularly surprising result as this variable could be thought of as a relative measure by respondents (for example, plot 1 is better than plot 2). Conceivably, it is less likely that respondents would consider an indicator like color to be a relative indicator.

Table 2 — Intrahousehold Variation (% of households with more than one cultivated plot reporting the same indicator across all plots)

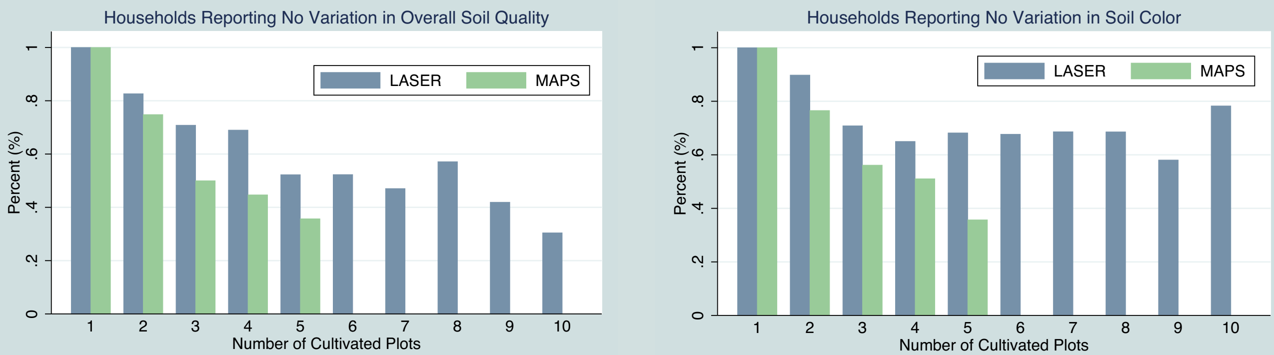
	LASER		MAPS	
	%	Std. Dev.	%	Std. Dev.
Overall Quality	63%	0.48	64%	0.48
Type	71%	0.45	68%	0.47
Color	73%	0.45	67%	0.47
Texture	68%	0.47	64%	0.48
Mean Plot Count	4.98		2.61	
N	788		488	

Source: Authors' calculations.

Note: MAPS includes only maize plots.

The results reported in Table 2 are useful for comparing variation across subjective questions but must be taken with a grain of salt when making conclusions about *levels* of intrahousehold variation as the number of plots cultivated are not accounted for here. Figure 5 disaggregates the data from Table 2 into the number of plots cultivated per household and illustrates the lack of intrahousehold variation in overall soil quality and color. In both MAPS and LASER, about 80 percent of households that cultivated two plots reported the same overall quality for both plots. MAPS data exhibit more variation, with about 40 percent of households that cultivate four plots reporting the same quality on all plots, compared with approximately 70 percent in LASER. The results for variation in soil color are similar (see Figure 5). While the lack of variation may partially reflect true homogeneity of soils within household, the rough granularity of the categorical subjective questions leaves much to be desired. Besides the improvements in accuracy, an advantage of the objective soil measurements is the refined scale on which soil is measured, allowing for distinction between seemingly similar soils.

Figure 5



Note: Limited to households with <= 10 plots for LASER and <=5 plots for MAPS.
MAPS data includes only maize plots.

Note: Limited to households with <=10 plots for LASER and <=5 plots for MAPS.
MAPS includes only maize plots.

In addition to the subjective questions asked to respondents, enumerators were asked to record their own observations while on the plot. Enumerator observations were sought only for plots from which soils were sampled for laboratory testing and are therefore not available for all cultivated plots within the household. Enumerators recorded the soil color using the same color categories as the household respondents. Their assessment of soil texture was slightly different, however. Rather than assess texture on the basis of "fine," "coarse," etc., they recorded (1) the percentage of rock or gravel coverage (in a categorical manner), and (2) whether the soil was "smooth," "gritty," or "neither" upon completion of the ribbon test and in-field texture analysis (detailed in Section 11.2.2 below).

One might expect respondent- and enumerator-reported soil color to align closely. While the color is the same more often than not, there are some notable discrepancies between the color reported by the farmer and that reported by the enumerator.[7] Table 3 presents a matrix of respondent- and enumerator-reported soil colors. Particularly concerning is the discrepancy on soils that the enumerator has reported as "white/light," as 45 percent and 24 percent of respondents reported these as black soils in MAPS and LASER, respectively. The following section will illustrate the importance of the soil color indicator.

A comparison of respondent-reported soil texture and enumerator indication of rock/gravel percentage and in-field texture yields the expected results, even if not entirely precise. Looking at Table 4, increased gravel percentage should indicate a coarser texture and vice versa. This is indeed reflected in the greater concentration of "fine" soils in the lower-gravel-percentage categories. Similarly, there is a greater concentration of "fine" soils in the enumerator-reported "smooth" category. Although the majority of the data move in the expected direction, with enumerator observation reflecting respondent assessment, the presence of discrepancies illustrates the noisy nature of subjective data.

7 It is possible that differences in moisture content contributed to observed differences in the color reported by farmers and enumerators. That is, enumerators were instructed to wet a handful of soil as part of their texture analysis procedure and could have reported the color of the wet soil. However, this is not likely to explain contradictions observed in very different soil color categories.

Table 3 — Enumerator Observation versus Respondent Assessment: Soil Color

		Respondent Reported Soil Color						
		Black	Red	White/Light	Yellow	Brown	Other	Total
Enumerator Reported Soil Color	LASER							
	Black	72%	22%	7%	0%	●	●	100%
	Red	13%	77%	9%	0%	●	●	100%
	White/Light	24%	25%	50%	1%	●	●	100%
	Yellow	18%	18%	35%	29%	●	●	100%
	MAPS							
	Black	73%	4%	8%	●	15%	0%	100%
	Red	48%	37%	4%	●	9%	2%	100%
	White/Light	45%	1%	43%	●	10%	1%	100%
	Brown	21%	7%	8%	●	63%	1%	100%
	Other*	50%	25%	25%	●	0%	0%	100%

Note: Row percentages reported.

* <= 20 observations (row-wise)

● Category not applicable for respective study

Source: Authors' calculations.

Table 4 — Enumerator Observation versus Respondent Assessment: Soil Texture

		Respondent Reported Soil Texture					
		Very Fine	Fine	Between	Coarse	Very Coarse	Total
Enumerator Reported Rock & Gravel Content	LASER						
	< 5%	4%	54%	35%	7%	0%	100%
	5 - 40%	1%	40%	36%	22%	2%	100%
	> 40%	0%	13%	38%	38%	13%	100%
	MAPS						
	< 5%	5%	57%	30%	8%	0%	100%
	5 - 40%	1%	34%	55%	9%	1%	100%
	> 40%*	0%	13%	63%	25%	0%	100%
Enumerator Reported Texture	LASER						
	Smooth	4%	60%	31%	4%	0%	100%
	Gritty	2%	35%	39%	23%	1%	100%
	Neither	2%	46%	41%	9%	1%	100%
	MAPS						
	Smooth	6%	67%	23%	4%	0%	100%
	Gritty	2%	33%	51%	13%	1%	100%
	Neither*	10%	40%	40%	10%	0%	100%

Note: Row percentages reported.

* <= 20 observations (row-wise)

● Category not applicable for respective study

Source: Authors' calculations.

7. LABORATORY ANALYSIS

Laboratory analysis consisted of conventional soil analysis via wet chemistry methods and a series of spectral soil analyses. The suite of spectral analyses included the following tests: mid-infrared diffuse reflectance spectroscopy (MIR), laser diffraction particle size distribution analysis (LDPSA), x-ray methods for soil mineralogy (XRD), and total element analysis (TXRF). MIR and LDPSA spectral tests were conducted on all top- and subsoil samples (n = 3,611), while the x-ray tests, XRD and TXRF, were conducted on the same 10 percent on which conventional testing was executed. Ultimately, approximately 50 variables were predicted for each top- and subsoil sample, containing both chemical and physical soil properties. For details on the prediction methods, refer to Shepherd and Walsh (2002).[8] To lend confidence to the method, the predictive power is first illustrated, followed by summary statistics of the predicted data.

7.1 PREDICTIONS FROM SOIL SPECTRA

Figure 6 illustrates the predictive power of the mid-infrared spectroscopy on key soil properties, while Table 5 summarizes select predicted properties, disaggregated by top- and subsoil. The predictive models are successful in that, of the variables predicted, the lowest correlation between predicted value and actual value (using the reference sample upon which CSA was conducted) was 0.942 (prediction of phosphorous concentration using Mehlich 3 method, in MAPS). The highest correlation was in the prediction of total carbon concentration in MAPS by TXRF, with a *rho* of 0.994. Key soil properties such as organic carbon (%), total nitrogen (%), clay (%), and pH were strongly predicted with correlation coefficients of 0.98 or greater.

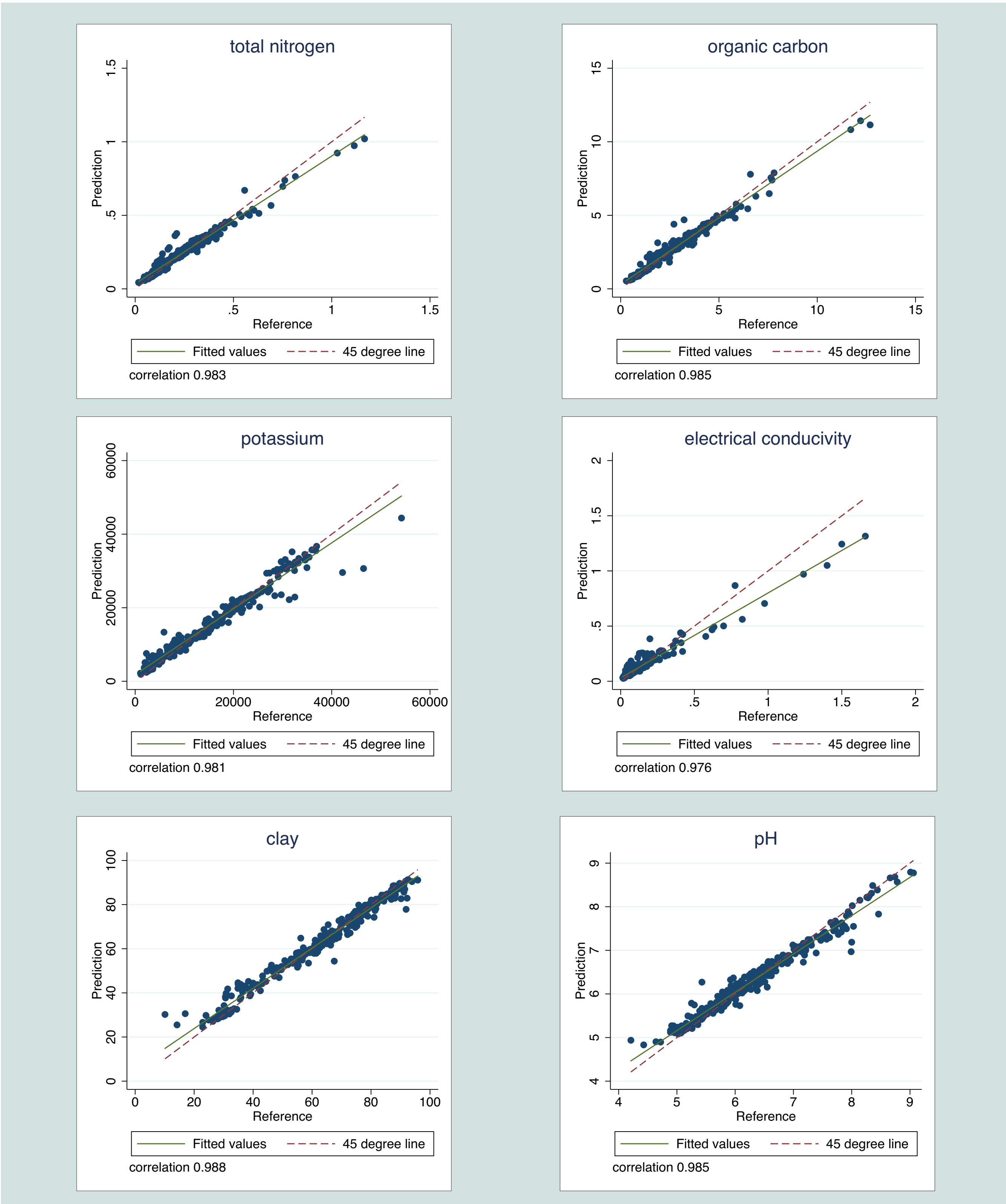
7.2 SUMMARY STATISTICS

Mean values of key soil properties are reported in Table 6, by soil depth. LASER data exhibit a higher level of organic carbon content, with greater variation, than the MAPS samples. Significant differences are observed between the top- and subsoil samples. In addition to the means, the *t*-test significance level for the difference in means between top- and subsoil are also reported in Table 6. Levels of all presented properties are significantly different between top- and subsoil, with the exception of exchangeable magnesium in MAPS, which is not significantly different. The significant difference in values validates the need to collect and analyze both a top- and subsoil sample, but the magnitude of the difference may not warrant the added cost depending on particular study objectives. The rooting depth of the crop(s) of interest should be considered when determining if top- and/or subsoils should be tested, as it is preferable to test the soil properties at the level at which the plant absorbs the majority of its nutrients (Lorenz and Lal, 2005).

In addition to variation across soil depths, the levels of key soil properties vary across administrative zones and districts. Figure 7 illustrates the distribution of organic carbon and pH by administrative zone for LASER and by district for MAPS. While variation across a large administrative area such as a zone or district may be expected, variation is also present within enumeration areas. This explored in Section 9.1 below

8 The data presented in this Guidebook was predicted using a Random Forest model. Since writing of this Guidebook, ICRAF has begun using an improved prediction method, namely, an ensemble method. This revised method combines the Random Forest model with other approaches, in an effort to limit overfitting. The data released for LASER and MAPS, therefore, may differ slightly in that the data predicted via the ensemble approach will be made public.

Figure 6



total nitrogen
Prediction
Reference
Fitted values
45 degree line
correlation 0.983
organic carbon
Prediction
Reference
Fitted values
45 degree line
correlation 0.985
potassium
Prediction
Reference
Fitted values
45 degree line
correlation 0.981
electrical conducivity
Prediction
Reference
Fitted values
45 degree line
correlation 0.976
clay
Prediction
Reference
Fitted values
45 degree line
correlation 0.988
pH
Prediction
Reference
Fitted values
45 degree line
correlation 0.985

Table 5 — Predictive Power of Random Forest Model

Variable	Correlation (Predict, Reference)	
	LASER	MAPS
acidified carbon	0.985	0.993
acidified nitrogen	0.983	0.984
cec	-	0.986
clay	0.988	0.980
ecd	0.976	0.974
exac	0.963	0.947
exbas	0.985	0.988
m3al	0.985	0.981
m3b	0.967	0.956
m3ca	0.985	0.987
m3cu	0.982	0.973
m3fe	0.987	0.966
m3k	0.976	0.945
m3mg	0.983	0.987
m3mn	0.977	0.975
m3na	0.978	0.950
m3p	0.958	0.942
m3s	0.961	0.960
m3zn	0.946	0.944
ph	0.985	0.985
psi	0.983	0.990
sand	0.984	0.980
silt	0.986	0.969
total carbon	0.984	0.994
total nitrogen	0.983	0.984
N	355	180

Note: "m3" prefix indicates measure using Mehlich 3 method.

Source: Authors' calculations.

Table 6 — Spectral Soil Analysis Summary Statistics

Select Soil Properties	LASER			MAPS		
	Topsoil (0-20 cm)	Subsoil (20-50 cm)	Difference in means	Topsoil (0-20 cm)	Subsoil (20-50 cm)	Difference in Means
	Mean	Mean		Mean	Mean	
Physical						
% Sand	12.2	11.8	*	22.6	20.1	***
% Clay	65.0	67.3	***	56.7	63.2	***
% Silt	22.6	20.8	***	20.2	17.1	***
Chemical						
pH	6.3	6.3	***	6.4	6.3	***
Cation Exchange Capacity (CEC)	-	-	-	13.9	13.1	**
Macronutrients:						
Acidified (Organic) Carbon (%)	3.3	2.8	***	1.5	1.2	***
Total Nitrogen (%)	0.28	0.24	***	0.12	0.10	***
Exchangeable Calcium (mg kg^-1) + °	3445	3193	***	1736	1588	***
Exchangeable Potassium (mg kg^-1)+°	742	663	***	240	224	**
Exchangeable Magnesium (mg kg^-1)*°	540	510	***	277	272	-
Micronutrients:						
Iron (mg kg^-1)+	160	148	***	142.3	138.6	*
Zinc (mg kg^-1)+	5.6	5.11	***	4.8	4.5	**
Exchangeable Manganese (mg kg^-1)+	182	173	***	218.9	236.1	***
N		1599			872	

Note: Data limited to plots with both top- and subsoil samples.

+ Extracted with Mehlich 3 method

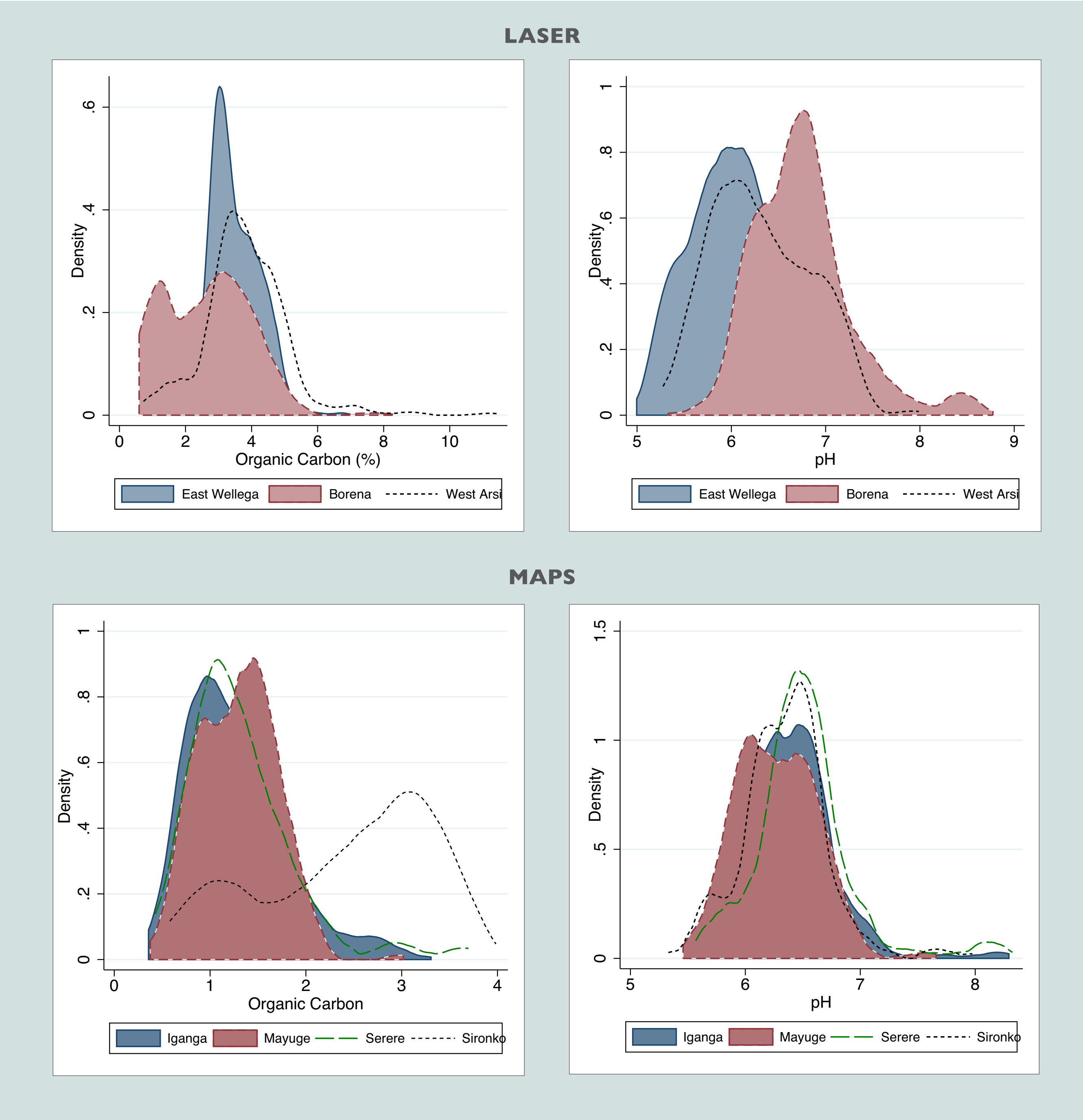
* Extracted with wet method

*** p<0.01, ** p<0.05, * p<0.1

°Units for MAPS converted from cmol/kg using conversion factors found here: http://www.aora.org.au/pdf/Interpreting_soil_tests_DHall.pdf; 200:1 for calcium, 120:1 for magnesium, 390:1 for potassium.

Source: Authors' calculations.

Figure 7 — Distribution of Organic Carbon (%) and pH, by Administrative Area: Top-Soils



8 GEOSPATIAL DATA

In order to provide a brief comparison of the plot-level soil analysis results of this project with publicly available geospatial data, soil organic carbon content was extracted from soil property maps of Africa (Hengl et al., 2015). The AfSoilGrids250m dataset is the result of a careful combination of the Africa Soil Profiles point database, the AfSIS Sentinel Site point datasets, and remote sensing imagery. Using these two point datasets, with more than 28,000 sample points in total, and an additional set of covariates, spatial predictions were made using a random forests model (Hengl et al., 2015). The AfSoilGrids250m spatial data contains predictions of several soil functional properties critical to agriculture including organic carbon, total nitrogen, pH, cation exchange capacity, bulk density, and sand, silt, and clay fractions, among others (Hengl et al., 2015).

While comparison ought to be made to more than one source of geospatial data, AfSIS data is among the highest-resolution geospatial soil data currently available in public datasets (250-meter resolution) for Ethiopia and Uganda (http://africasoils.net). It also may be the most comparable to the methodological studies presented here, as both are conducted following similar methods. For these reasons, the comparisons made here may present an upper bound of comparability, at least in this particular context. Values were extracted from the AfSIS geospatial dataset using the GPS coordinates of the specific plots. In the following section, comparison is made between organic carbon content (%) as measured by plot-level spectral testing and that indicated in the AfSIS map.

9. COMPARISON OF METHODS

Given the complexity of soil and the varying needs of different crops and agricultural systems, assessing the overall quality of soil at an objective level is difficult. Comparing categorical subjective questions to the array of objective measurements and evaluating how well those subjective data assess the true soil quality is even more challenging. This is necessary, however, to motivate and validate the need to conduct objective analysis instead of, or in addition to, subjective assessment. If subjective soil quality assessment sufficiently captures the information attained through laboratory analysis, this costly analysis can be forgone. Additionally, if soil maps generated through remote sensing and other geospatial data accurately reflect plot-level soil analysis, national soil maps, which are becoming increasingly available, could be used rather than conducting detailed laboratory analysis.

This section first analyzes the correlation between laboratory results and two national-level soil map sources and then attempts to explain which subjective questions most accurately reflect laboratory results and how well they do so.

9.1 LABORATORY ANALYSIS AND GEOSPATIAL DATA

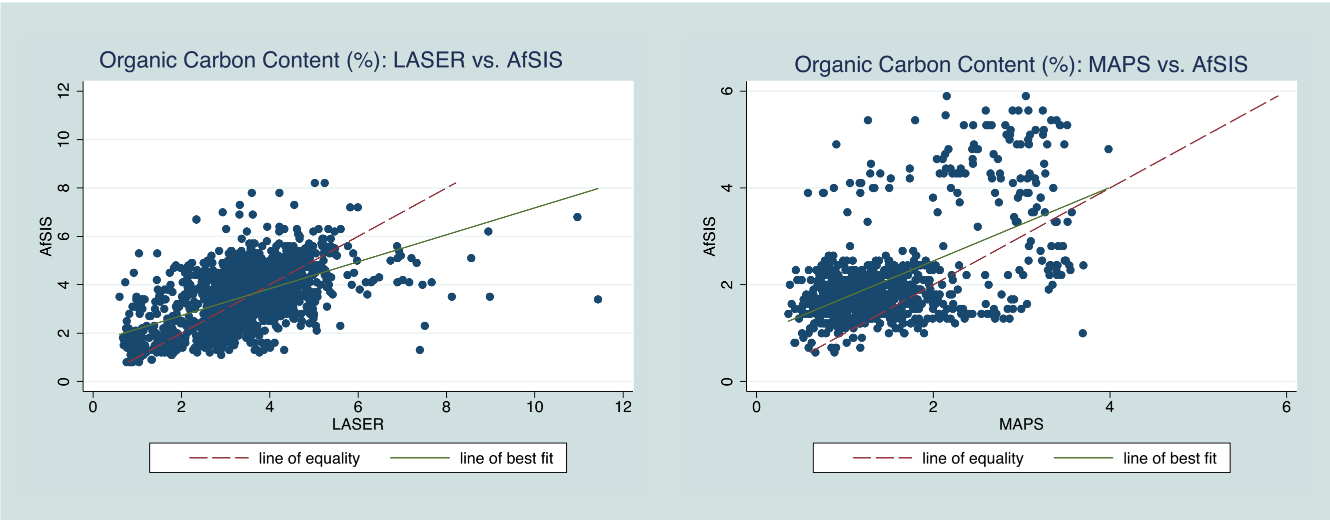
A brief comparison of the AfSIS AfSoilGRids250m data and plot-level spectral soil testing results from LASER and MAPS is conducted to demonstrate the value added in conducting such plot-level tests. Table 7 summarizes the mean organic carbon content observed in LASER, MAPS, and AfSIS. Organic carbon is used here as a proxy for overall soil health. The difference in means between both methodological datasets and the respective AfSIS data is statistically different from zero at the 1 percent level. Although the magnitude of the difference may be immaterial depending on the research question of interest, it is important to note that the correlation between the two measures is only 0.59 and 0.56 in

Table 7 — Organic Carbon Levels in LASER, MAPS, and AfSIS Geospatial Data

Topsoil	Mean		Cor-relation	N
	Study	AFSIS		
LASER				
Total	3.35	3.48	0.586	1674
Borena Zone	2.83	2.65	0.636	494
West Arsi Zone	3.83	3.80	0.417	591
East Wellega Zone	3.66	3.49	0.403	589
EAs with lowest 25% variance	2.78	2.88	0.715	412
EAs with highest 25% variance	3.74	3.77	0.387	429
MAPS				
Total	1.51	2.12	0.559	879
Iganga District	1.27	1.74	-0.001	327
Mayuge District	1.29	2.07	0.305	200
Serere District	1.32	1.49	0.321	180
Sironko District	2.42	3.56	0.330	172
EAs with lowest 25% variance	1.55	2.21	0.482	208
EAs with highest 25% variance	1.56	1.95	0.450	224

Source: Authors' calculations.

Figure 8 — Overall Scatter Plots



LASER and MAPS, respectively. In both LASER and MAPS, the mean carbon content is lower than that measured by AfSIS. Drilling down to the zone and district level in LASER and MAPS, respectively, reveals inconsistency in the concordance of plot-level and AfSIS results. A notable deviation is found in the Iganga district of Uganda, where the correlation between the two measures is negative and not statistically different from zero.

Concerns about the use of geospatial data are often related to its ability to capture variation in soil properties within small areas. Indeed, a closer look at the correlation between the spectral analysis and the geospatial data reveals that the correlation falls when limiting the sample to the EAs with the highest quartile of variance in carbon content (as measured by spectral analysis). In EAs with the highest variance, correlation is only 0.39 and 0.45, while in EAs with the lowest variance, the correlation is 0.72 and 0.48 in LASER and MAPS, respectively (refer to Table 7). Surprisingly, in EAs with the highest variance there is no significant difference between the mean in LASER and AfSIS (although the difference in means is significantly different in MAPS).

Figure 8 presents scatter plots of the organic carbon levels as levels as measured by the geospatial data and plot-level results. The two sources of data are positively correlated, but not without error, suggesting that geospatial data may be sufficient for certain types of analysis. Further validation, against various sources of geospatial data, is necessary to draw stronger conclusions.

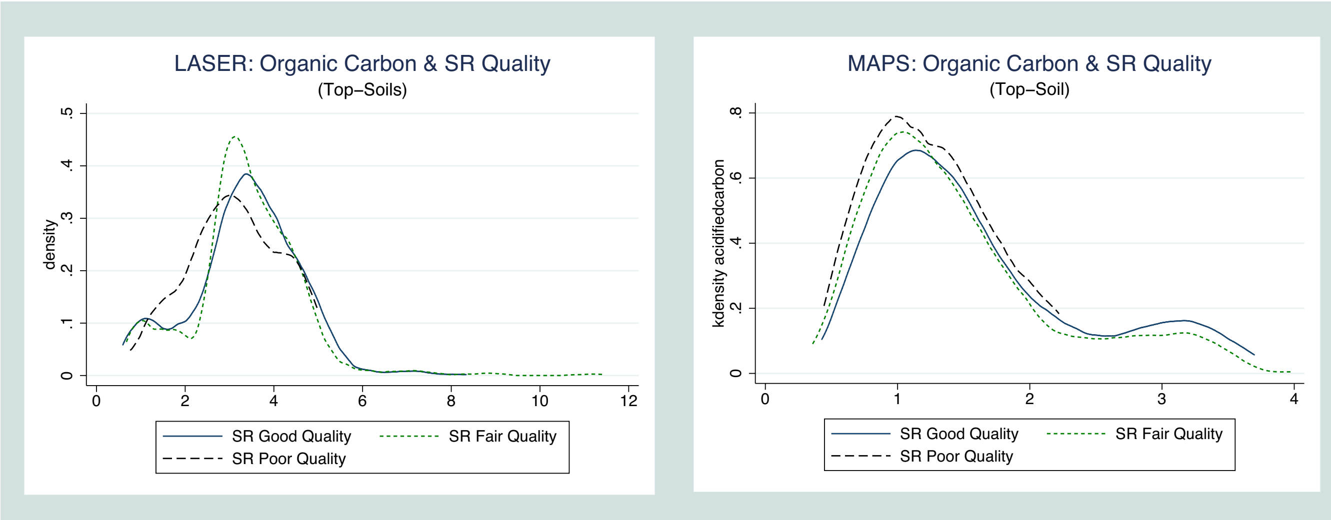
9.2 SUBJECTIVE ASSESSMENT AND LABORATORY ANALYSIS

It is critical to explore how subjective questions on soil health correlate with plot-level laboratory measures. Understanding the relationship between specific questions and their ability to explain true soil properties is important for both questionnaire design, to ensure the most appropriate questions are included, and for data analysis. We first analyze the ability of subjective questions to predict soil carbon levels, a proxy for overall soil health. Subsequently, in order to incorporate more of the rich laboratory data and better capture the dynamic nature of the soil, we construct three variations of soil quality indices. Descriptive analysis and basic ordinary least squares (OLS) regressions are used to identify which subjective questions, if any, significantly predict changes in the soil quality indicators. All analyses are conducted using topsoil (at a depth of 0–20 centimeters [cm]) measurements unless otherwise specified.

9.2.1 ORGANIC CARBON AS A PROXY

Organic carbon is often argued to be the best single property to serve as a proxy for overall soil quality. It is highly correlated with other key soil health indicators (chemical, physical, and biological), such as total nitrogen (with a correlation coefficient greater than 0.95 in both LASER and MAPS, in the top- and subsoils; refer to Annex 3). Organic carbon is generally correlated positively with crop yield (Bennett et al., 2010). It affects important functional processes in soil like the storage of nutrients (mainly nitrogen), water-holding

Figure 9 — Distribution of Organic Carbon by SR Soil Quality



capacity, and microbial activities (Lal, 2016). This section explores the question of how well subjective assessments of soil quality reflect objectively measured organic carbon levels.

Figure 9, panels A and B, illustrates the distribution of soil organic carbon by soils reported as "good," "fair," and "poor" by respondents in LASER and MAPS, respectively. If a farmer's overall assessment of soil quality clearly reflects carbon levels, we would expect to see the carbon distributions shifted with the distribution for "good" soil furthest to the right and "poor" furthest left. On the contrary, the distributions appear very similar to one another.

Descriptive analysis suggests that the relationship between subjective overall soil quality and organic carbon levels is highly variable across study regions, implying a lack of reliability in subjective estimates. The results for LASER and MAPS differ in a number of ways. First and foremost, in the LASER data, the mean carbon content in "fair" soils is slightly greater than that in "good" soils, although the difference is not statistically significant. In MAPS, however, the mean carbon content by subjective soil quality is as expected, with higher carbon content in good soils. The carbon content in "good" soils is greater than that in "fair" soils (with statistical significance), and the content in "fair" soils is greater than that in "poor" soils (also with statistical significance). In terms of distribution, Kolmogorov-Smirnov tests of equality of distribution suggest that in LASER topsoil, the distribution of carbon content is only significantly different between soils reported as "good" and "poor," and "fair" and "poor," but not between "good" and "fair." None of the carbon distributions is significantly different in LASER subsoil across soils reported as "good," "fair," and "poor." In MAPS, the only carbon distributions that are not statistically different are between "fair" and "poor" (in both the top- and subsoil). Table 8 summarizes these findings.

To incorporate the other subjective questions on soil health and their relationship with organic carbon levels, an ordinary OLS regression is executed with organic carbon on the left-hand side and subjective soil quality, color, and texture on the right. Table 9 presents the results. As seen above, the value of the subjective assessment of overall soil quality varies by study, with results from LASER contrary to expectations ("fair" soil has higher carbon content than "good" soil) and with limited statistical significance. In MAPS, however, the coefficients on overall soil quality are in the expected direction and hold greater statistical significance. The results from both studies suggest that subjective soil color and texture are more consistent predictors of organic carbon content, as black and fine soils have a higher carbon content than the other respective comparative categories (as expected). The analysis was repeated while controlling for manager characteristics such as education and sex, and results are consistent with those reported in Table 9. Other controls that might explain levels of soil carbon, such as crop rotation and input use, are not included here as the objective is not to assess the determinants of carbon levels, but rather to determine the relationship between subjective questions and objectively measured carbon content.

Table 8 — Distribution of Organic Carbon Content Across Subjective Quality Category

LASER							
	Mean Organic Carbon (%)	Difference of Means			Difference of Distribution		
		Good	Fair	Poor	Good	Fair	Poor
Topsoil							
Good	3.36		-	*		-	**
Fair	3.37	-		*	-		**
Poor	3.10	*	*		**	**	
Subsoil							
Good	2.82		-	-		-	-
Fair	2.84	-		-	-		-
Poor	2.74	-	-		-	-	

MAPS							
	Mean Organic Carbon (%)	Difference of Means			Difference of Distribution		
		Good	Fair	Poor	Good	Fair	Poor
Topsoil							
Good	1.60		**	***		*	**
Fair	1.47	**		**	*		-
Poor	1.24	***	**		**	-	
Subsoil							
Good	1.34		***	***		***	***
Fair	1.20	***		***	***		-
Poor	1.00	***	***		***	-	

*** p<0.01, ** p<0.05, * p<0.1

Difference in means: T-test

Difference in distribution: K-Smirnov test

Source: Authors' calculations.

9.2.2 SOIL QUALITY INDICES

While carbon is commonly used as a proxy for soil health, it may not be the primary limiting factor of soils in the sample. To achieve a more dynamic measure of soil quality, multiple indices are created and modeled against subjective soil quality indicators. From the existing literature, it appears a consensus does not exist on the optimal soil quality index construction. For the purposes of this Guidebook, two approaches to soil quality indices were implemented following the guidance set forth by Mukherjee and Lal (2014) in their comparison of three approaches to soil quality indices. For additional detail on the construction of these selected indices as well as additional approaches using the same LASER data, refer to Gourlay et al. (2017).

A simple additive and a weighted additive approach were adapted from Mukherjee and Lal (2014). The indices proposed by Mukherjee and Lal include three components: root development capacity, water storage capacity, and nutrient storage capacity. Data are available only for the construction of the nutrient storage component, which is 40 percent of the weight of the complete weighted additive soil quality index. Therefore, results presented here only indicate constraints related to nutrient storage capacity.

Mukherjee and Lal (2014) used their expertise and existing literature to assign linear scores to relevant soil properties ranging from 0 to 3 based on the constraint posed by the level of the specific property. These linear scores are

Table 9 — Soil Organic Carbon and Subjective Indicators: Regression Analysis

	LASER				MAPS			
	Topsoil		Subsoil		Topsoil		Subsoil	
Dependent Variable: Organic Carbon (%)								
Self-Reported Soil Quality								
Fair	0.003	0.143**	0.017	0.107*	-0.134**	-0.075	-0.135***	-0.078*
Poor	-0.265**	0.023	-0.085	0.124	-0.355***	-0.168**	-0.338***	-0.172***
Self-Reported Color (Collapsed, 'Black' Omitted)								
Red		-0.588***		-0.355***		-0.203***		-0.197***
White/Light		-0.586***		-0.496***		-0.451***		-0.354***
Brown		N/A		N/A		0.053		-0.018
Self-Reported Soil Texture (Collapsed, 'Fine' Omitted)								
Between Coarse and Fine		-0.022		0.017		-0.441***		-0.348***
Coarse		-0.265**		-0.202**		-0.511***		-0.405***
Constant	3.364***	3.674***	2.825***	3.023***	1.602***	1.800***	1.341***	1.514***
N	1677	1677	1665	1665	872	872	878	878
R^2	0.002	0.060	0.000	0.037	0.018	0.157	0.022	0.132

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Robust standard errors.

Source: Authors' calculations.

summed to create the simple additive soil quality index (SA SQI). While Mukherjee and Lal assign scores for a multitude of soil properties, data in the LASER study allow for the inclusion of pH, organic carbon content (%), total nitrogen content (%), and electrical conductivity, the properties that together make up the nutrient storage capacity component. Unlike the weighted additive index (discussed below), the SA SQI is not normalized on the sample and therefore provides an indicator of overall soil quality that is not relative to the study sample.

The weighted additive index, referred to henceforth as the WA SQI, was constructed by assigning linear scores to the relevant soil properties (pH, soil electrical conductivity, organic carbon [%], and total nitrogen [%]), normalizing the scores for each individual property over the sample and then applying the indicated weights and summing the scores.[9] The linear scores for each included property ranged from 0 to 1 and were determined by dividing all observations by the highest value in the sample for soil properties in which a higher value is more beneficial (carbon and nitrogen) and dividing all observations by the lowest value in the sample for properties in which a lower value is preferred. Soil electrical conductivity and pH have an optimal range, and these were treated as such.[10] This method follows Mukherjee and Lal (2014), who learn from Karlen and Stott (1994) and Fernandes et al. (2011).

To understand the relationship between the subjective questions and soil quality as measured by the above indices, simple OLS regression was conducted. Table 10 presents the results for both LASER and MAPS. The first specification includes only the overall soil quality as reported by the farmer. Then soil color and texture are included individually. The fourth specification includes all three subjective indicators: soil color, texture, and overall soil quality. Similar to the results found when using carbon as a proxy for soil quality, soil color comes through as a strong predictor of soil quality, with red and light soils having a lower index score, and therefore a lower nutrient storage capacity, than black soils. In MAPS, subjective soil texture also comes through with the expected sign and statistical significance, with coarser soils

9 Scores for each of the four soil properties were normalized as (observation score – sample min)/(sample max – sample min). Weights were applied as follows: pH (0.3); electrical conductivity (0.3); organic carbon (0.2); total nitrogen (0.2). Scores and weights taken from Mukherjee and Lal (2014).

10 For properties that have an optimal range, the observations were split into those above and below the critical thresholds (as defined by Mukherjee and Lal, 2014), with those below the threshold treated as though a higher value is preferred and those above the threshold treated as though a lower value is preferred.

Table 10 — Soil Quality Indices and Subjective Indicators: Regression Analysis

Dependent Variable:	LASER								MAPS							
	Simple Additive SQI				Weighted Additive SQI (normalized over sample)				Simple Additive SQI				Weighted Additive SQI (normalized over sample)			
Self-Reported Soil Quality																
Fair	-0.024			0.138*	-0.009**			-0.002	-0.101			-0.055	-0.025***			-0.016**
Poor	-0.375*			-0.011	-0.017**			-0.005	-0.373***			-0.211***	-0.060***			-0.033***
Self-Reported Color (Collapsed, 'Black' Omitted)																
Red		-0.623***		-0.640***		-0.033***		-0.032***		-0.332***		-0.233***		-0.055***		-0.041***
White/Light		-0.889***		-0.866***		-0.027***		-0.025***		-0.354***		-0.234***		-0.082***		-0.065***
Brown		N/A		N/A		N/A		N/A		0.009		0.114		-0.022***		-0.007
Self-Reported Soil Texture (Collapsed, 'Fine' Omitted)																
Between Coarse and Fine			-0.067	-0.02			-0.008*	-0.005			-0.451***	-0.436***			-0.064***	-0.056***
Coarse			-0.428***	-0.239*			-0.015**	-0.009			-0.499***	-0.449***			-0.078***	-0.063***
Constant	4.640***	5.039***	4.675***	5.001***	0.461***	0.475***	0.460***	0.478***	2.432***	2.415***	2.552***	2.589***	0.506***	0.510***	0.517***	0.536***
N	1677	1677	1677	1677	1677	1677	1677	1677	872	872	872	872	872	872	872	872
R2	0.002	0.048	0.006	0.052	0.005	0.041	0.004	0.043	0.012	0.022	0.063	0.084	0.033	0.077	0.118	0.180
Dependent Var. Mean	4.61				0.46				2.36				0.49			
Dependent Var. Std. Dev.	1.59				0.08				0.91				0.10			

*** p<0.01, ** p<0.05, * p<0.1

Robust standard errors.

Note: Topsoils only.

Source: Authors' calculations.

(corresponding to greater sand and gravel percentage) having a lower nutrient storage capacity. The coefficients on overall subjective soil quality are mixed. In the models with the WA SQI, which is normalized on the individual country sample, subjective overall soil quality is significant only when other subjective questions are excluded in LASER, while it is significant in MAPS even when additional questions are included. This is consistent with the results observed in the previous section on carbon content. In the model with the SA SQI, which is not normalized on the sample, subjective overall quality explains very little in LASER, while distinguishing only the "poor" soils from "good" soils in MAPS. In LASER, subjective soil color has the most explanatory power, while in MAPS, soil texture has the most explanatory power.

The results presented above do not control for interhousehold differences. Because the LASER study included soil analysis on up to two plots per household, it is possible to look strictly at intrahousehold variation by including household fixed effects. Unfortunately, this analysis is not possible with MAPS data because only one plot was measured per household. Within the full LASER sample, and not controlling for differences across households, the subjective indicators of soil quality do not exhibit strong predictive power of the objective soil quality indices, but there is *some* relationship. Looking strictly at intrahousehold effects by including household fixed effects (and limiting the sample to households that had topsoil samples for two plots), suggests that *within* households, subjective indicators have even less relationship with soil quality indices. Rather, the rank of plots within households in terms of overall quality is insignificant at the 5 percent level when the full spectrum of subjective indicators is included, as are the variables on color and texture (in the specification on the SA SQI). Table 11 presents the results with the inclusion of household fixed effects in the LASER data. Once household fixed effects are included, subjective soil color is insignificant in both the weighted additive and simple additive models, which may be largely attributable to the low intrahousehold variation observed in these indicators (refer to Figure 5). Subjective assessment of overall soil quality is a significant predictor of the WA SQI when no other covariates are included, suggesting that plots may be ranked appropriately within households, yet the fit of the model was extremely poor ($R^2 = 0.01$).

On the whole, the analysis suggests that subjective indicators of soil quality better reflect objective measures in the MAPS study. This may be attributable to the lower variation in soil properties in the sample, the smaller sample size, the study area, or differences in farmers' understanding of soil quality and assessment. The strength of the relationship between subjective overall soil quality and objective measures of soil quality differ across study, with very little relationship in LASER and a weak but statistically significant relationship in MAPS. Subjective soil color appears to be the most consistent indicator of soil quality across studies, but low intrahousehold variation in reported soil color may limit the value of this question in terms of ranking the quality of plots within households.

Table 11 — Soil Quality Indices and Subjective Indicators: Regression Analysis, with Household Fixed Effects

	LASER							
Dependent Variable:	**Simple Additive SQI**				**Weighted Additive SQI (normalized over sample)**			
Self-Reported Soil Quality								
Fair	-0.188			-0.172	-0.015**			-0.012*
Poor	-0.109			-0.096	-0.033***			-0.030**
Self-Reported Color (Collapsed, Black' Omitted)								
Red		-0.049		-0.041		-0.014		-0.013
White/Light		0.165		0.191		0.004		0.006
Brown		N/A		N/A		N/A		N/A
Self-Reported Soil Texture (Collapsed, 'Fine' Omitted)								
Between Coarse and Fine			-0.252*	-0.238			-0.021**	-0.020**
Coarse			0.047	0.096			-0.027*	-0.023
Constant	4.841***	4.732***	4.822***	4.899***	0.467***	0.463***	0.467***	0.479***
N	1384	1384	1384	1384	1384	1384	1384	1384
R2	0.003	0.002	0.006	0.011	0.010	0.005	0.010	0.023
*** p<0.01, ** p<0.05, * p<0.1								

Household fixed effects, robust standard errors.

Note: Topsoils only.

Source: Authors' calculations.

Part III – Implementing Spectral Soil Analysis in Household Surveys: A Step-By-Step Guide

10. CONSIDERATIONS FOR SAMPLE DESIGN

The approach to sampling will vary with the objective of the survey, the sampling frame, and resource availability, among other factors. The sample design must be such that it leads to an unbiased sample of households and their agricultural lands. Depending on the scope of the study and/or the homogeneity of soils in the study region, one may elect to sample soils from one or more agricultural plots per household. Similarly, the degree of clustering may vary (i.e., number of households selected per enumeration area). Survey practitioners are encouraged to engage with a sampling expert in the survey design phase.

Sampling frameworks, the strategies by which households and agricultural lands are selected, are designed to reduce sampling error, avoid biased selection of sampling sites, and guide where and how many samples to include in a given study. It is vital to be clear on the decision or sets of decisions that the measurement will support before designing the sampling framework, bearing in mind that the main purpose of measurement is to reduce decision uncertainty. Because this Guidebook is focused on implementing soil testing in *household* surveys, it is working under the assumption that the household is the primary sampling unit and that the study has its own predetermined household sample selection protocol. This chapter therefore focuses primarily on additional factors that need to be taken into consideration when integrating soil testing with the household survey.

Randomizing soil collection sites within the target area or sampling strata is important to provide unbiased estimates of carbon stocks and other land health indicators within a stratum and allow inference to be made to the whole area. Providing unbiased data on the statistical distribution of variables not only is useful for reporting the prevalence of land health problems (e.g., low soil carbon content), but also provides a means of setting local reference values (defining what is low, moderate, or high), which can in turn be conditioned on various factors (e.g., soil texture). A small probability sample generally provides much more useful information than a large biased sample.

The sampling design should be driven by the objectives of the study. Before designing the sample, it must be clear what level of representativeness is desired (if any) and the geographic area of interest. If the study is targeting specific crops and/or populations, that too must be made explicit.

Once the objectives are clear, the following questions must be addressed:

1. How many households will be included in the sample?
2. How many agricultural plots from each household will be subject to soil testing?
3. How many soil samples will be collected from each plot?
4. Where will the soil samples be collected within the plot?

Questions 1 and 2 are study-specific decisions and must be made with the objectives in mind. It may be the case that the aim is to integrate soil sampling into an existing household survey, in which case the household selection is completed without regard for the soil component.

Questions 3 and 4 are more generalizable. Depending on the expected variation in the soils, the average size of the agricultural plots in the study area, and the method through which the sample collection sites are identified, it is likely sufficient to test a single topsoil sample and a single subsoil sample from each selected plot. Soils provide different types of support to crops at different depths, and crops vary in their soil depth requirements. Maize, for instance, requires deeper soil than teff (Calviño et al. 2003; Evert et al., 2009). Thus, it is generally advisable to test both top- and subsoil samples, but this should be reviewed in light of the crop of interest and overall study objectives.

Question 4, the location of sample collection points within the plot, is critical, and fortunately the most straightforward to implement. If the aim is to assess the soil quality of the plot as a whole (and not a specific point within the plot), the soil sample collection points must make up a representative sample. Therefore, it is strongly recommended to use composite samples. The process of physically collecting the soil samples, as well as the identification of where the samples should be collected, question 4, are discussed in detail in the following section. For an example of a sampling strategy, refer to Box 4, which describes the sampling strategy for the Ethiopia LASER study.

BOX 4 — SAMPLING STRATEGY FOR LASER

The objectives of the LASER study were multifaceted and included indicators related to soil properties, crop type, and socioeconomic characteristics, among others. Additionally, the focus was on methodological validation rather than producing nationally representative statistics. Because there were multiple indicators, calculating the sample size based on the variance of a single indicator was not the preferred approach. Instead, a multistage nested approach using a practical allocation of enumeration areas (EAs) across agroecological zones was used.

Given the methodological focus of the study, it was preferable to implement a smaller-scale survey operation that could be closely supervised. Yet it was also imperative that the study area include substantial variation in soil properties so that soil quality measurement methods could be compared in different contexts. Therefore, the study was limited to a single administrative region. Oromia was selected because it represents a large area of Ethiopia and encompasses areas with great variation in rainfall, elevation, and agroecological zone.

The sample was restricted further to three administrative zones of the Oromia region, which were selected based primarily on agroecology and geographic diversity. Secondary consideration was made for the availability of local soil research centers that could be used for soil processing. The three selected zones are East Wellega, West Arsi, and Borena. Using the Agricultural Sample Survey (AgSS) of the Central Statistical Agency of Ethiopia (CSA) as the sampling frame, a total of 85 EAs were selected using a practical allocation and implicit stratification of EAs across agroecological zones. Finally, within each EA, 12 agricultural households were randomly selected from the AgSS household listing completed in September 2013.

The decision-making process for the number of plots subject to soil testing per household was driven by not only the desire to allow for a comparison of subjective and objective measures of soil quality while controlling for household characteristics (therefore, requiring more than one plot to be selected per household), but also the low expected variation of soil properties across plots cultivated by the same household (assuming geographic proximity). Up to two plots were measured per household. First, if any plots contained pure-stand maize, one was randomly selected. Then, a second plot was randomly selected from the remaining cultivated plots irrespective of crop type. If no plots contained pure-stand maize, two plots were randomly selected. The preference for maize in the first plot selection was purely to satisfy the maize crop-cutting component of the study. The random plot selection was completed by the computer assisted personal interviewing (CAPI) application to prevent selection bias.

The determination of the number of samples per plot was based on the existing AfSIS Land Degradation Surveillance Framework (LDSF). From each crop field, one composite sample was collected from the topsoil (0–20 cm depth) from four points and one central sample from the subsoil (20–50cm depth). Ideally, composite samples would be collected for the top- and subsoils rather than a single central subsoil sample. If resources allow, a composite sample at each depth is recommended. The guidelines presented here will reflect this recommendation.

BOX 5 – COMPUTER ASSISTED PERSONAL INTERVIEWING (CAPI)

With the expansion of computer assisted personal interviewing (CAPI) opportunities, georeferencing and barcode scanning offer useful features for implementing soil sample collection in household surveys. Capturing plot coordinates directly prevents data entry errors and cuts down on the need to procure separate GPS devices.

Similarly, barcode scanning can significantly reduce mislabeled soil samples and minimize loss of data as samples move through the hands of enumerators, soil processing technicians, and ultimately laboratory analysts. Depending on the structure of the study, soil sample identification labels may be lengthy and complex, as they may include a household identifier, a parcel identifier, and a plot identifier, as well as the depth of the soil sample. Scanning a barcode directly with the CAPI tablet will simplify the process while increasing efficiency and minimizing data entry problems. Be sure to test the barcode scanner with the particular type of barcode before procuring the labels, as not all barcode formats are readable by all hardware and software combinations.

Conducting a survey using CAPI not only facilitates barcode scanning and georeferencing, but also allows rapid, near-real-time data receipt. This can aid in catching fieldwork problems before they infiltrate the entire operation and focus supervisor attention on enumerators who need it most.

If using CAPI, consider procuring protective cases for the tablets as the nature of soil sampling is, well, dirty. Hardware should be as durable as possible and resistant to dirt and water.

11. IN THE FIELD: SOIL SAMPLE COLLECTION ON AGRICULTURAL PLOTS

The importance of having a consistent in-field protocol that can be applied under all expected conditions cannot be overemphasized. After the sampling strategy has been identified and it is clear how many households will be visited, how many parcels or plots will be selected for soil sampling, and how many soil samples will be collected from each selected parcel or plot, you can prepare for fieldwork implementation.

11.1 PREPARATION FOR FIELDWORK

Proper preparation is critical to ensure a successful soil sampling campaign and for the well-being of the field team. Before fieldwork, it is important to have a good understanding of the area to be surveyed, including its topography, climate and vegetation characteristics, accessibility, and security situation.

It is important to consider the following points before commencing fieldwork:

- Collate existing information about the area to be surveyed including maps (topographical, geological, soils, and/or vegetation), satellite images, and historical aerial photographs.
- Confirm that you have the necessary tools required for soil sample collection (see below).
- Train the field teams (enumerators and supervisors), and pilot all procedures.
- Prepare logistics in terms of transport, local guides, interpreters, and accommodation (if needed).
- Inform local government officers and community leaders about your activities, and obtain permission from the land owner(s) to sample a given area, making sure that all parties understand what you are doing.

For most enumerators, soil sampling will be a new concept. It also requires much more physical exertion than enumerating a typical household survey. This fact should not be underestimated when planning fieldwork timelines as teams may not be able to complete as many households in a single day as they would in standard household survey operations. Extra days should also be planned for training. On average, LASER enumerators spent approximately 40 minutes per field collecting soil samples. In MAPS, the average was 24 minutes. The efficiency gains observed in MAPS are likely attributable to lessons learned in LASER, including the benefit of using barcoded soil sample labels. Additionally, maize plots, which made up the entire MAPS sample, are somewhat easier to navigate than some crops (such as *teff*) because enumerators can walk between plants without worrying about crop damage.

Enumerator training must be thorough and convey the seriousness of sampling and handling soils with great care. Soil samples are quite fragile; testing results can be biased if the samples are not handled properly. Contamination of soil samples (as a result of inadequately cleaned equipment, for example) or failure to dry wet soil samples within 5–10 days of collection can lead to misrepresented results. Training should include a theoretical overview of the motivation for the study (field teams will need to explain this to respondents), review of key concepts and terminology, review of the enumerator manual (which can be based on this Guidebook), and group and individual hands-on training.

In each study, 2–3 days were dedicated to soil training, and 1–3 days were devoted to field practice. Training for the soil components of LASER and MAPS was conducted by an expert from ICRAF to ensure the use of best practices. While hands-on training was the most effective, it was imperative that the strategy, terminology, and importance of each step were reviewed in a classroom setting before the distribution of equipment and the outdoor demonstration.

All equipment must be procured before enumerator training, for use in plot practice. The list of equipment appears in Box 6, and cost estimates for key equipment appear in Annex 4.

BOX 6 — EQUIPMENT REQUIRED FOR SOIL SAMPLE COLLECTION

Below is a list of the basic tools and materials necessary for soil sample collection from agricultural plots. Unless otherwise noted, it is recommended to have one unit per enumerator. Cost estimates for key equipment are provided in Annex 4.

a) GPS device, preferably with ability to store coordinates (and land area, if desired by study)

b) Soil auger marked at 20 cm and 50 cm from tip

Note: Auger heads are designed differently for different types of soil. That is, sandy soils require a different auger head than clay soils. Distribute materials to field teams accordingly.

c) Measuring tape

d) Plastic sample bags (at least 400-gram capacity): 4 bags per parcel/plot subject to soil sampling

e) Buckets: 2 per enumerator, preferably of different colors so as to easily distinguish top- and subsoils.

f) Mixing trowel or spade

g) Water bottle filled with water (with hose, or punch a small hole in the cap)

h) A board, tray, or plastic sheet for coning and quartering; a clean plastic bag can also suffice

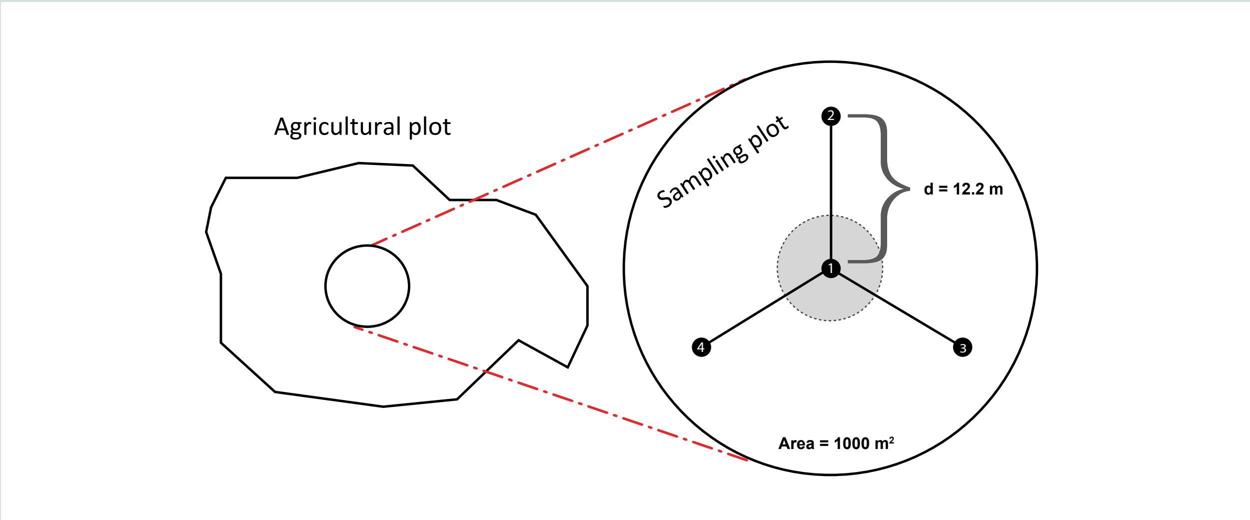
i) Labels or barcodes

j) Permanent marker pens

k) Stationery like pencils and a field notebook.

l) Texture chart for hand classification (see Figure 14)

Figure 10 — Sample plot layout in a crop plot, with four points (dotted circles). The distance between the center point and the other three points is 12.2 meters, which represents a 1,000-square-meter sampling plot.



11.2 SOIL SAMPLE COLLECTION PROTOCOL

This section presents a step-by-step protocol for ensuring that a representative soil sample is collected from each field. Composite samples, those collected from multiple points in the plot, are suggested to increase representativeness.

Soil sampling on agricultural plots requires that enumerators enter and use an auger in the plot. Thus, there is a risk of a small area of crop damage in the area of sampling.[11] Stable soil properties will not be affected by the time of sample collection. For some crops, such as maize, sampling is possible earlier in the agricultural season because samples can be taken from between the plants. For other crops such as teff, it may be necessary to wait until the harvest is completed to avoid excessive crop damage. If possible, try to collect soil samples without causing much damage to the crop by timing the sample collection appropriately. It is also advisable to avoid soil sampling when the soil is too wet because it will be difficult and may require a lot of time to collect and dry.

11.2.1 PLOT LAYOUT

As mentioned above, the location of the soil sample collection points are derived from the AfSIS LDSF 1,000-m^2 design (Figure 10), placed over the center of the crop plot. The AfSIS LDSF design serves as an initial template for soil sampling but may need to be modified to accommodate agricultural plots that are too small or irregularly shaped to contain a 1,000-m^2 soil sample plot (see Figure 11). The protocol implemented in LASER and MAPS and recommended for future studies is as follows:[12]

Step 1: Define the field center point by measuring halfway along the longest side and halfway along the shortest side of the field (Figure 10). Record the GPS coordinates of the plot center, or save the waypoints in the GPS unit with the appropriate label. The coordinates may also be saved in the GPS device.

Step 2: Using a measuring tape, measure out the distance (12.2 m) from the center point (point 1; Figure 10) directly uphill (where applicable) to the second point (point 2).

11 Originally, the intention was to conduct bulk density analysis as well as the conventional and spectral soil testing as part of LASER. However, the bulk density test requires a metal plate (approximately 40 cm x 40 cm) to be laid in the plot. During fieldwork training it was determined that the bulk density plate caused undue damage to the crop, and therefore it was excluded from the study.

12 In both MAPS and LASER, a composite sample was collected from the topsoil, but only a single subsoil sample was collected from the center point. However, if resources allow, a composite sample is recommended for both the top- and subsoils. Therefore, this Guidebook describes a protocol in which composite samples are collected at both depths.

Step 3: Mark points 3 and 4 at 120 and 240 degrees from the up-point (point 2), respectively, and 12.2 meters from the center point. The angles can be measured using a compass or estimated once the field team develops experience in plot layout.

The distance should be corrected when plots fall on steep terrain (slope > 10 degrees). Use the following formula to calculate the distance from the center point to the other point (for slope > 10 degrees):

$$Slope\ distance = \frac{horizontal\ distance}{cos\ (slope)}$$

Take the cosine values from the backside of your clinometer if you have one, or you may prepare and print a cosine table to carry in the field. You can also get cosine values from the Internet if you have Internet connectivity in the field. For instance, for a field with a 15-degree slope, the slope distance will be 12.2 m/0.9659 = 12.6 m.

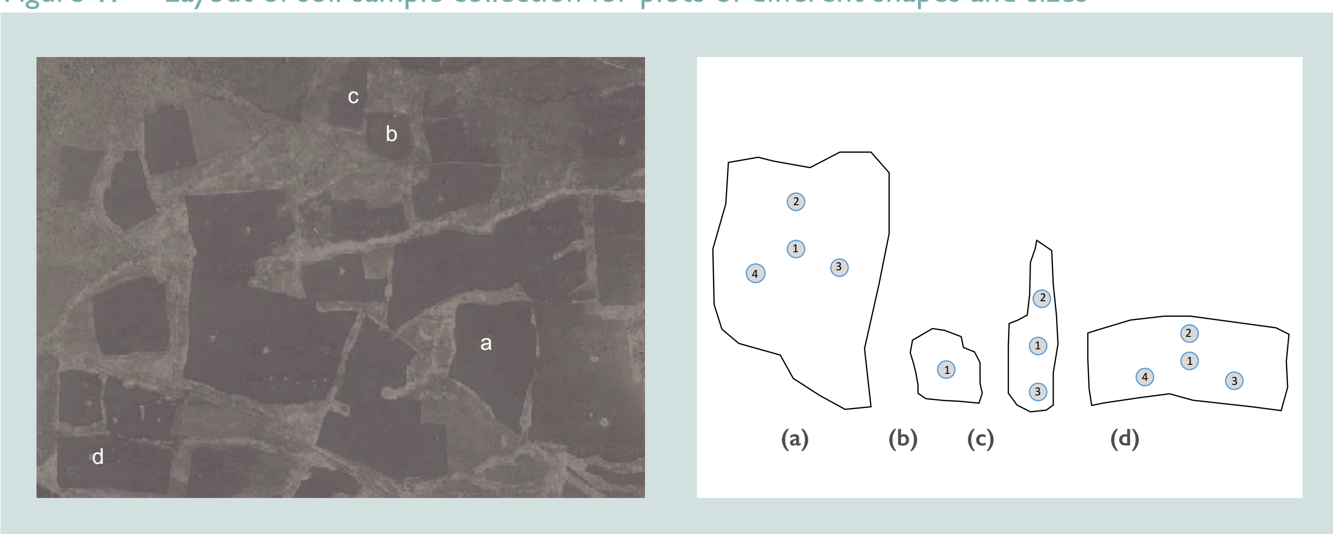
In many contexts, agricultural plots can be quite small and/or irregularly shaped. In these circumstances, the AfSIS LDSF design may not fit within the plot boundaries. If the plot is too small, the point should be placed 2 meters inside the boundary in order to limit border/edge effects. It may also be the case that plots are irregularly shaped and cannot accommodate the LDSF format. Figure 11 provides examples of alternative sample collection points aimed at achieving soil samples representative of the full plot.

11.2.2 SOIL SAMPLING

In general, it is advisable to test both a top- and subsoil sample in order to capture variation in key soil properties at different depths, which in turn affect crops differently. The decision to analyze top- and subsoil samples should be reviewed in light of the crop of interest and overall study objectives. This Guidebook describes the scenario in which samples are collected from two depth ranges (0–20 cm and 20–50 cm). Every plot selected for soil sampling is subject to the following:

- One composite topsoil sample collected at 0–20 cm. This sample is collected from four points within the plot (points 1–4 in Figure 10).
- One composite subsoil sample collected at 20–50 cm. This sample is collected from four points within the field (points 1–4 in Figure 10). If necessary, subsoil may be

Figure 11— Layout of soil sample collection for plots of different shapes and sizes



Source: Authors.
Note: Agricultural plots have different shapes and sizes that may require the sample collection layout to be modified. Examples: (a) shape and size of the crop plot allow a 1,000-m^2 sampling layout; take a composite sample from four points; (b) crop plot is less than 100 m^2; take sample from one point only; (c) shape of the crop plot does not allow an LDSF type of layout; take a composite sample from three points, (d) one side of the crop plot does not allow a full LDSF type of layout; leave a 2-m buffer from the boundary for point 2 (place it closer to center point) and take a composite sample from four points.

collected from a single central point for cost-savings, but a composite sample is recommended.

11.2.2.1 IN-FIELD SAMPLING PROCEDURE

The in-field sampling procedure is as follows:

Step 1: Mark the auger at 20 and 50 cm (e.g., using a permanent marker).

Step 2: Place the auger in the center sampling point, and begin to auger straight down. You will use the same auger for all depths. If augering becomes crooked, stop and start a new hole, otherwise you will get an inaccurate measurement of the depth.

Step 3: Auger down to a depth of 20 cm, and transfer all of the soil from the auger into the bucket designated for topsoil.

Step 4: The next sample is from 20–50 cm. Continue augering (in the same 0–20-cm hole) until you reach the 50-cm mark on the auger. Empty the soil from the auger into the separate bucket designated for subsoil.

Step 5: Repeat step 3 for the remaining collection points on the field (points 2–4 on Figures 10 and 11). Place all top- and subsoils collected into the bucket designated for each depth. Now you will have two buckets that contain composite samples from all four collections points for the top- and subsoils. Mix each bucket with a trowel, cleaning the trowel between buckets.

Step 6: If the auger was not able to reach the desired depth (due to depth restrictions from a rock layer, for example), record the auger depth restriction (the maximum depth attainable).

Step 7: Conduct the in-field soil texture analysis (see Figures 13 and 14).

Step 8: Conduct the coning and quartering procedure for the topsoil and subsoil separately. The end result should be approximately 400 grams (g) of topsoil and 400 g of subsoil. Instructions for the procedure are found in the section below (Figure 12).

Step 9: Bag and label the samples with the household identification, plot identification, depth of the soil sample, and auger depth restriction (if applicable).

If the soil is very dry, it may be difficult to auger and collect all of the soil from the depth increment; in this case prewetting the soil before augering each increment may be helpful.

11.2.2.2 SUB-SAMPLING VIA "CONING AND QUARTERING"

Normally, soil-sampling procedures lead to collection of more soil than necessary for analysis. To get a representative sample of the appropriate volume, a standardized and consistent procedure must be followed. For this purpose, it is necessary to use the method of coning and quartering described below (and seen in Figure 12b). Continue the coning and quartering technique on the topsoil and subsoil samples to obtain a representative 400-g subsample of soil for processing and analysis. The process for coning and quartering is as follows:

Step 1: Place the sample on a strong, clean plastic sheet or similar material (Figure 12b).

Step 2: Thoroughly mix the soil sample, and spread the samples into a conical pile.

Step 3: Further mix the soil by circumventing the cone symmetrically, repeatedly taking a spatula full of soil from the base and transferring the soil to the apex of the cone.

Step 4: Ensure the spatula is large enough to reach center of the cone. Circumvent the cone twice.

Step 5: Flatten the cone to a height of about 1 cm (Figure 12b).

Step 6: Use a flat spatula or ruler to divide the pile into quarters with two perpendicular lines (Figure 12b).

Step 7: Select one pair of opposite quarters as the sample to be retained.

Step 8: If the sample is still too large, then repeat the procedure from the beginning.

Step 9: Take the representative subsample (about 400 g), and place it in a plastic bag. Label the bag, and place an extra label tag inside the bag.

Figure 12 — Soil Sample Collection and Subsampling


(a) Soil sample collection


(b) Soil subsampling via coning and quartering

Figure 13 — Soil Texture by Feel: Steps

TEXTURE BY FEEL ON SOIL SAMPLES

Step 1: Starting with the topsoil sample, moisten a handful of soil using water from the water bottle until the soil has a putty-like consistency but free water does not escape when ball is squeezed (a).

Step 2: Shape the soil into a ball. If the ball retains its shape, move to step 3.

Step 3: Using your thumb and forefinger, form a ribbon with the soil by smearing the ribbon with your thumb (b). Observe if the soil is shiny or dull.

Step 4: Measure the length of the ribbon when it breaks and record it in the questionnaire (c) The ribbon should be measured in millimeters (mm).

Step 5: Classify the texture according to the flow chart (Figure 14) and report in the questionnaire whether it is smooth, gritty, or neither.

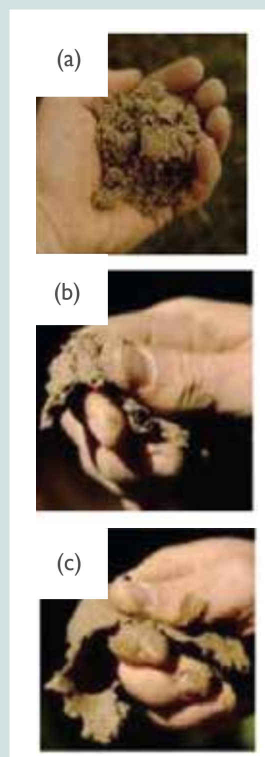
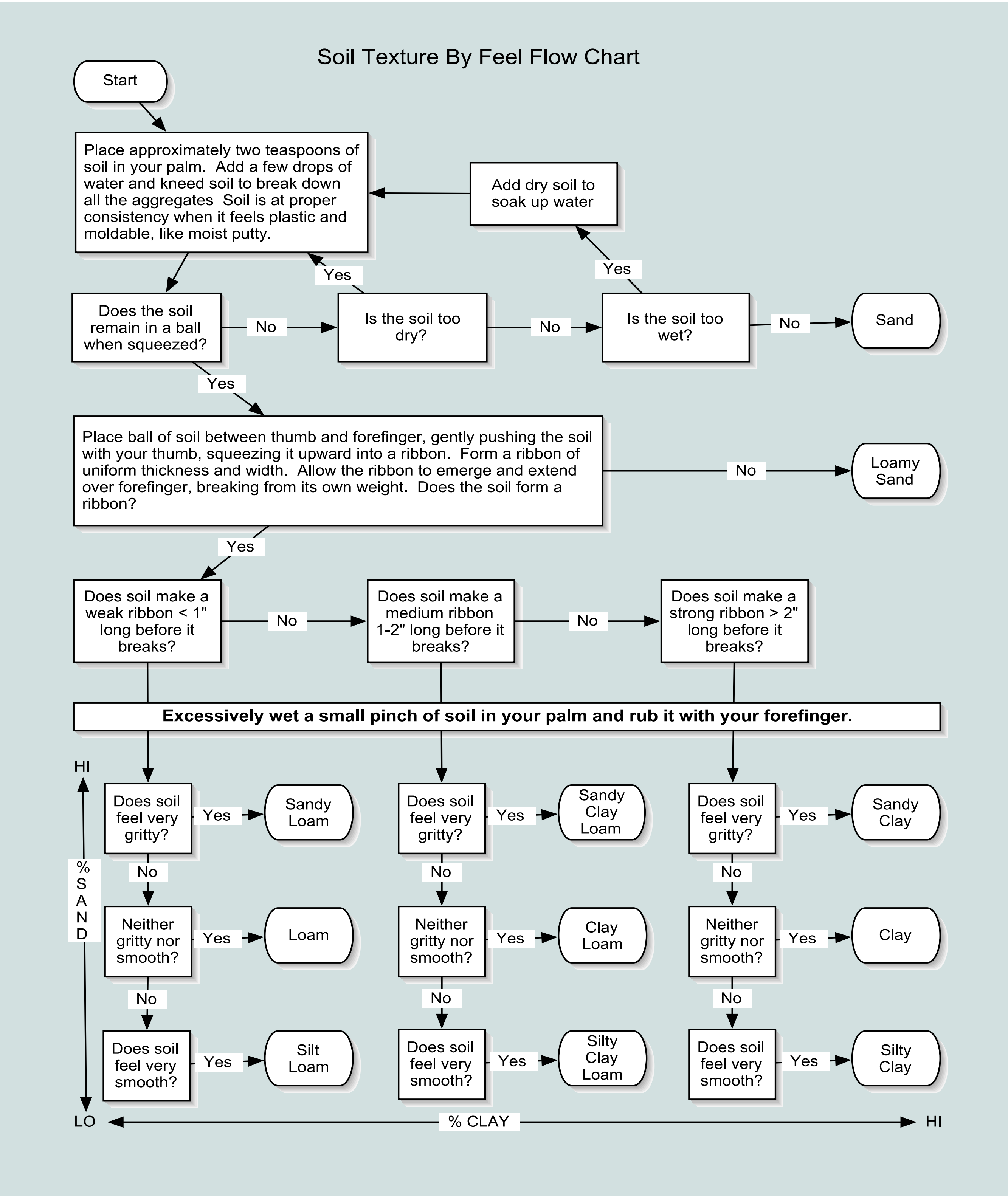


Figure 14 — Soil Texture by Feel: Flow Chart



11.2.2.3 IN-FIELD SOIL TEXTURE ANALYSIS

Soil texture is the amount of sand, silt, and clay in the soil and is important for determining many soil properties including aggregation, structure, and water and air movement through the soil. This section provides instruction on determining if the soil texture is smooth, gritty, or neither smooth nor gritty (Figures 13 and 14). Figure 13 also illustrates the soil ribbon test, which acts as a proxy for soil structure and texture.

11.2.2.4 SOIL SAMPLE LABELING

Labeling is critical. To ensure that results from soil analysis are linked to the correct household and plot, several pieces of information must be captured. The unique household identifier, the parcel and/or plot identifier, and the depth of the soil sample must be listed on the sample bag (with a duplicate label placed inside the bag in case of damage to the outer label and for use by the laboratory). The labeling scheme used in LASER is illustrated in Table 12.

For example, for a plot with Household ID 3108, parcel ID 03, and plot ID 02, you would have the following labels:

- 3108–03–02 0–20 cm
- 3108–03–02 20–50 cm

In case of soil depth restrictions, indicate the actual depth in the label. For example, the subsoil label for a site where a soil depth restriction occurred at a depth of 35 cm would be the following:

- 3108–03–02 20–35 cm

Sample IDs should be legibly recorded with a permanent marker on the outside of the plastic bags. A paper label containing the same information (written in pen or pencil) should also be placed inside the bags.

When possible, the use of barcoded labels is highly encouraged, especially for surveys administered via CAPI. Preordered barcodes with serialized numbers printed on them can greatly reduce data entry problems. A duplicate of every barcode should be ordered such that one barcode is placed on the outside of the bag and the second is placed inside the bag (without the backing peeled so it is not sticky). The duplicate bag can then be easily used by the laboratory, as they will likely take a subsample of the soil and store it in a separate bag. Ensure that the type of barcode you choose can be read by the CAPI hardware and software. This protocol was followed in MAPS, and fieldwork time was reduced.

11.2.2.4 SOIL SAMPLING SUMMARY

The process to collect soil samples from agricultural plots is a multistage process but is not overly technical. Enumerators can be trained to effectively implement the modified AfSIS LDSF sample layout, collect soils via augering, subsample the collected subsoils via coning and quartering, test the texture of the soils, and properly label the samples. A summary of the steps in soil sample collection is found in Table 13.

12. IN THE LAB(S): SOIL PROCESSING AND LABORATORY ANALYSIS

Section 12 describes the stages of soil processing and testing. While much of the content is directly relevant to the laboratories where drying, processing, and analysis take place, it is essential for survey practitioners to fully understand the process.

12.1 SOIL PROCESSING

Before analysis, soil samples must be processed. This involves drying, crushing, sieving, weighing, and subsampling the soils. The process by which this was completed in LASER and MAPS is outlined below.

Table 12 — Examples of Soil Sample Labels used in LASER

Label for soil samples	Number of samples	Note
HHHH-PP-FF 0-20 cm	1	HHHH = household; PP = parcel; FF = plot
HHHH-PP-FF 20-50 cm	1	
Total	**2**	

Table 13 — Major Steps in Soil Sample Collection

Step	Agricultural Plot	
	Top soil (0-20 cm)	Sub-soil (20 -50 cm)
Step 1: Using the soil auger collect topsoil (0–20 cm) from the four points and place in a bucket (Figure 12a).	*	
Step 2: Using the soil auger, collect subsoil (20–50 cm) from the four points and place in a separate bucket.		*
Step 3: Analyze the texture and measure the ribbon size for the top- and subsoils according to the instructions in Figures 13 and 14.	*	*
Step 4: Take a representative (about 400 g) subsample of the top- and subsoils following the coning and quartering procedure, and place them in separate plastic bags. Label the bags accordingly (as in Table 12 or as otherwise determined by the project). Place an extra label inside the sample bag.	*	*
Step 5: If there are auger depth restrictions, adjust the label accordingly. For example, if the auger will only dig to 15 cm, label the sample as HHID-parcel ID – Plot ID 0–15 cm (rather than 0–20 cm).	*	*

12.1.1 SCOPE AND APPLICATION

All soil samples should be transported to a regional laboratory for processing using this standard operating procedure. Soil laboratories found in various national and regional agricultural research institutes and academic institutions found closer to a study area could be used for soil processing. The LASER study used the soil laboratory facilities and technicians from the Awassa Agricultural Research Center (for West Arsi), Ambo University (for Wellega), and Yabello Pastoral and Dryland Agricultural Research Center (for Borena). In MAPS, all soil processing was conducted at Uganda's National Forestry Resources Research Institute in Kampala. Soil drying and/or processing may be conducted in-country before transportation to the regional laboratories to avoid changes in soil properties from storage of wet samples and to reduce the cost of shipping a large volume of soils. In the case of LASER and MAPS, samples were dried, sieved, and weighed before being shipped to ICRAF for analysis. Note that the drying of samples is critical and should be completed within a week of collection in order to minimize any decomposition of organic material, especially in wet soils.

12.1.2 PRINCIPLES

Sampling and sample processing, or *pretreatment*, make up an important stage of soil analysis because conclusions about a site are often based on the analysis of representative soil samples collected during this stage. Because of high spatial variation in the soil, it is important that the process followed should lead to the collection of a sample that is truly representative of the site. Errors in sampling and sample pretreatment can influence the final results of a soil analysis.

Soil collected from an agricultural plot is a mix of gravel (fraction of soil with a diameter of > 2 mm), sand (fraction between 0.05 mm and 2.0 mm), silt (fraction between 0.002 mm and 0.05 mm), and clay (fraction smaller than 0.002 mm). Since the contribution of the gravel fraction to the dynamics of soil nutrient cycles and supply to plants is minimal, it is excluded from the analysis and reporting of plant-available nutrients. During the preparation of soil samples, this fraction should not be crushed and pulverized, because then it would be considered part of the fine soil and result in low values of the analyses owing to the dilution effect. However, aggregates of > 2 mm formed by fine particles have to be crushed in order to pass through a 2-mm sieve and be included in the analysis. Normally, soil-sampling procedures lead to the collection of more than the required amount of soil, and to get a representative sample of the necessary volume, it is important to follow standardized and consistent procedures of coning and quartering.

12.1.3 LAB PROCEDURES: SOIL PROCESSING

Soil processing involves sample reception, drying, crushing and sieving, and subsampling of fine particles, all while ensuring the health and safety of the lab technicians. Soil processing does not require technical equipment. It requires only the items listed in Box 7 and a clean working environment with space for drying the soil samples. The procedures for soil processing are described here in a step-by-step fashion.

12.1.3.1 SOIL SAMPLE RECEPTION

- Lay out the samples received in order of labeling, and

BOX 7 – EQUIPMENT REQUIRED FOR SOIL PROCESSING ACTIVITIES

Below is a list of the basic tools and materials necessary for soil processing. Soil processing involves drying the soils, crushing and sieving them to ensure that only the fine portion of the soils is analyzed, and weighing out a smaller subsample for laboratory analysis.

- Drying trays
- Wooden rolling pin
- 2-mm sieve
- Plastic sheet
- Markers
- Brown paper bags (size 5)
- Balance
- Plastic zip-lock bags
- Particulate respirator (e.g., N95 of 3M brand)
- Nitrile gloves
- Damp cloth
- Forced-air drying oven (optional)

check against the master list of samples received from the plot. If barcoded labels are used, the lab can simply scan the inventory.

- Make detailed notes in a laboratory record book of any labeling discrepancies or problems due to damaged sample bags or lost samples.

12.1.3.2 DRYING

Step 1: Spread the soil out as a thin layer into shallow trays or plastic or paper sheets. It is important to ensure that no material from a sample is lost or discarded (Figure 15).

Step 2: Break up clods as far as possible to aid drying. Take care to avoid crushing gravel-sized particles.

Step 3: Great care should be taken at all stages to ensure that sample labels remain with the samples.

Step 4: Exercise care to avoid contamination from dust, plaster, or other potential contaminants during drying, as soils are subjected to trace element analysis.

Step 5: Air dry the samples in shade, not sun. Drying can also be done in a large room, custom-made solar dryer, or a forced-air oven at 40° C.

Step 6: Drying time will depend on the condition of the samples and ambient conditions, but the samples should be thoroughly dried.

12.1.3.3 CRUSHING AND SIEVING

Step 1: Spread the sample onto a plastic sheet on a solid table (Figure 16).

Step 2: Using a wooden rolling pin, crush the sample

Figure 15 — Drying of MAPS Soil Samples

enough to allow it to pass through a 2-mm sieve.

Step 3: While crushing, remove any plant materials (e.g., roots) and any possible pieces of gravel (making sure they are gravel and not soil aggregates) and place in a separate pile (the coarse fraction).

Step 4: Pass the crushed sample through the 2-mm sieve. DO NOT use the sieve as a grinder; i.e., do not rub or mash the soil on the sieve, but shake the sieve gently to allow the soil to pass through. If a large amount of soil needs to be sieved, it is easier to do it in small batches rather than all at one time.

Step 5: Place whatever remains on the sieve back onto the plastic sheet and crush again gently. Then pass again through the 2-mm sieve.

Step 6: Transfer anything that now remains on the sieve into the coarse fraction pile

Step 7: The whole sample should be processed, and no material should be discarded. You will remain with two fractions:

- The coarse fraction (> 2 mm), which cannot pass through the sieve. Discard the coarse fraction.
- The soil fines (< 2 mm), which have passed through the sieve.

Step 8: Clean off the table with a damp cloth to remove soil dust, to prevent contamination from one sample to another.

Figure 16 — Sample Crushing and Sieving

12.1.3.4 SUBSAMPLING OF FINE FRACTIONS

Step 1: If the weight of the soil fines is more than 400 g, subsample the soil fines using coning and quartering to give about 350–400 g of fine soil.

Step 2: Continue the coning and quartering technique on all samples to obtain a representative 20-g subsample of soil fines for shipping to the laboratory designated for specialized spectral analysis.

Step 3: Place the 20-g subsample in a zip-lock polythene bag labeled properly. All of the 20-g samples will be delivered to the lab conducting the spectral analysis.

Step 4: Place the remaining +/-350-g sample of soil fines into a strong size-5 brown paper bag, labeled properly, and store for possible future use. Note: This is when you will need a duplicate barcode or other label (with the same identification information).

Step 5: A select subset of the 350-g soil fine samples will be tested with conventional analysis. This is typically in the range of 10–25 percent of all samples. The exact samples will be identified following completion of the spectral analysis on all samples, thereby showing the variation of soil properties present in the samples. The selected 350-g reference samples will be shipped to the ICRAF Soil-Plant Spectral Diagnostics Lab in Nairobi or other diagnostic lab for reference analyses. Soil fine samples that are not shipped should be stored at the regional laboratory in case they are needed for future analysis.

12.1.3.5 SOIL PROCESSING: HEALTH AND SAFETY

- Wear nitrile gloves to reduce the incidence of skin contact with potentially contaminated soil and to reduce the risk of cross-contamination.

- Wear a respirator that covers the mouth and nose to filter out harmful dust particles. Inhaling such particles irritates the nostrils and sinuses and may lead to lung diseases.
- Refer to the site-specific health and safety plan for other safety concerns and applicable personal protective equipment.

12.2 LABORATORY ANALYSIS: SPECTROSCOPY

While all technical analysis will be conducted by expert technicians, the information below regarding the processes followed by the laboratory will equip survey practitioners with the background necessary to plan and implement a successful study.

Soils samples can be analyzed for chemical (e.g., nitrogen) and physical properties (e.g., texture) at the Soil-Plant Spectral Diagnostics Lab of the World Agroforestry Centre (Figure 16) or other laboratory with the necessary equipment and expertise. All soil samples are scanned for mid-infrared soil spectroscopy (IR) and laser diffraction particle size distribution analysis (LDPSA), while 10–25 percent from the total sample are subject to reference analysis (including conventional wet chemistry, x-ray methods for soil mineralogy [XRD], and total element analysis [TXRF]), which is used to calibrate and validate MIR-spectral prediction for the remaining samples (75–90 percent).

Results from the conventional and spectral soil testing are presented to the end user in the form of a dataset, complete with all identification variables (which are necessary to merge the data with the household survey) and soil-quality indicators included in the testing. Whenever possible, make the data publicly available, as this will increase the visibility of the data by making them available to researchers, students, and policy figures. However, household surveys require a degree of confidentiality. Exact coordinates of households, agricultural plots, or soil collection points must not be released.

Figure 17 — Left: MIR spectrometer. Right: a team of three from the LSMS project of the World Bank and the Central Statistical Agency (CSA) of Ethiopia attending a three-day soil infrared spectroscopy exposure training at ICRAF's Soil-Plant Spectral Diagnostics Laboratory in Nairobi.

Part IV – Conclusions

This Guidebook provides a step-by-step guide to implementing spectral soil analysis in household surveys as well as providing results of two methodological studies, both of which illustrate the inability of subjective farmer assessment to adequately capture true soil properties.

Knowledge of soil quality indicators and overall health is becoming increasingly important as food security issues become more pressing and climate change threatens to change the face of agriculture. Soil health, both perceived and actual, can have impacts on the targeting and uptake of improved agricultural practices, which can improve both the quality and quantity of food produced. For instance, Marenya and Barrett (2009) show that fertilizer effectiveness, and in turn farmers' demand for fertilizer, are dependent on soil carbon content. However, results of the LASER and MAPS studies suggest that subjective soil quality indicators fail to effectively reflect true levels of organic carbon, limiting the value of subjective assessments of soil quality in policymaking.

Asking a farmer to categorically rate overall soil quality has limited benefit. This particular subjective soil quality question does not successfully consistently distinguish between soil carbon levels or predict soil quality index scores, at least within these methodological research studies. Subjective questions on soil color and texture are more effective at predicting soil quality index scores and organic carbon content, but the low explanatory power of these variables leaves much to be desired. Furthermore, the severe lack of variation in subjective soil quality indicators given by households reporting on multiple plots calls the value of this approach into question.

Evidence from the LASER and MAPS studies suggests that subjective farmer assessments of soil quality poorly explain objective laboratory results and lack intrahousehold variation. Spectral analysis has been proven to near-perfectly predict key soil parameters as measured by conventional wet chemistry methods, while also providing highly detailed data that can be useful in policy aimed at increasing agricultural output and nutritional value, such as fertilizer input programs, as well as in agricultural productivity analysis.

From a fieldwork implementation standpoint, the LASER and MAPS studies suggest that it is feasible to integrate soil spectroscopy into socioeconomic household panel surveys. The methodology is a relatively rapid and cost-effective soil measurement technique that could unlock further understanding of the effects of farm management practices and changes in soil health over time.

The body of research on implementing spectral soil testing in household surveys, and validating objective measurements against subjective assessments, is at an early stage. Given the emerging nature of this type of research, and the complexities of soil-quality measurement, we encourage further validation of such projects, particularly under soil conditions different from those presented here. Additional research is also needed to validate the use of the growing number of tools and methods for in-field soil analysis. As these methods are developed with increasing capabilities, their accuracy must be assessed against standard methods, such as conventional and spectral soil analysis, before they can be reliably used in household surveys.

REFERENCES

AfSIS (Africa Soil Information Service). (2014). *Africa Soil Information Service.* Retrieved from http://www.africasoils.net.

Aitkenhead, M., Donnelly, D., Coull, M., & Gwatkin, R. (2016). Estimating soil properties with a mobile phone. In Hartemink, A. E., & Minasny, B. (Eds.), *Digital Soil Morphometrics* (pp. 89–110). New York: Springer.

Aynekulu, E., Vågen T.-G., Shephard, K., & Winowiecki, L. (2011). A protocol for modeling, measurement and monitoring soil carbon stocks in agricultural landscapes. Version 1.1. Nairobi: World Agroforestry Centre.

Aynekulu, E., Carletto, C., Gourlay, S., & Shepherd, K. (2016). *Soil sampling in household surveys: Experience from Ethiopia.* Washington, DC, and Nairobi: World Bank and World Agroforestry Centre. Retrieved from http://go.worldbank.org/PYIZRV60K0

Beaman, L., & Dillon, A. (2012). Do household definitions matter in survey design? Results from a randomized survey experiment in Mali. *Journal of Development Economics, 98*(1), 124–135.

Bennett, L. T., Mele, P. M., Annett, S., & Kasel, S. (2010). Examining links between soil management, soil health, and public benefits in agricultural landscapes: An Australian perspective. *Agriculture, Ecosystems and Environment, 139,* 1–12.

Bouis, H. E. (2003). Micronutrient fortification of plants through plant breeding: Can it improve nutrition in man at low cost? *Proceedings of the Nutrition Society, 62,* 403–411.

Calviño, P. A., Andrade, F. H., & Sadras, V. O. (2003). Maize yield as affected by water availability, soil depth, and crop management. *Agronomy Journal, 95,* 275–281. doi:10.2134/agronj2003.2750

Ethiopian ATA (Agricultural Transformation Agency). (2017). EthioSIS. Retrieved from https://www.ata.gov.et/highlighted-deliverables/ethiosis/

Evert, S., Staggenborg, S., & Olson, B.L.S. (2009). Soil Temperature and Planting Depth Effects on Tef Emergence. *Journal of Agronomy and Crop Science*, *195,* 232–236. doi: 10.1111/j.1439-037X.2008.00343.x

FAO. (1986). *Ethiopian highlands reclamation study*. Final Report, AG:UTF/ETH/037/ETH. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2005). *A system of integrated agricultural censuses and surveys*. FAO Statistical Development Series, 11. Rome: Food and Agriculture Organization of the United Nations.

Fernandes, J. C., Gamero, C. A., Rodrigues, J. G. L., & Miras-Avalos, J. M. (2011). Determination of the quality index of a Paleudult under sunflower culture and different management systems. *Soil and Tillage Research, 112*, 167–174.

Fischer, G., Nachtergaele, F., Prieler, S., van Velthuizen, H. T., Verelst, L., & Wiberg, D. (2008). *Global agro-ecological zones assessment for agriculture (GAEZ 2008)*. Laxenburg, Austria, and Rome, Italy: International Institute for Applied Systems Analysis and Food and Agriculture Organization of the United Nations.

Gourlay, S., Aynekulu, E., Shepherd, K., & Carletto, C. (2017). *Collecting the dirt on soils: Advancements in plot-level soil testing and implications for agricultural statistics.* Policy Research Working Paper 8057. Washington, DC: World Bank . Retrieved from http://documents.worldbank.org/curated/en/748621494523429244/Collecting-the-dirt-on-soils-advancements-in-plot-level-soil-testing-and-implications-for-agricultural-statistics

Grosh, M., & Glewwe, P. (2000). *Designing household survey questionnaires for developing countries: Lessons from 15 years of the Living Standards Measurement Study.* Volumes 1, 2, and 3. Washington, DC: World Bank.

Hengl, T., Heuvelink, G. B. M., Kempen, B., Leenaars, J. G. B., Walsh, M. G., Shepherd, K. D., et al. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PLoS ONE, 10(6),* e0125814. doi:10.1371/journal.pone.0125814

Herrick, J. E., Urama, K. C., Karl, J. W., Boos, J., Johnson, M.V.V., Shepherd, K. D., Hempel, J., Bestelmeyer, B. T., Davies, J., Guerra, J. L., & Kosnik, C. (2013). The global Land-Potential Knowledge System (LandPKS): Supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. *Journal of Soil and Water Conservation, 68*(1), 5A–12A.

Ji, W., Shi, Z., Huang, J. & Li, S. (2014). In situ measurement of some soil properties in paddy soil using visible and near-infrared spectroscopy. *PLoS ONE, 9,* 1–11.

Karlen DL, Stott D.E. (1994). *A framework for evaluating physical and chemical indicators of soil quality.* In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA, editors. Defining soil quality for a sustainable environment. Madison, WI: Soil Science Society of America. pp. 53–72.

Karltun, E., Lemenih, M., & Tolera, M. (2013). Comparing farmers' perception of soil fertility change with soil properties and crop performance in Beseku, Ethiopia. *Land Degradation and Development, 24,* 228–235.

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. *Food Security, 1,* 45–57.

Lal, R. (2016). Soil health and carbon management. *Food and Energy Security, 5*(4), 212–222.

Lorenz, K., & Lal, R. (2005). The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. *Advances in Agronomy, 88,* 35–66.

Marenya, P., & Barrett, C. B. (2009). Soil quality and fertility use rates among smallholder farmers in western Kenya. *Agricultural Economics, 40*(5), 561–572.

Mehlich, A. (1984). Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. *Communications in Soil Science and Plant Analysis, 15*(12), 1409–1416.

Minasny, B., & Hartemink, A. E. (2011). Predicting soil properties in the tropics. *Earth-Science Reviews, 106*(1–2), 52–62.

Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLoS ONE, 9*(8), e105981. doi:10.1371/journal.pone.0105981

Nocita, M., Stevens, A., van Wesemael, B., Brown, D. J., Shepherd, K. D., Towett, E., Vargas, R., & Montanarella, L. (2015). Soil spectroscopy: An opportunity to be seized. *Global Change Biology, 21*(1), 10–11. doi:10.1111/gcb.12632

Randall, S., & Coast, E. (2015). Poverty in African households: The limits of survey and census representations. *Journal of Development Studies, 51*(2), 162–177.

Sanchez, P. A., Denning, G. L., & Nziguheba, G. (2009). The African Green Revolution moves forward. *Food Security, 1*(1), 37–44.

Shepherd, K. D., & Walsh, M. G. (2002). Development of reflectance spectral libraries for characterization of soil properties. *Social Science Society of American Journal, 66*(3), 988– 998.

Shepherd, K. D., & Walsh, M. G. (2004). Diffuse reflectance spectroscopy for rapid soil analysis. In Lal, R. (Ed.), *Encyclopedia of Soil Science.* New York: Marcel Dekker.

Shepherd, K. D., & Walsh, M. G. (2007). Infrared spectroscopy: Enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. *Journal of Near Infrared Spectroscopy, 15,* 1–19.

Takoutsing, B., Weber, J., Aynekulu, E., Martín, J. A. R, Shepherd, K. D., Sila, A., Tchoundjeu, Z., & Diby, L. (2016). Assessment of soil health indicators for sustainable production of maize in smallholder farming systems in the highlands of Cameroon. *Geoderma, 276,* 64–73.

Tittonell, P., Shepherd, K. D., Vanlauwe, B., & Giller, K. E. (2008). Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya: An application of classification and regression tree analysis. *Agriculture, Ecosystems and Environment, 123,* 137–150.

Tulchinsky, T. H. (2010). Micronutrient deficiency conditions: Global health issues. *Public Health Reviews, 32*(1), 243–255.

United Nations. (2008). *Principles and recommendations for population and housing censuses revision 2.* New York: United Nations, Department of Economics and Social Affairs, Statistics Division.

Welch, R. M., & Graham, R. D. (2004). Breeding for micronutrients in staple food crops from a human nutrition perspective. *Journal of Experimental Botany, 55*(396), 353–364.

Wenjun, J., Zhou, S., Jingyi, H., & Shuo, L. (2014). In situ measurement of some soil properties in paddy soil using visible and near-infrared spectroscopy. *PLoS One, 9.* doi:10.1371/journal.pone.0105708

ANNEXES

Annex 1

Key Definitions Used in the Uganda National Panel Survey 2011/12

These definitions are from the Interviewer's Manual of Instructions for Uganda National Panel Survey 2011/12 – Agriculture Module, Uganda Bureau of Statistics.

Agricultural Holding

1. This is ***an economic unit of agricultural production under single management*** comprising all livestock kept and all land used wholly or partly for agricultural production purposes, without regard to title, legal form, or size. Single management may be exercised by an individual or by a household, jointly by two or more individuals or households, by a clan or tribe or a cooperative or government parastatal.

2. A holding may consist of one or more parcels located in one or more separate areas, provided the parcels share the same production means utilized by the holding, such as labor, farm buildings, farm implements, and machinery or drought animals. The requirements of sharing the same production means should be fulfilled to a great degree to justify the consideration of various parcels as components of one economic unit.

3. In the case of a family which lives together and shares meals, all parcels cultivated by the household members will constitute one holding. On the other hand, if part of land is cultivated by relatives who live separately, even though they share work on the land, each of them will normally know which parcels/plots belong to them. In this case, the total area is not a holding, but several holdings, depending on the number of persons having claim to the parcels in question.

4. Some of the area of the holding may be cultivated, fallow, under forest trees, belonging to the holder, or may be wholly and partly used for grazing livestock.

5. The following points will assist in getting the concept of holding clearer:

(i) There are holdings that do not have a significant area, e.g., poultry or piggery units or hatcheries for which much land is not absolutely necessary.
(ii) There are holdings that may be operated by holders who have another occupation in addition to being holders.
(iii) There may be holdings that may be operated jointly by two or more individuals.
(iv) Land which is open to communal grazing is not considered a holding.

Parcel

1. A parcel is a contiguous piece of land with identical (uniform) tenure and physical characteristics. It is entirely surrounded by land with other tenure and/or physical characteristics or infrastructure e.g., water, a road, forest, etc., not forming part of the holding. This implies that a parcel is part of a holding that is physically separate from other parts of the holding. A holding is made up of one or more parcels.

Plot

1. A plot is defined as a contiguous piece of land within the parcel on which a specific crop or a crop mixture is grown. A parcel may be made up of one or more plots.

Total Holding Area

1. Total holding area is the area of all parcels that are operated by the holder. Forestland and other land owned and/or used by the holder should be included. Land rented from others and operated by the holder should be included in the holding. But land owned by the holder but rented to others should not be included in calculating the holding area. It should be, however, noted that information on parcels owned by the household, but rented to others (operated by others) will be collected in this survey even if it will be excluded in computing total holding area (cultivated area) at the analysis stage.

2. The holding area includes land under crops and pastures as well as land occupied by farm buildings. Land area of the holder's house is also included in the total holding area if the house is not located outside the holding (e.g., a house for residential purposes in a village or town) and is not used solely for residential purposes. It should be noted that data on nonagricultural land in general and residential land in particular irrespective of the location is collected in the socioeconomic questionnaire under Section 13: Non-Agricultural Land by All Households and Agricultural Land by Non-Agriculturalists.

3. The total area of a holding practicing shifting cultivation should include area under crops during the reference period and areas prepared for cultivation but not sown or planted at the time of enumeration. It should exclude land abandoned prior to the reference period. Holders having access to communal grazing land should not include their estimated share of such land in their total land area.

Annex 2

Subjective Questions on Soil Quality

Below is an excerpt from the Ethiopia LASER post-planting questionnaire. The questions below were administered to the most knowledgeable household member for each cultivated field. The full questionnaire and data are available on the LSMS website (worldbank.org/lsms).

SOIL						
PARCEL ID	FIELD ID	5. What is the predominant soil type of this [FIELD]? READ ANSWERS SANDY..........1 CLAY..........2 MAINLY MIXTURE OF SAND AND CLAY..........3 OTHER (SPECIFY)..........4 .	6. What is the color of the soil? READ ANSWERS BLACK..........1 RED..........2 WHITE/LIGHT..........3 YELLOW..........4 OTHER (SPECIFY)........5 .	7. What is the soil quality of this [FIELD]? READ ANSWERS GOOD..........1 FAIR..........2 POOR..........3 .	8. How do you know the soil quality of [FIELD]? READ ANSWERS SCIENTIFICALLY TESTED..........1 OWN EXPERIENCE........2 OTHER PERSON.......3 OTHER (SPECIFY).....4 .	9. What is the texture of the soil on this [FIELD]? READ ANSWERS VERY FINE..........1 FINE..........2 BETWEEN COARSE AND FINE..........3 COARSE..........4 VERY COARSE..........5 .

10. Were there any problems with erosion on [FIELD] this agricultural season? YES..........1 NO.......2 (► 12)	11. What is the cause of these problems? WIND..........1 RAIN..........2 ANIMALS..........3 CULTIVATION WHICH DOES NOT COMPLY WITH SOIL CONSERVATION....4 OTHER (SPECIFY)........5 .	12. Is [FIELD]? prevented from erosion? YES..........1 NO.......2 (► 14)	13. What is the way of preventing erosion on [FIELD]? TERRACING..........1 WATER CATCHMENTS......2 AFFORESTATION..........3 PLOUGH ALONG THE CONTOUR ....4 OTHER (SPECIFY)..........5 .

Annex 3 Correlation of Soil Properties from LASER and MAPS

LASER

Topsoil

	Organic Carbon	Total Nitrogen	pH	Sand (%)	Silt (%)	Clay (%)	Exchangeable Acids	Exchangeable Bases	Potassium	Phosphorous	Boron
Organic Carbon	1										
Total Nitrogen	0.961	1									
pH	-0.170	-0.151	1								
Sand (%)	-0.236	-0.259	0.350	1							
Silt (%)	0.342	0.281	0.125	0.520	1						
Clay (%)	-0.092	-0.039	-0.248	-0.839	-0.882	1					
Exchangeable Acids	0.204	0.179	-0.671	-0.319	-0.188	0.28	1				
Exchangeable Bases	0.217	0.209	0.715	-0.034	0.123	-0.049	-0.394	1			
Potassium	0.508	0.508	0.235	0.104	0.420	-0.307	-0.093	0.305	1		
Phosphorous	0.534	0.552	0.236	0.333	0.514	-0.475	-0.091	0.308	0.663	1	
Boron	0.537	0.586	0.528	0.008	0.200	-0.115	-0.186	0.645	0.534	0.589	1

MAPS

Topsoil

	Organic Carbon	Total Nitrogen	pH	Sand (%)	Silt (%)	Clay (%)	Cation Exchange Capacity	Exchangeable Acids	Exchange-able Bases	Exchangeable Potassium	Phospho-rous
Organic Carbon	1										
Total Nitrogen	0.963	1									
pH	0.118	0.061	1								
Sand (%)	-0.757	-0.749	0.098	1							
Silt (%)	-0.311	-0.295	0.221	0.617	1						
Clay (%)	0.682	0.671	-0.118	-0.936	-0.807	1					
Cation Exchange Capacity	0.863	0.854	0.238	-0.613	-0.179	0.528	1				
Exchangeable Acids	0.023	0.092	-0.291	0.097	-0.044	-0.055	0.050	1			
Exchangeable Bases	0.867	0.848	0.350	-0.607	-0.139	0.512	0.984	-0.025	1		
Exchangeable Potassium	0.833	0.880	0.190	-0.634	-0.241	0.568	0.908	0.099	0.896	1	
Phosphorous	0.203	0.221	0.489	0.172	0.439	-0.246	0.416	0.152	0.451	0.402	1
Boron	0.540	0.528	0.560	-0.342	-0.004	0.282	0.493	-0.037	0.584	0.546	0.504

Source: Authors' calculations.

Annex 4

Cost Estimates for Key Equipment and Processes

Equipment/Process	Unit	Unit Cost (US$)	Quantity Needed
Field Sampling Equipment			
Buckets	Piece	2.5	2 per enumerator
Sample bags	Piece	0.2	4 per field selected [a]
Barcodes	Roll of 1,000	75	2-3 barcodes per soil sample
Augers	Piece	300	1-2 per enumerator [b]
Spades	Piece	10	1 per enumerator
Handheld GPS Device	Piece	100-300	1 per enumerator
Soil Analysis			
Spectral Analysis	Per sample	3	1 per soil sample collected
Reference Analysis (wet chemistry, carbon and nitrogen test, etc.)	Per sample	75 - 135	10-25% of total sample
Expert Trainer	4 days + expenses	3,000	1
Other Considerations	*Cost estimate depends on study design, quantity of samples collected, and location of labs with respect to study area.*		
Shipment of Soils			
Fuel [c]			
Soil Processing (drying, sieving, weighing)			

Notes:

[a] Assuming one topsoil sample and one subsoil sample per agricultural field.

[b] One auger per enumerator is sufficient unless they are covering very diverse soil types, in which case they may require one for built for sandy soils and one built for clay.

[c] Soils must be delivered to processing labs for drying within 5-10 days of collection. This will add mileage to typical household survey estimates.

Annex 5

Glossary

Agroecological zone	Geographic area categorized by similar climactic conditions, such as elevation, temperature, and rainfall.
Bulk density	A measure of soil compaction; the weight of soil in a given volume.
Field	A piece of land in a parcel separated from the rest of the parcel by easily recognizable demarcation lines, such as paths, cadastral boundaries, and/or hedges. A field may consist of one or more plots. Definition according to FAO (2005).
Parcel	Any piece of land, of one land tenure type, entirely surrounded by other land, water, road, forest, or other features not forming part of the holding, or forming part of the holding under a different land tenure type. A parcel may consist of one or more fields or plots adjacent to each other. Definition according to FAO (2005).
Plot	A part or whole of a field on which a specific crop or crop mixture is cultivated. Definition according to FAO (2005).
Waypoint	Also referred to as a geographic coordinate. Waypoints, or coordinates, identify the position of a single point in terms of a designated coordinate system.

SELECT LSMS GUIDEBOOKS

The Use of Non-Standard Units for the Collection of Food Quantity
Gbemisola Oseni, Josefine Durazo, and Kevin McGee
July 2017

Measuring the Role of Livestock in the Household Economy
Alberto Zezza, Ugo Pica-Ciamarra, Harriet K. Mugera, Titus Mwisomba, and Patrick Okell
November 2016

Land Area Measurement in Household Surveys
Gero Carletto, Sydney Gourlay, Siobhan Murray, and Alberto Zezza
August 2016

Measuring Asset Ownership from a Gender Perspective
Talip Kilic and Heather Moylan
April 2016

Measuring Conflict Exposure in Micro-Level Surveys
Tilman Brück, Patricia Justino, Philip Verwimp, and Andrew Tedesco
August 2013

Improving the Measurement and Policy Relevance of Migration Information in Multi-topic Household Surveys
Alan de Brauw and Calogero Carletto
May 2012

Design and Implementation of Fishery Modules in Integrated Household Surveys in Developing Countries
Christophe Béné, Asafu D.G. Chijere, Edward H. Allison, Katherine Snyder, and Charles Crissman
May 2012

Agricultural Household Adaptation to Climate Change: Land Management & Investment
Nancy McCarthy
December 2011

Agricultural Household Adaptation to Climate Change: Water Stress & Variability
Sushenjit Bandyopadhyay, Limin Wang, and Marcus Wijnen
August 2011

Comparative Assessment of Computer-Assisted Personal Interview (CAPI) Software Packages
Arthur Shaw, Lena Nguyen, Ulrike Nischan, and Herschel Sy
July 2011

Tracking in Longitudinal Household Surveys
Firman Witoelar
July 2011

Surveying Justice: A Practical Guide to Household Surveys
Kristen Himelein, Nicholas Menzies, and Michael Woolcock
January 2010

Living Standards Measurement Study
www.worldbank.org/lsms
data.worldbank.org