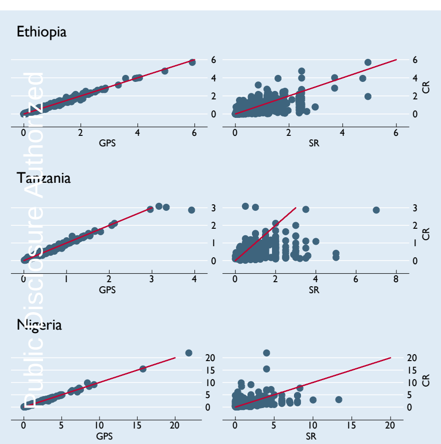

Note: Red line is line of equality between measurements

LSMS GUIDEBOOK
August 2016

Land Area Measurement in Household Surveys

Empirical Evidence & Practical Guidance For Effective Data Collection

Gero Carletto, Sydney Gourlay, Siobhan Murray, and Alberto Zezza

LSMS Living Standards Measurement Study

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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.

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TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

AgSS	Agricultural Sample Survey (Ethiopia)
CAPI	Computer Assisted Personal Interviewing
CR	Compass and rope area measurement, also referred to as traversing
EA	Enumeration area
EGNOS	European Geostationary Navigation Overlay Service
FAO	Food and Agriculture Organization of the United Nations
GHS	General Household Survey (Nigeria)
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Ha	Hectare
ICRAF	World Agroforestry Centre
LASER	Land and Soil Experimental Research study, Ethiopia
LSMS	Living Standards Measurement Study
LSMS-ISA	Living Standards Measurement Study – Integrated Surveys on Agriculture
MANR	Ministry of Agriculture and Natural Resources, Zanzibar, Tanzania
MCP	Measuring Cassava Productivity study, Zanzibar, Tanzania
NASA	National Aeronautics and Space Administration (United States)
OLS	Ordinary Least Squares
SR	Self-reported, also referred to as farmer-reported
UN	United Nations
VHR	Very High Resolution
WAAS	Wide Area Augmentation System

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EXECUTIVE SUMMARY

This Guidebook is intended to be a reference for survey practitioners looking for guidance on measuring land area in household surveys. The menu of available methods for measuring land area is diverse and selection of the appropriate method depends on several factors. In this Guidebook, we focus on those methods that are relevant for agricultural sample surveys, agricultural censuses, multi-topic surveys that cover agriculture (such as most Living Standard Measurement Study (LSMS) surveys), and other smaller-scale household surveys carried out for research purposes and project monitoring and evaluation.

Land area measurement is the cornerstone of agricultural statistics and analysis in both developed and developing countries alike. Along with family labor, land is arguably the most important productive asset for rural households across developing regions, and lack of access to land is often the key constraint preventing rural households from emerging from poverty.

For the same reason land is often used as a measure of wealth. Furthermore, disaggregated land ownership data are an input into analyses of agrarian structures, and yields (expressed as output over unit of cultivated land) are a favorite partial productivity measure of the performance of agricultural sectors. Several aspects of the analysis of gender differences in agriculture and the rural sector are also based on land area; two of the most pressing concerns when devising policies to address gender disparities in rural areas pertain to the lower agricultural productivity of women compared to men and, related to that, to the disparity in their asset base.

Practical guidance on land area measurement methods for household surveys

Three main methods are used in the context of agricultural statistics data collection for the measurement of land area: 1) compass and rope (also known as compass and tape or traversing), traditionally held as the 'gold standard', 2) self-reported land area, and 3) GPS-based measurement. The Guidebook provides practical guidance on how to implement these three methods, and discusses the main advantages and disadvantages of each method with particular reference to their application in large-scale national household and agricultural surveys. In doing so, the Guidebook focuses on the accuracy of each method, but also on their demands in terms of human, financial and time resources for survey practitioners.

Self-reporting by the respondent is by far the most common means of collecting land area data in household surveys. The method is inexpensive, quick, and does not require any particular equipment. However, concerns exist regarding the method's precision and accuracy, as well as the likelihood that the resulting data include systematic biases. One crucial aspect in designing the collection of self-reported land data is the handling of measurement units. This report recommends allowing the respondent to report the units they are more comfortable with and planning ahead for the collection and use of appropriate conversion factors.

Measuring land area with portable GPS devices has become increasingly popular among survey practitioners around the world. The method is relatively cheap, accurate and precise if careful measuring protocols are devised and implemented. The two main concerns with this method relate to the measurement of plots that cannot be visited by survey staff (resulting in missing data), and the accuracy of the measurement on very small plots.

The compass and rope method, or traversing, is considered the 'gold standard' of land area measurement. However, the method is more cumbersome and time consuming than self-reporting and GPS, which makes it impractical for use in large-scale household surveys. Given its accuracy (even on the smallest plots), it remains the approach of choice for specific types of data collection. However, for optimal results, this method must be implemented by experienced staff.

Despite the potential benefits of using remote sensing imagery for plot area measurement in household surveys, limitations in image resolution and availability, as well as practical implementation challenges, have inhibited the widespread use of this method in the developing country context to date. We highlight the potential for techniques based on remote sensing imagery to become more widely adopted in the future as the availability and resolution of the imagery improves, implementation costs go down, and technology advances.

What is the evidence on the relative performance of the main land area measurement methods?

In order to inform the choice of measurement methods and to understand how to best implement them under real survey field conditions, the Living Standards Measurement Study (LSMS) program of the World Bank has been conducting an ambitious program of methodological validation based on experiments in which the different methods are used on a large sample of plots and the results compared, using the compass and rope method as the benchmark. The Guidebook draws on the three experiments implemented to date in Tanzania (Zanzibar), Ethiopia and Nigeria. Data from national-level surveys implemented since 2009 in six African countries complement the evidence. Some very consistent, robust conclusions emerge from this work.

First, self-reported estimates of land area are subject to very large biases and systematic measurement errors. The observed differences between self-reported estimation and the objective measures (the compass and rope benchmark and the GPS) is very large and systematic in all the experiments as well as in national-level surveys. The mean self-reported and compass and rope measurements differ by as much as 143 percent on average (Tanzania). The mean difference is smaller in Ethiopia and Nigeria, at 23 and 5 percent respectively, but still considerably larger than the divergence observed between the objective measurements.

In each of the methodological studies, the area of the smaller plots provided by farmers is severely overestimated. The degree of overestimation falls with plot size and is eventually reversed with farmers on average underestimating the area of the larger plots. This, rather than greater accuracy, is what drives lower mean error in some studies. The result is also in line with evidence from national surveys where self-reported and GPS measures can be compared. This is a matter of concern when applied to the analysis of yields, as using self-reported measures will result in large systematic biases, leading to larger (smaller) plots appearing more (less) productive than they actually are.

Second, the GPS measure appears to be very accurate, and a valid alternative to compass and rope given the lower implementation costs. The mean difference between compass and rope and GPS measurement is very small, whether expressed in acres or as a percentage of the compass and rope acreage. The sample mean bias in the three experiments is +/- 0.01 acre, which translates in a 1-3 percent difference when expressed in relative terms (note that the values are not expressed in absolute value and as such negative and positive differences offset each other on average). The data do not exhibit any clear trends in terms of GPS underestimating plot size compared to compass and rope, neither on average nor across the distribution of plot sizes.

However, individual GPS measurements may carry larger errors, of which survey practitioners should be mindful. In small groups of data, GPS measures are on average very accurate. This may sometimes hide the presence of large negative and positive errors cancelling each other out, particularly when very small plots are surveyed. In the LSMS experiments, the number of observations with errors larger than +/- 10 percent is far from negligible, ranging from 17 percent in Nigeria to 31 percent in Ethiopia (where the share of very small plots is the highest).

Third, the compass and rope method is much more cumbersome than GPS: on average, a plot that will take fifteen minutes to measure with GPS will take an hour with the compass and rope method. While still considered the 'gold standard', the compass and rope method can also lead to measurement error generation processes not dissimilar from those associated with handheld GPS units. The Guidebook provides convincing evidence that, particularly when plots shapes are complex, enumerators will tend to cut corners and simplify shapes, adding noise to the land area measure in the process.

All in all, GPS emerges as clearly superior to the other methods evaluated in the Guidebook for most practical survey purposes. Despite the evidence that subjective measurements can be riddled with problems, farmer self-reported estimates of area should still be included in household surveys, but not as the primary measurement method. Objective measurements come with their own challenges, including time and equipment requirements, questions of accuracy at small-plot levels, and feasibility of full plot sample measurement. Subjective measurements have negligible fieldwork costs, and, more importantly, they can serve as a baseline for imputation where objective measurements may be missing. Therefore, the Guidebook recommends GPS measurement complemented by farmer self-reported estimated area (for all plots).

KEY GUIDEBOOK HIGHLIGHTS AND RECOMMENDATIONS

- The selection of land area measurement method has important implications for data quality in surveys.
- Regardless of the method of choice, it is important to carefully design and implement survey questionnaires and field protocols.
- Respondents' estimates of land area are subject to large, systematic bias.
- The area of the smaller plots tends to be overestimated by respondents, while the area of large plots is usually underestimated.
- The difference between self-reported and objective measures of land area is on average 51 percent in a sample of over 4,000 plots from three African countries.
- Using properly implemented objective measurement methods can minimize measurement error, and reduce or eliminate bias.
- GPS and compass and rope area measurements differ by only 1 percent on average.
- Compass and rope measurement, considered the 'gold standard', requires as much as 4 times the amount of time as GPS measurement.
- Irregularly shaped plots pose additional challenges to the accurate measurement with the compass and rope method.
- Setting a threshold of 3 percent or less for closing error is a good rule of thumb to ensure accuracy in compass and rope measurements.
- GPS measures can be plagued by high percentage measurement error on the smallest plots. This error is however not systematic and uncorrelated with other variable of interest.
- Objective measurements are almost always subject to some degree of missingness. It is therefore good practice to collect farmer-estimates of area for all plots in addition to the objective measurement.
- Area measurement via remote sensing imagery does not to date provide a viable option for land area measurement in surveys of small plots in low income settings, but it might become one as technology improves.
- The report recommends always collecting GPS data complemented by farmers' self reports, on all plots.

Part I

Background and Definitions

Accurately measuring land area is a primary objective of any agricultural statistical system. This Guidebook offers practical guidance for survey practitioners on what to consider in evaluating competing methods for measuring land area, how to approach the design of the survey, and how to manage the fieldwork, data collection, and processing stages. The recommendations are based on an extensive review of the literature, evidence stemming from thirty years of LSMS experience, and new, purposely-designed methodological validation work on land area measurement.

1. INTRODUCTION

Land area measurement has been of concern to humanity since the dawn of time. Some of the buildings constructed in Ancient Egypt as early as 2700 BC testify to the knowledge of land surveying techniques. Evidence of boundary surveying in Mesopotamia and the Nile valley from around 1400 BC have also been found (Lyman and Wright, 2015). The word 'geometry' originated in ancient Greece from the Greek words for 'measure' and 'Earth'. Similarly, ancient traces of the command of surveying techniques have been found in China (Swetz, 1992) and India (Joseph, 1997). The need to measure land originated from concerns as diverse as the construction of buildings, tax collection, and the need to demarcate properties and boundaries. Those concerns are still valid today, and many of the basic principles and techniques have remained remarkably similar over the millennia, even though technology has certainly advanced and allows for measurements that are both easier and more accurate than in the past.

Land area measurement is the cornerstone of agricultural statistics, economics, and policy analysis in developed and developing countries alike. With over 70 percent of the developing world's poor residing in rural areas where agriculture is the primary means of livelihood (IFAD, 2010), high quality agricultural data and analysis are paramount to informing policies aimed at poverty reduction. Along with family labor, land is arguably the most important productive asset for rural households across developing regions, and lack of access to land is often the key constraint preventing rural households from emerging from poverty (Deininger, 2003; Binswanger et al., 1995).

The Global Strategy to Improve Agricultural and Rural Statistics (World Bank, 2011), a major international initiative on agricultural statistics, identifies a core set of indicators for national agricultural statistical systems to prioritize. Many of these indicators concern measuring land area or have land area as one of their elements, such as area harvested and planted, land cover and use, and yields (where area is the denominator). Additional variables in the core set may also rely on land area measures, such as indicators related to irrigation and soil degradation.

Area measurement holds significant value in the developed country context as well. In Europe, national authorities conduct a regular Farm Structure Survey employing a common methodology devised by Eurostat (Istat, 2007). The EU FIELDFACT Project[1] is one of many schemes that aim to raise farmer awareness about the use of GPS in land area measurement for the purposes of precision agriculture and more accurate and transparent subsidy claims through the EU's Common Agricultural Policy. Frequent land area measurement is encouraged by several high-income country governments (for example, USA, UK, Germany, Australia) at the individual farmer level in promotion of precision agriculture, whereby the production process is tailored to farmland size estimates obtained via GPS/GNSS and remote sensing. By knowing exact area measurements, farmers are able to adjust input use accordingly and thus optimize

[1] http://www.gsa.europa.eu/introduction-and-promotion-gnss-agriculture

yields while reducing costs. Effective land area measurement also contributes to a more focused application of fertilizers and pesticides which could in turn alleviate environmental degradation and pollution.

The menu of available methods for measuring land area is diverse and selection of the appropriate method depends on several factors. In this Guidebook, we focus on those methods that hold relevance for agricultural and household surveys.[2] Readers interested in a broader approach to the measurement of agricultural land are referred to FAO (1982) and Sud et al. (2016). This is an important distinction, as several measures of agricultural land that are important for agricultural statistics can be collected separately from information about the holding or the household (for example, when the goal is to estimate crop land or area under specific crops at the national or other administrative level). For the analysis of household level processes and outcomes, on the other hand, it is vital that the land area being measured can be reliably linked to other variables concerning agricultural production, welfare outcomes, or other variables of interest for the same household or holding.[3]

The main types of surveys for which these measurements are relevant are agricultural sample surveys, agricultural censuses, multi-topic surveys that cover agriculture (such as most Living Standards Measurement Study (LSMS) surveys), and other smaller-scale household surveys carried out for research purposes and project monitoring and evaluation. Achieving accurate area measures in a household survey setting is a challenging endeavor. Surveys are inevitably implemented with finite financial resources and a strict timeline, which requires balancing numerous considerations when designing the survey and selecting the appropriate method. Features such as the logistics of transportation to plots, the length of the questionnaire, respondent and enumerator fatigue, and the security of teams and equipment all enter the equation to determine an optimal survey design and choice of method.

This Guidebook aims to inform the selection of land measurement methods based on:

- a review of the evidence provided in the available literature;
- the experience and data accumulated in the last decade on employing GPS as a land measurement tool alongside farmers' self-reports;
- analysis of new evidence drawn from primary data collected specifically for this purpose by the World Bank's Living Standards Measurement Study (LSMS) team in Ethiopia, Tanzania, and Nigeria.

The Guidebook strives to serve as a practical tool for those implementing household surveys and to provide recommendations for best practices in area measurement with consideration for specific plot characteristics and country contexts. We focus on challenges involved in surveys implemented under conditions typically found in low-income countries, but practices used in higher-income countries are also incorporated where relevant.

Furthermore, while the focus of the report is on rural areas and agricultural settings, the accurate measurement of land area is becoming an increasingly important issues for surveys implemented in urban areas as well. Targets and indicators on secure land tenure rights disaggregated by urban and rural areas are currently under consideration in the framework of the Sustainable Development Indicators 2030 Agenda. Most of the lesson for data collection included in this report apply equally to survey operations in urban areas.

After a review of the uses of land area measurement from household surveys, and a discussion of basic concepts and definitions (Part I), the remainder of the document illustrates the various methods available for land area measurement, as well as their limitations and advantages, providing practical guidance for survey practitioners on what to consider in evaluating competing methods, how to approach the design of the survey, and how to manage the fieldwork, data collection, and processing stages (Part II). Part III presents an assessment of the comparative performance of the main competing methods, based on data collected by the LSMS team, assessing the main attributes of each measurement in terms of accuracy, cost, time, feasibility under 'real-life' survey conditions, and sensitivity to problems in survey implementation. A summary of main messages is provided in the concluding chapter, which also highlights areas where further validation work is needed.

2. USES OF LAND AREA MEASURES FROM HOUSEHOLD SURVEYS

Land area measurement underpins virtually every domain of agricultural economics and policy analysis. Analyses of wealth and inequality, agrarian structures, agricultural yields and

[2] The focus is also on low income countries with little or no cadastral or administrative information to integrate this type of data collection.

[3] Similarly, for plot level productivity analysis it is essential that input and output data can be combined at the plot level.

productivity, natural resource management, and gender differentials in agriculture all depend on accurate measures of land area.

The uses of land area in the analysis of agricultural issues are too numerous to list. As previously mentioned, the focus of this Guidebook is on area measures not geared only towards yielding point estimates for selected indicators at some level of geographic aggregation, but specifically on data that can be used to understand the differences across holdings or households. Bivariate (e.g. cross-tabulation) or multivariate (e.g. regression) analyses of household- or farm-level outcomes require the ability to link different pieces of information to the basic enumeration unit (generally the household or the farm), either by collecting them together in a survey or by devising a system to match them after the completion of data collection. The advantage of having data integrated in this manner is that it allows for comparisons across households and farms, and, in general, analysis of the heterogeneity and variability between households or producers.

In rural areas, land is often the most important productive asset, and for that reason it is often used as a measure of wealth. Households may be ranked in groups according to the amount of land owned, either in classes according to amount of land owned, or in specific percentiles of land ownership. This is often done in the analyses of rural livelihoods, particularly those based on the sustainable livelihoods approach and the importance of different types of capital. An example based on a small scale survey in Uganda is provided in Table 1, reproduced from Ellis and Bahiigwa (2003). In a cross-country study of rural poverty, Valdes et al. (2010) use land ownership as one of four asset categories (the others being education, infrastructure and livestock) to create a typology of rural households. Following the work of Filmer and Pritchett (2001), numerous researchers have used principal component or factor analysis to generate wealth indices based on combinations of assets, of which land ownership is usually a key component.

Furthermore, disaggregated land ownership data are an input into analyses of agrarian structures and how these evolve with economic and demographic change, as well as the related analyses of land inequality and how it relates to trends of income inequality. Notable examples are the work of Deininger and Squire (1998) and Deininger and Olinto (1996) on the relationship between asset distribution and income inequality, as well as the related work of Michael Carter on agrarian structures and inequality (Carter, 2000).

Unequal distribution of land has been linked to less pro-poor growth, participation in and occurrence of civil strife, and

Table 1 — Use of Land Ownership Classes for Ranking Households, Uganda

Area owned	District			Total n = 315 (%)
	Mbale n= 105 (%)	Kamuli n = 105 (%)	Mubende n = 105 (%)	
<0.5 ha	34.3	67.6	21.9	41.3
0.5-1 ha	26.7	11.4	14.3	17.5
1-2 ha	16.2	11.4	26.7	18.1
2-3 ha	6.7	2.9	14.3	7.9
3-4 ha	4.8	1.0	9.5	5.1
>4 ha	11.4	5.7	13.3	10.2
Total	100.0	100.0	100.0	100.0

Source: Ellis and Bahiigwa (2003).

delayed long-run human capital development (Deininger and Squire, 1998; Macours 2011; André and Platteau, 1998; Baten and Juif, 2014). Carletto et al. (2015) find that the area measurement methodology used in calculating the Gini coefficient has consequences on the level of inequality observed, with self-reported area estimates resulting in underestimated land inequality. Failure to adequately measure land limits the ability to analyze the agricultural economy and its impact on land inequality.

Farm-level land area data is the staple of analyses looking at the long-term changes in agrarian structures, be these national or international comparisons (e.g. Eastwood et al., 2010; see Table 2), studies into the future of small holder farmers and their role in poverty reduction (e.g. Collier and Dercon, 2009; Wiggings et al., 2010; Nagayets, 2005), or studies in agricultural transformation following major reforms (such as those in formerly centrally-planned countries transitioning to a market economy (Spoor, 2012) or in rural China since the introduction of the Household Responsibility System in 1978 (Huang et al., 2012).

Often, studies of structural transformation are motivated by the ultimate objective of understanding differences in productivity over time or space, or across farm types. Yields (expressed as output over unit of cultivated land) are one of the core Global Strategy indicators and a favorite measure of performance for descriptive reports on the agricultural sectors. An extensive strand of literature has investigated the relationship between farm size and productivity, with one issue of contention being precisely the extent to which land measurement error might bias results in favor of an inverse relationship between the two

(Binswanger et al., 1995; Barrett, 1996; Lamb, 2003; Carletto et al., 2013).

Yield estimates are crucially dependent on land area, which appears on the denominator, but land area also enters efficiency analyses whether performed via stochastic frontier analysis (e.g. Ali and Flinn, 1989; Kumbhakar, 1994), or Data Envelopment Analysis (e.g. Lovo, 2011; Shafiq and Rehman, 2000). These measures are important not only for broad policy analysis, but can also have direct relevance to programming, as they are the outcome measures of choice when evaluating interventions whose stated objective is enhancing the efficiency or productivity of agricultural producers.

Existing literature suggests that the method of measuring agricultural land area can result in different productivity estimates as well as interfere with our understanding of agricultural relationships. For example, Carletto et al. (2013) analyze the relationship between land size and agricultural productivity with both farmer self-reported estimates and GPS measurements of land area, showing how relying on GPS area estimates results in a significantly stronger inverse productivity relationship. In a similar cross-country study, however, Carletto et al. (2015) find conflicting results, with three of four countries exhibiting a weaker (although still present) inverse productivity relationship when using GPS land area measures. The inconsistency in results adds further doubt to the use of subjective farmer

Table 2 — Use of Land Area Data to Analyze Global Farm Size and Distribution Measures

Continent		Mean	Gini	% Permanent pasture	% Holdings < 2 ha	% Area < 2 ha
Sub-Saharan Africa	Mean	2.4	0.5	9.0	69.2	32.0
	N	15.0	11.0	1.0	12.0	8.0
	SD	1.4	0.1	-	23.1	27.7
Central America and the Caribbean	Mean	10.7	0.8	38.0	62.8	12.4
	N	11.0	10.0	9.0	9.0	9.0
	SD	10.2	0.1	27.9	27.0	11.0
South America	Mean	111.6	0.9	74.6	35.7	0.9
	N	10.0	10.0	8.0	4.0	3.0
	SD	149.5	0.1	14.5	17.3	1.0
South Asia	Mean	1.4	0.5		77.8	40.1
	N	4.0	4.0		3.0	3.0
	SD	1.2	1.1		19.1	26.9
East Asia	Mean	1.0	0.5		92.2	59.2
	N	3.0	2.0		3.0	3.0
	SD	0.3	0.2		3.7	11.9
Southeast Asia	Mean	1.8	0.6	1.4	57.1	23.6
	N	6.0	6.0	3.0	4.0	4.0
	SD	1.0	0.1	0.3	16.8	14.5
West Asia and North Africa	Mean	4.9	0.7	7.1	65.0	24.7
	N	11.0	10.0	5.0	9.0	8.0
	SD	4.6	0.1	7.1	27.3	23.3
Europe	Mean	32.3	0.6	35.9	29.9	3.8
	N	21.0	20.0	18.0	18.0	17.0
	SD	25.7	0.2	21.2	24.6	4.9
Canada		273.4		96.1	6.8	
United States		178.4	0.8	47.9	4.2	0.0
Australia		3601.7	--	96.1	--	--
New Zealand		222.6			6.8	

Source: Reproduced from Eastwood et al. (2010).

self-reported areas as the impact on agricultural analysis of using such estimates is potentially biased and ambiguous. Dillon et al. (2016) confirm the finding of earlier studies on the biased estimates of the inverse farm size productivity relationship with self-reported data and extend the analysis to demonstrate the presence of similar biases in input demand functions (fertilizers, household labor).

Several aspects of the analysis of gender differences are also based on measurements of land. Two of the most pressing concerns when devising policies to address gender disparities in rural areas pertain to the lower agricultural productivity of women relative to men and, related to that, to the disparity in their asset base. Recent research based on LSMS data demonstrates that when accounting for differences in cultivated area and geography, the measured gaps in productivity between male and female farmers become much larger (World Bank and ONE, 2014).

Reliable land area measurement is also key for analyses related to natural resource use in agriculture. Simple descriptive analyses of the extent and distribution across farmers of a range of issues, from soil degradation to irrigation to the adoption of improved varieties, require a measure of the land area associated with these phenomena. In order to move from counting the number of farms to measuring the incidence of soil erosion among a given population in terms of share of acreage, for instance, collecting information on exactly which plots are affected and their specific areas will be an obvious first step.

More broadly, investigations of issues related to agricultural intensification (Boserup, 1965) hinge on being able to relate measures of land scarcity to farmers' choices, constraints and incentives. While these analyses are often undertaken at farming system level (Lele and Stone, 1989), analyses based on a finer degree of disaggregation – with farms as the unit of analysis – are increasingly common as researchers strive to explain farmers' responses (or lack thereof) to policies and programs aiming at promoting certain agricultural technologies such as mechanization (Binswanger and Pingali, 1988; Binswanger and Savastano, 2014; Jayne et al., 2014).

In summary, land area measurement underpins virtually every aspect of agricultural economic and policy analysis, from simple descriptions of basic characteristics of agricultural holdings, to more sophisticated analyses of the determinants of agricultural productivity, to long-term reflections into the future of agricultural sustainability and the evolution of agrarian structures.

3. CONCEPTS AND DEFINITIONS[4]

Holding, parcel, field and plot are concepts with internationally accepted statistical definitions. Land area measurement can take place at any of these levels. The objectives of the survey and the trade-offs associated with measuring land at the different levels should be paramount in informing this decision. For most practical purposes, measurement should take place at the parcel or plot level.

Any measurement effort must start with a clear definition of what is being measured. Before turning to methods, therefore, this section briefly reviews concepts and definitions that are relevant when designing a survey involving the measurement of agricultural land area.

In agricultural surveys and censuses the primary statistical unit is the agricultural holding, whereas in population-based 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 labour, farm buildings, machinery or draught animals."

According to the 'housekeeping-concept' adopted by the United Nations (UN, 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

[4] This section draws heavily on FAO (2005)

> 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 and Glewwe, 2000; Beaman and Dillon, 2012; Randall and Coast, 2015).

In agricultural surveys, the holdings may pertain to the household sector or to the non-household sector (e.g. corporate farms). 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 will have land, most normally will. 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 fields 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 boundaries 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 it is important that survey designers 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 National Bureau of Statistics to enumerators in the implementation of its National Panel Survey. The definition of the measurement level must be explicitly stated prior to commencement of the survey, as local definitions may vary across countries.

To illustrate how the nesting of holding, parcel, field and plot levels is implemented in practice, Table 3 offers examples based on six of the countries participating in the Living Standards Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA) program. The first three rows in the table identify the different levels at which the surveys collect information, and the following rows identify the information that is collected at each level. As can be clearly seen, approaches vary across countries. Some countries use three different hierarchical levels to collect data, others use two, and others collect all data at the most disaggregated level (the plot). In the surveys listed in the table, acreage is collected at three different levels: parcels, fields, or plots.

In deciding the level at which to conduct area measurement, survey designers should consider the objectives of the survey and the type of analytical uses that are envisaged for the data. Measuring the parcel has the advantage of focusing measurement operations on the portion of land that is more clearly defined. It may, therefore, pose fewer issues in terms of identification of what is to be measured. Also, the parcel is bound to remain more stable over time than plots or fields, which might facilitate comparisons in longitudinal surveys – or even make the measurement unnecessary if an accurate measurement is available from the initial survey round, and the parcels can be clearly identified and matched across rounds. Plots, on the other hand, vary frequently and it is not uncommon for them to vary within a survey year in countries with more than one agricultural season.

Productivity analysis and the computation of yields are, however, often of paramount importance to surveys covering

Table 3 — Holding Subdivisions and Levels of Data Collection in LSMS-ISA Surveys

		Ethiopia 2011/12 Post-planting	Malawi 2013	Niger 2010/11 Post-planting	Nigeria 2012/13 Post-planting	Tanzania 2014/15	Uganda 2011/12
Holding subdivision	Largest unit	Holder	Garden (munda)	Field (champ)	Plot	Plot	Parcel
	Sub-unit 1	Parcel	Plot	Plot (parcelle)	--	--	Plot
	Sub-unit 2	Field	--	--	--	--	--
Levels at which data collection takes place, by land attribute	Acreage	Field (GPS and self-reported)	Garden (GPS and self-reported); Plot (GPS and self-reported) and, separately, crop (self-reported)	Plot, and separately, crop	Plot (GPS and self-reported) and, separately, crop (self-reported)	Plot (GPS and self-reported);	Parcel (GPS and self-reported) and separately, plot (area planted) (self-reported);
						Crop as fraction of plot	Crop as fraction of plot if intercropped
	Acquisition method	Parcel	Plot	Plot	Plot	Plot	Parcel
	Tenure status	Parcel	Plot	Plot	Plot	Plot	Parcel
	Current use	Field	Plot	Plot	Plot	Plot	Parcel
	Crops cultivated	Field	Plot	Plot	Plot	Plot	Plot

Source: World Bank, LSMS Team.

agriculture. For productivity analysis, the measurement is more appropriately run at the plot level, as the denominator in the computation of the yield of a crop needs to be the portion of a parcel actually cultivated with that crop, not the overall surface of the parcel. In many countries, the two are very likely to differ. Similarly, surveys aimed at analyzing gender dimensions of agricultural productivity would benefit greatly from plot-level measurements.

The decision of what to measure bears important consequences for both fieldwork organization and the analysis of data. Measuring the plots implies taking a larger number of measurements than if parcels are measured, and on tracts of land with more uncertain boundaries. On the other hand, if one goal of the analysis is to compute the area cultivated or yields associated with different crops, measuring parcels will require collecting auxiliary information (which are bound to be very inaccurate) on the portion of the parcel cultivated to each plot.

The decision to measure parcels, plots, or fields cannot be made in a blanket recommendation; the balance of trade-offs between each approach will depend on the survey objectives.[5] Differences in approaches, such as those observed in Table 3, may be related to the fact that countries tend to stick to one approach over time (often for the sake of preserving inter-temporal comparability), but may also stem from broader differences in survey design across countries. For example, some countries visit households only once and collect data on all agricultural seasons, while other countries use multiple visits.

One proposal for structuring the data collection on land area and its uses is to introduce a parcel roster to collect data on the characteristics of land area that do not change with the season (and can therefore be collected only in one visit), and a plot roster to be filled in separately for each agricultural season, to capture the land features (such as plot area) that may vary with the season.[6] This approach can help respond to the analytical needs of those interested in understanding land use and productivity at the plot level. While this is not the only way to address this concern, it is desirable that data are collected so that it is possible to identify plots across agricultural seasons, irrespective of whether the data are collected in one or multiple visits.

[5] In much of what follows we will for simplicity refer to the measurement of plots, but the discussion applies equally to the measurement of fields and parcels.

[6] Sara Savastano and Hans Binswanger-Mhkize, personal communication, 2014.

Part II

Methods for Land Area Measurement in Surveys

Three main methods are used in the context of agricultural data collection for the measurement of land area: 1) compass and rope (also known as compass and tape, or traversing), traditionally held as the 'gold standard', 2) respondent self-reported land area, and 3) GPS-based measurement. The use of satellite or remote sensing imagery as a tool for land area measurement is another option, although less widespread, especially in the developing country context.

Each area measurement option has unique costs and benefits that need to be carefully assessed in view of the scale of the data collection of which they are a part, the intended use of the data, and the characteristics of both the plots to be measured and the respondents to the survey. Different methods also present different challenges in terms of their implementation: a potentially accurate method can become highly inaccurate if poorly implemented in the field, or it may simply not be feasible on a larger scale. The specific limitations, challenges, and benefits of each of the abovementioned measurement methods are addressed in detail below, in addition to practical considerations for implementation.

This paper does not discuss rapid approximation approaches to area measurement, which have traditionally been popular, but the use of which is in decline with the introduction of GPS devices, such as rectangulation, triangulation, perimeter square (P2/A), or pacing. A discussion of these methods can be found in FAO (1982), Casley and Kumar (1998), Fermont and Benson (2011).

4. SELF-REPORTED AREA ESTIMATION

Self-reporting of land area by the respondent is by far the most common means of collecting land data in household surveys. The method is inexpensive, quick, and does not require any particular equipment. However, concerns exist regarding the method's precision and accuracy, as well as the likelihood that the resulting data include systematic biases. One crucial aspect in the design of the collection of self-reported land data is the handling of measurement units.

4.1 SELF-REPORTED AREA ESTIMATION: PRACTICAL CONSIDERATIONS

To collect farmer self-reported data on land area, surveys include a direct question to the farmer asking her to report on the area of a given plot, field or farm. Examples of such questions are provided in Figure 1. The phrasing of the question is straightforward, but attention should be given to providing space for the desired number of decimal points, and to the choice of measurement units (more on this below) and related coding. Even though self-reporting is in principle a straightforward method for collecting data on land area, there are a number of decisions that need to be made during survey design and implementation, and when documenting the data for dissemination, that can help reduce measurement error and increase the value of the data for the users.

A survey can collect measures of land area in standard units, non-standard units, or a combination of both. The country context will, to a large extent, determine the most appropriate choice. In a country where non-standard or traditional units are most appropriate, care should be exercised to ensure that high quality conversion factors exist. It is not unusual for non-standard units with the same name to correspond to different measures even within the same country: in such cases, conversion factors will need to be location-specific. If a satisfactory set of unit conversion factors is not available, they should be collected as part of the survey.[7] The Ministry of Agriculture or National Statistics Office often maintain libraries of conversion factors, even though these may not always be complete or available in electronic format. The importance of certain conversion factors cannot be overemphasized, as area data may be unusable if they cannot be converted to a common metric. When designing a panel of repeated survey rounds or when planning to compare self-reported data with other household survey data, attention should be paid to the units used in the other instruments to ensure comparability.

The decision made regarding allowable measurement units will inform the design of the relevant sections in the questionnaire. The questionnaire clips in Figure 1 are examples from LSMS-ISA surveys in Malawi, Ethiopia, and Nigeria. Note that any observations with an "other, specify" response will be very difficult to use, unless appropriate conversion factors can be recovered. The use of this category should be as limited as possible, but it can be useful during the initial phases of the fieldwork to capture key units of measurements that had not been listed in advance. To limit such occurrences, it is necessary to run careful pilots of the questionnaires, and to discuss the matter with local experts (it is unlikely that a pilot will have the required geographical coverage to capture the diversity of units that may be found in one country). Note also that when collecting both self-reported farmer estimates of area and objective measurements of area (e.g. GPS), the self-reported measurement must be assessed first so as not to be affected by the objective area estimation. Care should also be exercised in training to instruct enumerators not to amend the self-reported land area measure to match the GPS measure.

The time of the survey interview can also provide the opportunity to inquire about the existence of a land title. When available that would allow verifying the self-reported information on land area, as well as important ancillary data on tenure status. In many low income countries this will be a rare occurrence, but in those where land registration and titling is more advanced, official land records can be an extremely useful aid to survey data collection.

4.2 SELF-REPORTED AREA ESTIMATION: KEY ISSUES AND LIMITATIONS

Simply asking the farmer, "What is the area of [PARCEL/PLOT NAME]?" is certainly the quickest, most cost-effective means of assessing plot area. The added cost of including area estimations in an existing household survey is negligible, and item non-response for this variable is usually negligible in existing surveys. However, the minimal financial investment required by this method does not come without challenges, both in terms of implementation and data quality. Several factors influence the accuracy of subjective farmer self-reported estimates of area, including respondent characteristics, plot characteristics, and the land registration or titling system. The most worrying aspect of some of the measurement error associated with self-reporting is that it may be systematic, and associated with key variables of interest.

For one, the accuracy of subjective estimates may be sensitive to respondent characteristics. More educated farmers might be more numerate and more at ease at quantifying their own land area, while absentee landlords, or respondents for which farming is only a secondary activity, may be less aware of the characteristics of their plots. Using LSMS-ISA data from Uganda, Carletto et al. (2013) analyze the determinants of the difference between farmer self-reported plot area and GPS measurements. The age of the household head has a significant and positive relationship with measurement bias, which the study defines as GPS minus self-reported area.

The quality of data collected through farmer self-reporting is also significantly degraded by the natural inclination of respondents to round off numbers. Distributional analysis of GPS and self-reported areas of the 2010/2011 Malawi Integrated Household Survey shows clear evidence of heaping at whole numbers and common fractions, such as 0.5 acres (Figure 2). Carletto et al. (2013 and 2015) and Desiere and D'Haese (2015) find rounding to be a significant factor in the discrepancy between GPS area and farmer self-reported estimates.

[7] This does not necessarily imply that the conversion factors be collected in tandem with the household interviews. Conversion factors are often collected by field teams dedicated specifically to the task, and this may be timed differently from the household questionnaire administration to ease the workload for the enumerators over time.

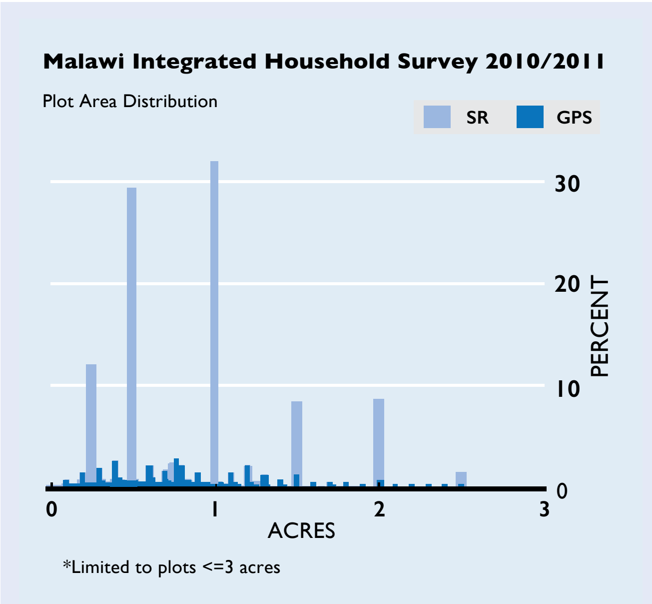
Figure 1— Examples Of Self-Reported Land Area Questions

Malawi IHPS 2013	
1. What was the area planted during the 2011/2012 rainy season?	
CODES FOR UNIT	
Acre 1	
Hectare 2	
Square Metres 3	
Other (Specify) 4	
AREA	UNIT
_ _ _ _ . _ _	_ _ _ _ . _ _
_ _ _ _ . _ _	_ _ _ _ . _ _

Ethiopia ERSS 2013/14	
ASK HOLDER: What is the area of [FIELD]?	
CODES FOR UNIT	
Hectare 1	
Square Metres 2	
Timad 3	
Boy 4	
Senga 5	
Kert 6	
Tilm 7	
AREA	UNIT
_ _ _ _ . _ _	_ _ _ _ . _ _
_ _ _ _ . _ _	_ _ _ _ . _ _

Nigeria GHS - Panel 2012/2013		
ASK HOLDER: What is the area of [PLOT]? Enumerator: Ask the farmer to estimate the area. After the interview: Measure the plot using the GPS and enter the result here. Do not omit recording zeros to the right of the decimal point.		
CODES FOR UNIT		
Heaps 1		
Ridges 2		
Stands 3		
Plots 4		
Acres 5		
Hectares 6		
Square metres 7		
AREA	UNIT	GPS MEASURED IN SQ. METRES
_ _ _ _ . _ _		_ _ _ _ . _ _
_ _ _ _ . _ _		_ _ _ _ . _ _

Figure 2 — Plot Size Distribution



Plot characteristics, such as boundary delineation and the existence of property rights, are known to significantly influence the measurement bias (Carletto et al. 2013, 2015). Plot slope or crop-type may also play a role in the ability of a farmer to estimate plot size. De Groote and Traoré (2005) assessed the accuracy of a method in which farmer self-reporting is elicited during a visit to the plot and a discussion with a trained enumerator. Comparing this method to rope and compass in southern Mali they find that, on average, plots areas were underestimated by 11 percent. The observational error was strongly related to plot size, with smaller plots being overestimated and larger plots underestimated. The observational error also varied with the crop planted, being smaller for cotton fields than for cereals. The analysis was repeated at the farm level, where the bias in estimating the total area per farm was an 8 percent underestimation.

Subjective estimates can also change significantly over time and/or based on enumerator interactions. In panel surveys, one may observe improvements in the subjective measurements over time if, for example, a GPS measurement is also conducted as part of the survey and the respondents are informed afterwards of the GPS-measured area.

Farmer self-reported area estimates can also be influenced by a variety of cultural considerations and logistics of survey implementation. Not least of the factors complicating these estimates is the prevalence of traditional or non-standard units. Respondents are often not familiar with standard measurement units such as acres, square meters, or hectares. Depending on the country context, one is more likely to encounter a variety of traditional units, and often those units vary in size by region, or even across villages or farms. In Ethiopia, for example, one of the most common non-standards units is the timad, traditionally defined as the amount of land a pair of oxen can plough in one day. This measure will vary significantly by region, even by farmer. For Eastern Ghana, Goldstein and Udry (1999) report a correlation between self-reported and GPS measured plot size of just 0.15, which they attribute to the agricultural history of the region where local field measurements are traditionally based on length rather than area, and respondents are not accustomed to converting them to two dimensional area measures.

Forcing the use of standard units is a tempting shortcut for survey designers in the presence of numerous, highly variable and site-specific traditional or non-standard units, particularly where conversion factors do not already exist or are deemed to be incomplete or unreliable. Experience shows that forcing respondents to estimate plot area in a unit unfamiliar to them is likely to result in increased measurement error, and should be avoided. The evidence from the methodological work summarized in Part III of this paper provides a strong case against forcing the use of standard units on enumerators and respondents. Survey designers should be extremely mindful of the handling of land measurement units, as in some instances these can create issues large enough to render the collected data unusable.

The existing literature confirms the presence of a systematic bias in self-reported area measures. The inclusion of both farmer self-reported estimation and GPS measurement in LSMS-ISA national panel surveys allows for analysis of the accuracy of self-reported (SR) areas, if one assumes GPS to be the more accurate of the two measurements. Carletto et al (2015), using LSMS-ISA data from Malawi (2010/11), Tanzania (2010/11), Niger (2011) and Uganda (2009/10), identify a common trend in the magnitude of measurement bias, defined as self-reported minus GPS area: the smallest of plots (less than 0.5 acres) are systematically over-reported. The degree to which these are over-reported varies, but in all countries the mean self-reported area is overestimated by at least 90 percent of the mean GPS area of plots in that particular class of plots. With increasing plot size, the degree of overestimation decreases and eventually reverses to underestimation for the largest plots. Carletto et al (2013) find the same trend holds in 2005/6 data from Uganda.

De Groote and Traore (2005) find that the same is true in Southern Mali, comparing self-reported area estimates with compass and rope measurements. Farmers (aided by expert observers in this case) are inclined to overestimate the area of plots smaller than one hectare, while increasingly underestimating large plots as plot size increases.

The absolute difference in measurement between farmer self-reported estimates and GPS measurements is large enough to translate into significant biases when the measures are employed for agricultural economics or policy analysis. Carletto et al (2015), for example, conclude that the use of self-reported estimates results in underestimated land inequality, an indicator with non-trivial outcomes, while Carletto et al (2013) show that the use of self-reported as opposed to GPS area measures affect estimates of the magnitude of the inverse relationship between farm size and productivity.

5. MEASUREMENT WITH HAND-HELD GPS DEVICES

Measuring land area with portable GPS devices is becoming increasingly popular among survey practitioners around the world. The method is relatively cheap, accurate and precise, if careful measuring protocols are devised and implemented. The main concerns with the method relate to the measurement of plots that cannot be visited by survey staff (resulting in missing data), and the accuracy of the measurement on very small plots.

5.1 GPS AREA MEASUREMENT: PRACTICAL CONSIDERATIONS

Employing GPS devices for area measurement in household surveys requires attention to detail and involves incurring costs that are not relevant when only self-reported measures are collected. Potential trade-offs implied by dealing with these concerns should be evaluated with care at the survey planning stage. Once the choice is made to use GPS devices, the following aspects should be carefully considered in survey design and implementation.

Protocols for selecting plots for GPS measurement: GPS measurement requires that the enumerator first traverse and clear the plot boundary with the farmer. After clearing the boundary so that it is clearly visible and can be paced without obstruction, the enumerator then begins at a designated corner of the plot, commences the area measurement function on the GPS unit, paces the perimeter (pausing at all corners to allow for point capture) and completes the area measurement upon returning to the initial corner (instructions may vary by GPS unit). An example protocol for GPS measurement can be found in Annex 2.

The plot will often be in a different location from where the main household interview takes place. To keep implementation time and survey cost in check, rules are often formulated in advance on which plots should be measured, based mostly on distance/location. Guidelines as to which plots require GPS measurement should be decided and documented in advance of fieldwork and clearly stated in the enumerator manuals (see Box 1 for examples).

The choice of the protocol should strike the appropriate balance between not overburdening the field team while still ensuring the quality of the resulting data. On the one hand, a protocol that includes very restrictive rules on plots to be excluded may require enumerators to travel for hours just to measure one plot. On the other hand, a protocol that allows too many exceptions to GPS plot measurement will result in a large number of missing data points in the final datasets. For instance, the examples provided in Box 1 resulted in very different rates of missingness (item non-response) of the GPS measure, clearly correlated with how strict or lax the survey protocol rule was in requiring that plots be measured. In Uganda, where enumerators were allowed to forgo GPS measurement of any plot located outside the enumeration area, over 40 percent plots were not measured. In Malawi, where conditions for the enumerators to be allowed to forgo measurement were far more stringent, only 3 percent of the plots were not measured (Table 4).

Since the identification of the plot and the plot boundaries will require the presence of a household member knowledgeable of the plot, time and budget should be factored into the survey design and the planning of fieldwork to allow for travel to the plots. The measurement of the plot need not occur immediately after the administration of the questionnaire. To minimize refusals, appointments can be made to suit the respondent schedule.

Plot outlines: Most handheld GPS devices have the capacity to store not only coordinates, but also the outlines of the plot. A decision on whether to save plot outlines should be made at the survey planning stage. Storing the plot outlines

BOX 1 — EXAMPLES OF GUIDELINES FOR THE INCLUSION OF PLOTS FOR GPS MEASUREMENT IN LSMS-ISA SURVEYS

Malawi Integrated Household Panel Survey 2013, Enumerator Manual

"For a GARDEN [parcel] that lies more than **2 hours of walking distance** from the dwelling (regardless of being in a rural or urban EA), the enumerator MUST consult their supervisor concerning the decision about measuring the GARDEN. You are expected to capture as many GARDENS as possible by possibly grouping together measurements of distant gardens that are close to one another."

Tanzania National Panel Survey 2012-2013, Interviewer Manual

"All plots must be measured that are within **one hour's travel of the household (either on foot, bicycle, motorbike, etc.)**. If you think a plot is too far to measure, you must receive permission from your supervisor not to measure it."

Uganda National Panel Survey 2011-2012, Enumerator Manual

"…measurement should be conducted only on those parcels **located within the EA** [enumeration area]."

has several advantages and requires little additional effort over simply recording the area. By storing the plot outlines, one collects the raw GPS data to allow for the monitoring and analysis of enumerator walking speed, polygon closure and the complexity of plot shapes. The plot outlines can also assist in the cleaning of the plot coordinate data from the questionnaire as the raw GPS file will not have any data entry issues (as long as the track is named so that it can be associated with the corresponding plot, as detailed below). As high resolution (≤ 2 m) satellite imagery becomes increasing available and affordable, capturing the plot outlines will also allow analysts to complement the survey data with detailed geospatial data. For many GPS devices, the stored track will be exported as a gpx file, which can be opened in geospatial software. These files may also contain the elevation (if the device is equipped accordingly) and the time of collection.

Table 4 — GPS Missingness in Select LSMS-ISA Surveys

Country	Ethiopia 2011	Malawi 2013	Niger 2012	Nigeria 2013	Tanzania 2011	Uganda 2012
Measured	26,107	18,284	4,739	5,340	4,723	2,499
Missing	5,343	640	1,895	776	1,315	1,996
Total	31,450	18,924	6,634	6,116	6,038	4,495
GPS missingness rate	17%	3%	29%	13%	22%	44%

Source: LSMS-ISA data.

Naming conventions: When saving raw GPS data on the device (coordinates and/or track outlines), a clear naming convention needs to be identified and included in enumerator training. The name saved in the GPS device must uniquely identify the household and plot in order to match the questionnaire data. The GPS device will typically autofill the file name in a numeric sequence – *this should be overwritten by the enumerator.* A naming convention such as "Household ID-Plot ID" will ensure an easy match between the questionnaire and the raw GPS data. For example, Plot 3 in Household 1234, would be saved as "1234-03". Typos are very common on the small keypads or screens of the handheld GPS units, and, therefore, the number of digits in the unique ID should be minimized to the extent possible.

Device selection: Handheld GPS devices come with a range of features and vary significantly in price. It is advisable to select a unit that is compatible with both GPS and GLONASS, as this increases the number of satellites available to the device (increasing accuracy and acquisition time). If operating in the United States, Europe, or Asia, compatibility with the local augmentation system (WAAS, in the US, for example) will increase point accuracy. When determining the best device for a survey, survey designers should assess the features that are needed for a particular activity and keep in mind that the number of device features is generally negatively correlated with battery life. Some examples of common feature options:

- Direct area measurement functionality: This functionality is essential if area measurement is the goal. For surveys only collecting plot or household locations, this functionality is not necessary.

- Storing plot outlines: If plot outlines are to be captured, the track capacity of the device needs to be evaluated. If the device does not have the storage capacity to hold all plots in its memory, it will complicate fieldwork as enumerators will have to stop to download the data to free up space on the device for further measurements to be taken. This requires time and increases the risk of losing plot outlines. When possible, it is advised to procure units with enough track memory to hold all plots (per enumerator). That is, if each enumerator is expected to measure 150 plots, procure a device with the capacity to store 200 or more tracks, not one with only 100 track storage capacity.
- Other common features include built-in camera and barometric altimeter.

***Batteries*:** Enumerators should be instructed to keep the device powered down until necessary. The brightness of the display should be kept as low as possible to extend battery life. At the time of writing, the battery life of Garmin handheld units ranges from approximately 16 – 25 hours, depending on the model. Survey planners should budget for backups and provide each team with a set of replacements.

Device set-up: Before distributing the GPS devices to field teams, all settings should be adjusted properly and in accordance with the questionnaire. Device set-up must be completed centrally to ensure uniformity across devices. Critical settings to be adjusted include: satellite system (GPS and GLONASS, if available), distance units (e.g. meters versus feet), area units (e.g. square meters versus acres), map datum and spheroid (e.g. WGS 84, for example), coordinate format (e.g. in degrees and decimal minutes, hddd° mm.mmm'), and time (24-hour format is recommended). Settings should be checked at the close of enumerator training and periodically throughout fieldwork. Additionally, features of the device that are not necessary for the survey should be hidden from view in order to limit distractions and reduce time spent on the device.

Training: Training requirements will vary significantly with enumerator competencies. Field teams with little or no technological experience will require more basic introductions to the use of the keys, joysticks, and other buttons. Regardless of the experience of the field teams, surveys using GPS devices must plan for at least one full day of training and include hands-on practice in the field. Trial runs (even in a parking lot) will improve enumerator understanding and highlight errors in procedure and file naming. Practice should also be conducted on agricultural plots to ensure enumerators are pacing the perimeter with precision. The training should also be used as an opportunity to test the enumerators' individual ability to mastering the devices, which may vary not only with their overall familiarity with technology, but also with personal characteristics such as the quality of their vision. As necessary, the survey implementers should be ready to provide enumerators with reading glasses when poor vision proves to be a constraint to an accurate reading of the instruments (this also applies to the reading of the compass in the compass and rope method).

***Questionnaire design*:** The questionnaire needs to be designed to facilitate easy and consistent transfer of information from the GPS device to the questionnaire itself. First, the settings on the GPS device should match the format illustrated on the questionnaire. For example, if coordinates are to be recorded in degrees and minutes, the questionnaire should have the proper number of decimal places. Second, design the questionnaire to look as similar as possible to the GPS device. If the device lists latitude and then longitude, the questionnaire should do the same. When necessary, allow a space to specify "North" or "South". Such specification is critical when using universal transverse Mercator (UTM) zones and the sample spans both sides of the Equator. If asking for coordinates in different sections of the questionnaire (for example, at the dwelling and at the plot) ensure consistency – do not switch the order of latitude and longitude between modules. Examples from LSMS-ISA surveys in Malawi and Ethiopia are found in Figure 3.

If not saving plot outlines, it is highly recommended that waypoints are saved on the GPS device *in addition* to the coordinates recorded on the questionnaire. Labeling is often an issue and having the coordinates both in the questionnaire and the GPS device will facilitate data cleaning. Common mistakes in the transcription of GPS coordinates onto paper include annotating longitude values in place of latitude and vice versa, as well as using minutes when decimal degrees are required for coordinates. Failing to annotate whether the latitude is North or South, or if the longitude is East or West is also a challenge in countries that lie across the equator or

Figure 3 — Examples of Questionnaires Recording GPS Land Area Information

Malawi IHPS 2013					
4. What was the area of this [GARDEN]? **ENUMERATOR**: ASK THE FARMER TO ESTIMATE THE AREA FIRST. MEASURE THE AREA WITH THE GPS LATER. MAKE SURE TO MEASURE THE AREA WITH GPS **AT LEAST TWICE** TO GET A CONSISTENT VALUE. RECORD ZEROS TO THE RIGHT OF THE DECIMAL.			5. **ENUMERATOR**: RECORD THE COORDINATES FOR THE CORNER OF THE GARDEN AT WHICH YOU STARTED AREA MEASUREMENT. IF YOU DO NOT RECORD THE GPS COORDINATES, PLEASE SPECIFY WHY.		
CODES FOR UNIT			TOO FAR……………………....1		
ACRE...........................1			HOUSEHOLD REFUSED…...2		
HECTARE...................2			OTHER (SPECIFY)…………3		
SQUARE METRES....3					
OTHER (SPECIFY)...4					
a.		**a.**			
FARMER ESTIMATION		**GPS MEASURE**	**a.**	**b.**	
AREA	**UNIT**	**AREA IN ACRES**	**LATITUDE (S)**	**LONGITUDE (E)**	**REASON**
_ _ _ _ . _ _		_ _ _ _ . _ _	_ _ ° _ _ . _ _ _	_ _ ° _ _ . _ _ _	
_ _ _ _ . _ _		_ _ _ _ . _ _	_ _ ° _ _ . _ _ _	_ _ ° _ _ . _ _ _	

Ethiopia ERSS 2013/14	
5. RECORD AREA OF THE FIELD USING GPS.	GPS COORDINATES N=1 S=2 D M LAT LONG
AREA IN SQUARE METRES	
_ _ _ _ . _ _	
_ _ _ _ . _ _	

along the Greenwich prime meridian.[8] If plot outlines are saved, the waypoints can be extracted from that file.

Complementary questions: Survey planners should consider recording additional information in the questionnaire aside from the area and coordinates. Precision indicators include the number of satellites acquired at the time of measurement, slope of the plot, canopy cover around the perimeter of the plot, and cloud cover. If plot outlines are saved, some variables may be estimated using external geospatial data; however, resolution may be lower than if recorded at the plot level.

Data dissemination: Geo-referenced information should be handled with extreme care as it can allow for the identification of survey respondents, breaching the confidentiality agreement with respondents and, in most cases, national statistical laws. GPS coordinates and plot outlines should not be distributed with the household survey data and should be eliminated from the data files as they are anonymized ahead of public dissemination. Modified location information may be included in some form after first reducing precision through a process of aggregation, truncation or alteration of coordinates. Examples of this type of dissemination, for household data, include the LSMS-ISA project of the World Bank and Demographic and Health Surveys (DHS) program supported by USAID. We are not aware of similar examples for the dissemination of land area data.

[8] In total, 13 countries on the globe lie along the Equator, and 8 across the prime meridian.

However, the demand for more precise location is likely to grow, as very-high resolution (VHR) imagery becomes more widely available, and more research is needed to determine the effectiveness of different methods of masking in such a data-rich environment. Adaptive masking to limit distortion based on local characteristics, as well as the use of data enclaves that provide strictly limited access, or software solutions that produce results without allowing access to coordinates should also be evaluated. Most importantly, however, any plans for dissemination should be approved at the onset of field data collection and communicated clearly to both respondents and governing bodies.

5.2 GPS AREA MEASUREMENT: KEY ISSUES AND LIMITATIONS

GPS technology and GPS-enabled devices offer a practical approach to objective area measurement (Kelly and Donovan, 2008). Time can often be the most restrictive resource in survey implementation and existing studies comparing the time use for GPS and compass and rope find that compass and rope can take approximately 3.5 times as long as required for GPS (Schoning et al., 2005; Keita and Carfagna, 2009). Keita and Carfagna (2009) provide a discussion of the area measurement performance of different GPS devices compared to traversing. Their discussion is informed by a field experiment, the results of which indicate that the GPS-based area measurement is a reliable alternative to traversing and that 80 percent of the sample plots were measured with negligible error. Advancements in GPS technology show promise for increased accuracy in the coming years as more satellites are launched and the availability of satellite augmentation systems spreads to reach all world regions (at the time of this writing, augmentation systems do not currently extend across Africa to any useful degree).[9]

One major advantage of GPS, as with any objective measure, is that of being immune of the potential biases linked to respondent characteristics and the use of non-standard measurement units. Despite the great potential of GPS

[9] In 2011 the Russian Global Navigation Satellite System (GLONASS), which works seamlessly with the United States' GPS network, became globally operational with 24 satellites. Augmentation systems can improve the accuracy and speed of GPS measurement in the field. The Wide Area Augmentation System (WAAS), a real-time correction based on ground stations, has been proven to increase position accuracy by as much as five times according to a leading manufacturer. The WAAS system is only operational in North America, while Europe and Asia have their own regional solutions (Euro Geostationary Navigation Overlay Service (EGNOS) and Japanese Multi-Functional Satellite Augmentation System (MSAS), respectively). India's regional augmentation system (GAGAN) was cleared for navigational use in early 2014.

BOX 2 — COMPUTER ASSISTED PERSONAL INTERVIEWING (CAPI)

With the expansion of computer assisted personal interviewing (CAPI) opportunities, geo-referencing and measuring land area directly through tablets with built-in GPS technology becomes an attractive option. Capturing coordinates and measurements directly prevents data entry errors and cuts down on the need to procure separate devices. However, as with any other measurement, there are unique costs and benefits, such as issues of rapid battery drainage and potentially slow signal acquisition.

Experience and evidence from two ongoing LSMS methodological studies suggests that tablets have a significantly larger point accuracy radius. This is often presented as "accuracy" on the GPS device, with a smaller accuracy figure reflecting a lower position error.

If implementing a survey on CAPI, it is highly recommended to capture the plot coordinates directly through the tablet rather than recording the coordinates manually. This will eliminate any data entry errors associated with the coordinates and therefore expedite and simplify cleaning of plot outline labels. Area measurement using a tablet has not yet been validated on a sufficient scale. One small-scale (N=234) effort undertaken by the LSMS team to validate handheld versus CAPI measures in Ethiopia (unpublished, data available on request) revealed sufficient concurrence between the two measures. However, satellite acquisition was slow on tablets resulting in several occurrences of zero area measures. This is likely to change as technology improves, but at the time of writing, the recommendation is not to record area measures via tablet applications.

technology, GPS-based coordinates are subject to known types of measurement error stemming from satellite position, signal propagation, and receivers. Approximate contributions of these factors to the overall position error are significant, ranging from 0.5 to 4 meters (Hofmann-Wellenhof et al., 2008). The number of satellites, in particular, can cause the distribution of position error to be elliptical, rather than spherical (van Diggelen, 2007). Additional factors that may be expected to influence the quality of GPS measures include the presence of dense tree canopy or cloud cover, which may interfere with the signal. The quality of the GPS device used also has non-negligible impact on the magnitude and distribution of measurement error (Palmegiani, 2009). Although position estimates are subject to a certain level of inaccuracy and may be distributed in a non-spherical manner, in theory the error associated with area measurement should be random – that is, the factors that cause non-spherical position error are largely macro level factors that are unlikely to change in the short period of time required to pace the perimeter of a plot, rendering the position error distribution consistent at all points along the perimeter. A study by Bogaert et al. (2005) using simulated coordinates and European Geostationary Navigation Overlay Service (EGNOS) augmentation concluded that the position error can be reasonably assumed to be normally distributed.

Literature suggests there is some concern that errors in GPS measures may vary systematically with key plot characteristics, namely plot size, slope, and shape. Few published studies have tested the use of GPS measurement against the gold-standard measure, the traditional compass and rope method. Recent research by FAO points out possible effects of slope on the accuracy of GPS-based area measurement (Keita and Carfagna, 2009). Slope-related effects on area measurement are rooted in the fact that the actual area should be the horizontal projection of the plot, as opposed to the plot area itself (Muwanga-Zake, 1985). The difference between actual area and projection appears to be particularly important for slopes greater than 10 degrees (Fermont and Benson, 2011).

Bogaert, Delincè and Kay (2005) use modeling and simulations to conclude that "for GPS/EGNOS measurements made by an operator moving along the border of a field, area measurement error is linked both to the operator speed and to the acquisition rate of the GPS device. For typical field sizes found in the European Union, ranging from 0.5 ha to 5 ha, the coefficient of variation (CV) for area measurement errors is about 1 to 5 percent. These results depend on the field area, but they can be considered to be insensitive with respect to the field shape. They also show that field area measurement errors can be limited if an appropriate combination of operator speed and GPS acquisition rate is selected." This optimal operator speed is dependent on plot size and not a single preferred pace.

Fasbender and Lucau (2012), also find that plot shape as well as plot size affects GNSS area measurement error. In their synthetic simulation of four distinct parcel shapes (square, rectangular, elongated narrow rectangle, and irregular polygon), with simulations for areas from 1 m^2 to 10 ha, they find that the variance of the measurement on the elongated rectangle and irregularly shaped polygon are the most amplified. Specifically, they suggest that the error on such irregular parcels, which are common amongst African small-holder farmers, is primarily attributable to operator (enumerator) error (Fasbender and Lucau, 2012).

One concern with GPS measures in large-scale surveys, which does not apply to self-reported measures, is the rate of missingness in the data. Missingness rates of 20-30 percent are not uncommon in existing datasets, and the pattern of missingness is not random but tends to be correlated with both plot and respondent characteristics.

Kilic et al. (2013) show, with national data for Uganda and Tanzania, how plot distance from the interviewed household is the main factor determining which plots get measured, as field protocols normally include a provision not to measure plots beyond a given distance. Partly due to that, the plots that are not measured also differ systematically from those for which a GPS measure is taken in a number of (self-reported) characteristics, such as self-reported plot size, level of input use, and titling. Furthermore, some respondent characteristics are associated with higher missingness rates: plots belonging to older, less educated, poorer household heads who own fewer plots are more likely to be measured than other plots. This is a drawback of GPS data that raises concerns about possible biases introduced by relying on observed GPS plot measures alone.

In the presence of high rates of missingness, imputations are often necessary for analysts to be able to work with complete case datasets. Self-reported land area measures have been shown to be an important predictor of GPS area measures (Kilic et al., 2013; 2016). For this reason, it is recommended that GPS measures be taken in addition to, not instead of, self-reported ones.

6. THE 'GOLD-STANDARD': COMPASS AND ROPE MEASUREMENT

The Compass and Rope method is considered the 'gold standard' of land area measurement. However, the method is more cumbersome and time-consuming than self-reporting and GPS, which makes it impractical in large-scale household surveys. Given its accuracy even on small plots, it remains the approach of choice for specific types of data collection, but must be implemented by experienced staff for optimal results.

6.1 COMPASS AND ROPE: PRACTICAL CONSIDERATIONS

The compass and rope method (or traversing) is commonly considered to be the gold standard in objective area measurement (FAO, 1982). It does not rely on advanced technology, only basic geometry and often readily available equipment. With a compass, measuring tape, ranging poles, two to three persons and a programmable calculator or other computational tool, the area of a plot can be measured significantly more accurately than by subjective estimates. When carefully implemented, this method provides accurate estimates, and it can therefore be considered as a benchmark against which to assess the accuracy of other methods.

As in the GPS measurement, this method requires that the enumerator and respondent travel to the plot, and clear its boundaries from obstacles to the extent possible. Before the measurement can begin, the farmer must pace the perimeter of the plot with the enumerator in tow to ensure that the measurement captures the proper area. The enumerator will note the corners of the plot, where clearly available. When plots are irregularly shaped, enumerators use their best judgment in declaring the corner points. The boundary of bushy plots will need to be cleared (with the permission of the farmer) prior to commencing measurement in order for the ranging poles to be visible. Only then can the enumerator start the task of measuring the plot. Examples of instructions for completing the compass and rope measurement can be found in Annex 3 or in the FAO's 'Estimation of Crop Areas and Yields in Agricultural Statistics" (1982).

The enumerator will record the compass bearings and distances between all corners of the plot. To calculate the area of the plot and the closing error, the data need to be entered in a computational tool, be that an algorithm pre-programed in a spreadsheet software (e.g. Microsoft Excel) or a programmable calculator (for examples of programmable calculator code, see Annex 5 of FAO 1982). The closure (or closing) error is an important element of quality control in the compass and rope method. It is a measure of the gap between the reported start and end points of the constructed polygon, and gives an indication of the accuracy of the measurement. The survey designer should decide in advance of fieldwork what constitutes an acceptable closing error threshold beyond which the measure needs to be re-taken.[10] In order to allow for relatively easy re-measurement of plots with a higher than acceptable closing error (as dictated by the survey guidelines), it is recommended that the field teams be equipped with the computational tool so they can re-measure the plot immediately when needed. The alternative, computing the closing error at a central location, will result in extra effort and time delays for those plots which need to be re-measured.

Even if the area, perimeter, and closing error are the only pieces of data that will be used in analysis, the questionnaire should require the enumerator to enter all compass bearings and distances. This will allow for spot checks of the area measurements entered as well as facilitate data cleaning when area measurement outliers are identified. Including back bearings (the bearing from point B to point A, for example) will allow enumerators to more easily identify problem areas when they measure a plot with high closing error. An example of a questionnaire for the collection of this information is found below:

6.2 COMPASS AND ROPE: KEY ISSUES AND LIMITATIONS

The limitations to the compass and rope method lie primarily in its burdensome nature and time required to complete the measurement. Due to the extensive time requirements, this method is unsuitable for national level, large-sample surveys. The time requirements will vary by plot size but the compass and rope method is expected to be consistently and significantly more time-intensive than other objective measurement options such as GPS. The compass and rope technique requires traversing around the plot from corner to corner, taking the bearing and distance of each side, and subsequently calculating the area and perimeter. A study by Schoning et al. (2005) in Uganda found the average time

[10] Common thresholds observed in survey practice are 1, 3 and 4 percent.

Table 5 — Questionnaire Example: Compass and Rope Module

4. Computed Perimeter (m) ______ . ___		5. Computed Area (m^2) ______ . ___		6. Closing Error ______ . ___%	
Complete Q7-Q9 For the Final Measurement (Closing Error < 5%)					
7. Point		8. Compass Bearing (^{0})		9. Distance in Metres	
FROM	TO	FRONT	BACK		

Source: Ethiopia Land and Soil Experimental Research Study, Post-Planting Questionnaire.

required for compass and rope measurement to exceed 3 hours. However, this method is not as subject to the instrumental error typical of GPS devices, and when properly implemented is still considered the gold standard for precision and accuracy.

The challenges with this method are however not limited to the time it requires, as it also necessitates of specific skills and a good deal of precision on the part of the enumerators. Compass and rope is at its best when implemented by professional land surveyors, and can be problematic when working with enumerators unfamiliar with the method. The compass and rope method is also physically demanding and therefore not all enumerators will be well-equipped for successfully and thoroughly completing the measurement.

While accurate training is essential in all aspects of survey fieldwork, compass and rope measurement requires arguably more complex skills and intense training compared to the GPS method, and greater effort on their part. Enumerator fatigue is a real concern with compass and rope measurement. When planning fieldwork timelines, survey managers should not expect enumerators to be able to measure several fields in one day (the actual number will depend on the plot size and terrain, and travel time between plots). In particularly hilly or forested areas, the workload on the enumerator will be extremely heavy. This should also be considered in considering recruitment and remuneration of the enumerators.

To some degree, the measurement error associated with traversing is observable. If the closing error is calculated while in the field, the measurement can be conducted again when found to be above the pre-determined threshold. However, the closing error will not confirm that the plot corners have been accurately assessed, but only that the bearings and distances recorded form a full closed figure. The precision of the measurement is still subject to human error as identifying the plot corners can be a burdensome and noisy task on its own, particularly for irregularly shaped plots.

Irregular plot shapes appear to be more of a challenge for the proper implementation of the compass and rope method than the GPS method. While with GPS measurement an enumerator can pace the perimeter of the plot regardless of the shape, in the compass and rope technique the enumerator must first identify all corners of the plot, and when corners are not clearly defined (as is the case in many irregularly-shaped plots) they must plot the "best" corner they can while trying to preserve the true area of the plot. Then at each corner, the enumerator takes the compass bearings. With each additional corner, there is additional room for error in the misreading of the compass or the measurement of the distance between two corners. Misreading of the compass by one or two degrees on one corner is not likely to result in material changes to the area measurement. However, aggregated over several plot corners, these small deviations can add to a significant closing error, implying that the area calculation is not for the true plot boundaries. Cutting a corner when measuring via compass and rope results in a much greater time saving for the enumerator, who therefore has stronger incentive to do that than with the GPS method. While field protocols usually include closing error thresholds beyond which the measurement needs to be retaken, this will add considerably to the time necessary to take the measurement.

7. REMOTE SENSING IMAGERY

Remote sensing imagery has not been widely used for land area measurement in household surveys in low-income settings to date. Techniques based on the use of remote sensing imagery are, however, likely to become more and more tractable in all settings as imagery become cheaper and more detailed, and technology for its integration into computer-assisted interviews evolves.

Satellite imagery has been used extensively for land cover classification and cultivated area and yield estimation (for example, Boryan et al. (2011), GEOSS (2009), and Wardlow and Egbert (2008)). Carfagna and Gallego (2005) offer a comprehensive summary of the existing uses of satellite imagery for agricultural statistics. While these applications generally involve some ground data collection for validation, the samples are not likely to be connected to household data. The use of remote sensing specifically for parcel or plot area measurement has not yet been widely integrated into household-level surveys. In this section, we use the terms parcel and plot somewhat interchangeably. While these are different concepts and survey designers may target measuring one or the other depending on survey goals (see Section 3 above), many of the measurement challenges via remote sensing apply to both. Parcels will generally be an easier target than plots, as they are more permanent, larger, with more clearly identified boundaries, but the general discussion holds for both plots and parcels. One important exception is that if cadastral or administrative information is available at the parcel level, this can be used to augment satellite imagery to aid parcel identification.

Remote sensing imagery has the potential to eliminate the need for plot visitation by identification of plot boundaries on images and subsequent area measurement. This method would potentially reduce any bias due to exclusion of parcels that are either too large or too far away for respondents and enumerators to walk to or around them, or are in areas considered unsafe for fieldwork. Without the need to visit each plot and conduct the measurement, fieldwork time may be significantly reduced, although the time spent at the household might increase as respondents will need to identify the plot boundaries on images or maps. The effect on budget is more ambiguous. On one hand, the shortened duration of fieldwork and lighter transportation needs will reduce costs. On the other hand, additional costs may be incurred for purchase of imagery and any post-processing of the data.

Despite the potential benefits of using remote sensing imagery for plot area measurement in household surveys, limitations in image resolution and availability, as well as practical implementation challenges, have inhibited the widespread use of this method in the developing country context to date. One notable example of an upper- middle-income country using satellite imagery and other georeferenced information in the context of a large-scale farm survey is Mexico's National Agricultural Survey. Embedding a cartographic module in a CAPI interview interface, Mexico's national statistical office (INEGI) has implemented a national survey in which farmers were shown a digital satellite image (including preloaded additional layers of geographic information) that could be zoomed in or out according to need. The respondents were asked to locate and identify their land plots, which then allowed enumerators to identify the plot vertexes and generate a plot measurement on the visualized map (Pérez Cadena, 2015). This is clearly a promising experience, but we are not aware of any instance of such an approach being implemented in low-income countries. In the following sections, we explore some of the challenges for scaling up implementation of such an approach.

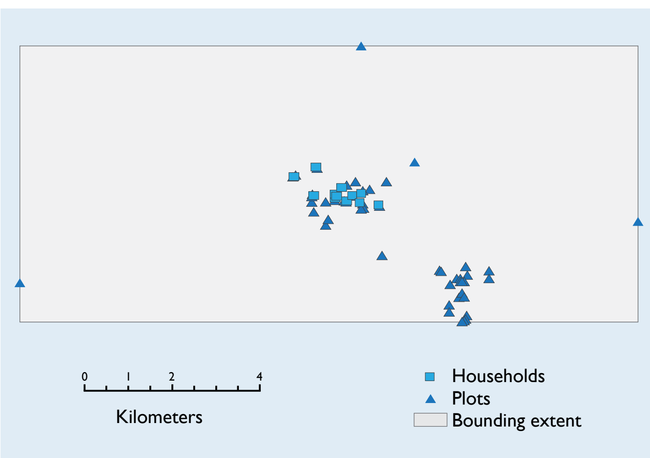
7.1 REMOTE SENSING IMAGERY: PRACTICAL CONSIDERATION

Finding Imagery. The main factors driving a search for imagery are location, reference period, spatial resolution and cost. In the case of agricultural plots, the precise location will not be known prior to the household visit, but a general area of interest can be identified based on survey protocols and some estimation. In LSMS-ISA surveys the average distance of households from EA center is less than 2 km, but plots are more dispersed (see Figure 4). The average bounding extent of an EA, the geographic area enclosing both plots and households, is approximately 8 km^2. Reference period, or date of acquisition, is also an important criterion, particularly when the object of interest is an agricultural plot, as plot dimensions and characteristics can change between seasons and over time. Spatial resolution describes the dimensions of the smallest resolvable element recorded in a digital image (akin to photo grain in film), and is a primary factor in determining the size of smallest detectable feature.

Many sources of remote sensing imagery exist with differing levels of resolution and costs. Landsat, a project executed by the US Geological Survey and NASA, has been collecting remote-sensing land data for over 40 years which is available free of charge. Its latest satellite launch, Landsat 8, captures images with pixel sizes of 15 – 30 m.[11] Due to the limited spatial resolution of Landsat and older SPOT imagery, these sources would be mostly suitable for plots larger than 1 hectare. The current SPOT satellites, operated by Airbus Defence and Space, offer images of 2.5 meter resolution and greater but at a significant cost (up to €8,700 for one 60 km x 60 km scene).[12] DigitalGlobe's WorldView and GeoEye products include sub-meter panchromatic images, with lower-resolution multispectral data.[13] Options are continually expanding with the launch of new satellites from companies like Terra Bella (formerly SKYBOX) and Digital Globe, as well as product lines maintained by national space agencies.

There are a variety of tools available that greatly simplify the process of searching image archives and requesting new imagery. These include NASA CEOS Cove Tool, ApolloMapping ImageHunter, DigitalGloble Geofuse, and i-cubed Data Doors, to name a few. While an image search is often driven by the area of interest and spatial resolution, it should be noted that spectral resolution is also an issue to be considered. Panchromatic imagery is generally highest resolution, but multi-spectral (visible through infra-red and thermal) provides useful information on vegetation type and condition, as well as enabling the production of color

Figure 4 — Example of Bounding Extent of Households and Plots



Source: LSMS-ISA data.

[11] http://landsat.usgs.gov
[12] http://www.intelligence-airbusds.com/en/122-price-lists
[13] https://www.digitalglobe.com/

composites that may be easier to interpret. A last step in image acquisition is the selection of processing level; options vary depending on vendor or source. At a minimum, imagery used for land area measurement should be geo-registered to a known coordinate system. However, only ortho-rectification, where the image is fit to a terrain model, enables true area measurements.

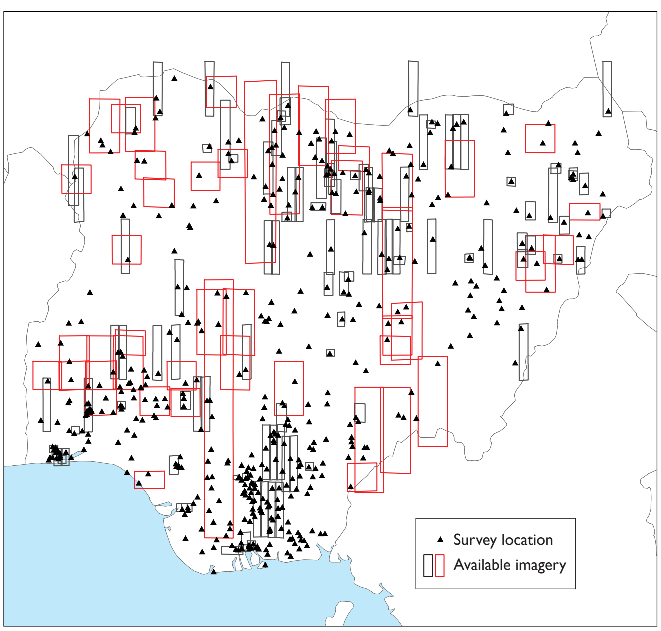
Given that the cost of imagery is a function of number and type of images, there is an obvious benefit to the clustering of sites that might occur in a localized survey such as a project-specific monitoring or impact evaluation survey. Conversely, the expectation is that utilizing VHR imagery in a nationally-representative survey could be cost prohibitive, due to the wide distribution of households. A simple query in the Data Doors online service using survey sites from the GHS panel survey in Nigeria shows that availability would also be a constraining factor. In this example, the query was limited to sources of at least 5m resolution, acquired between 1/1/2014 and 12/31 2014. Additional parameters included maximum 20 percent cloud cover and 20° incidence angle. Results shown in Figure 5 indicate that only 288 out of 500, or slightly more than half of the sites, are fully covered by at least one archived image. One possible explanation for the lack of coverage might be characteristics of the study area: cloud cover is a persistent issue in parts of Nigeria, and affects all optical sensors. Note that coverage could be increased if the temporal range is widened (at the loss of season specificity), or others parameters relaxed (at the loss of image quality). Also, many of the current satellites providing VHR imagery can be tasked so as to optimize image acquisition to cover a particular area of interest, but this process is costlier and may not be successful for coverage of many areas in close proximity (competing targets).

Plot delineation. The challenges that come with using imagery in household surveys differ from those encountered when estimating large crop area or land cover. In order for imagery to be a successful tool in measuring plot area, one needs to be able to precisely locate a single feature based on context and other reference features, rather than simply evaluating the content of each "pixel" or landscape unit. This requires both an unobscured view of the area of interest and an ability of the farmer to orient himself to the landscape from bird's-eye perspective. Additional complicating factors include cloud cover, tree canopy obscuring the plot boundaries and the parcel-plot concept in which parcel boundaries may be observable but plot boundaries are less clearly defined. The timing of image acquisition would likely be an issue for plots that are not permanent or continuously cultivated in the same size and/or shape.

The most efficient method of plot identification would be visual interpretation of an image, in either digital or hardcopy format. As noted above, if respondents have limited exposure to photography and other technologies, presenting an image taken from a satellite and having them simply point to all of their agricultural plots is not likely to be an easy task. Even without consideration for plot boundary definition, the respondents may have difficulty finding the location of the plot, especially for plots that are located away from the household. Digital format has the advantage of providing zoom and pan capabilities, which can help in identification of major landmarks and orientation to the imagery, and which are becoming easier to integrate in the standard household survey toolbox as the use of tablets for data collection becomes more common.

Once the location of the plot is determined, outlining the boundaries may still prove difficult. If under dense canopy, boundaries will not be visible. The ability to measure plots in woody terrain or in an area common for tree crops, therefore, is impaired. In some areas, plots are nested immediately next to neighboring plots, either managed by the same household or not. If the barrier between the two plots is no more than a row of fencing crops or a narrow footpath, differentiation between the two will be extremely difficult in the images. Additionally, in many agricultural contexts there exists a parcel, a larger piece of land often of more permanent dimensions, and within that parcel several contiguous plots. The cropping patterns and dimensions of the plots can vary by season. If the images that the farmer is presented with do not match the current plot dimensions, identifying the boundaries will not be possible (or reliable).

Figure 5 — Availability of VHR Imagery for Survey Sites in 2014, Nigeria



Assuming these practical challenges to implementation are overcome, and the feature of interest has been located, the enumerator would zoom in and draw a shape around the feature, much as the GPS operator does in delineating a plot by walking the perimeter. Similarly, area calculation may be done on the fly, depending on the image viewer capabilities, or the feature stored for later processing. This type of approach, enriched by the availability of georeferenced agricultural census and other information, has been successfully implemented in Mexico (Pérez Cadena, 2015), but has yet to be tested at scale in low-income countries. Clearly, the approach will be easier to implement in farming systems characterized by large plots and monocultures, and more difficult in countries with very small and irregular plots, with unclear demarcations, and hosting a wide variety of crops on a very limited surface.

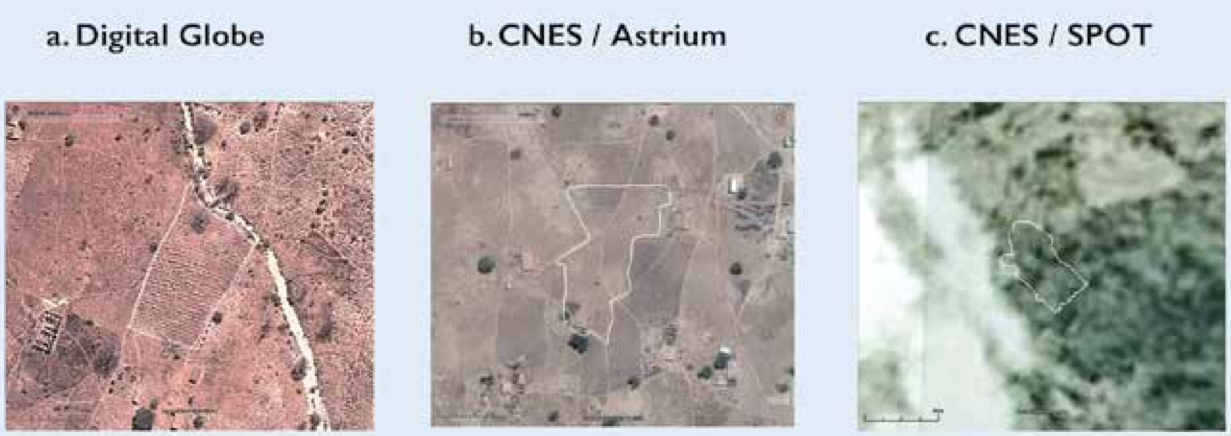
7.2 REMOTE SENSING IMAGERY: KEY ISSUES AND LIMITATIONS

While testing the use of remote sensing imagery has not been a part of the LSMS-ISA methodological field work to date, we have used the collected GPS field outlines to assess the feasibility of delineating plot boundaries using public domain imagery sources. We conducted an informal but systematic review of imagery available in the Google Earth platform in November 2014 to explore the effect of image resolution, seasonality and landscape characteristics on the ability to clearly identify plot boundaries and therefore measure area. Gpx tracks were converted to kml, opened in Google Earth, and assessments were made at different scales, determined by the zoom-to-feature tool. Historical imagery was used if a clearer image was available from 2012 onward. Each plot was evaluated based on the presence of clearly identifiable plot boundary, image source and date, presence of vegetation and country-specific season definition.

Approximately half of all plots reviewed (n=4025) had partly or completely visible outlines in the imagery, but this was not equally distributed across countries. Nigeria had the lowest percentage of completely clear boundaries, with 26 percent, and Ethiopia the highest, with 44 percent. Although certainly a contributing factor, spatial resolution does not explain all of the variation, as Ethiopia had the lowest level of VHR imagery and highest percentage of plots falling in images from Landsat (see Figure 6 for examples). Another finding of interest is that availability of recent imagery was most limited in Nigeria, where 59 percent of plot locations were in imagery dated prior to 2012, perhaps providing additional evidence of the difficulty of acquiring cloud-free imagery in certain settings. Seasonality may also play a role, although results are mixed across countries. A reasonable expectation would be that early or mid-season timing would provide an advantage, with the presence of vegetation allowing for clearer differentiation between plots. However, very few of the images evaluated in Ethiopia and Nigeria fell in early-mid season. The low incidence of imagery with this timing might be due to higher presence of clouds during the rainy season, but unfortunately prevents us from drawing any strong conclusion with regard to ideal timing. Tanzania presents an exception which may have more to do with an imprecise or inaccurate seasonal identification. Review results are detailed in Table 6.

In theory, the use of this remote sensing imagery in household survey fieldwork could reduce the duration of fieldwork as travel is minimized and measurement time is eliminated. While this has the potential to bring significant benefits, the challenges, primarily image resolution and identification of plot boundaries, suggest that the use of remote sensing for plot area measurement in the low-income country context is limited in feasibility, at least for the present. A blended or mixed approach, with the use of imagery as available, and GPS as alternative, might be suitable for early adoption, but we are not aware of instances where it has been applied, and would require testing.

Figure 6 — Examples of Different Image Sources



a. High-resolution imagery from WorldView, QuickBird or GeoEye
b. High-resolution imagery from Pleiades
c. Medium-resolution imagery, with significant cloud cover

Little research is available on the implementation of using remote sensing imagery for area measurement in household surveys. As technology advances and image resolution improves along with affordability, the use of this method becomes more feasible, and is likely to hold promise particularly for the measurement of large plots. Future research on the implementation of this method, including fieldwork challenges and respondent ability to identify plots, is highly encouraged. The empirical section of this paper therefore does not include a comparison of remote sensing to the other methods discussed earlier; rather, it is left for future research.

Table 6 — Results of Google Earth Plot Review

	Tanzania		Ethiopia		Nigeria	
Plot boundary detection						
	Plots	%	Plots	%	Plots	%
Clear	653	33%	751	44%	111	26%
Partly clear	434	22%	129	8%	75	18%
Not clear	763	38%	365	22%	210	49%
Not visible/ cloud cover	156	8%	449	27%	29	7%
Total	2006	100%	1694	100%	425	100%
Spatial resolution						
	Plots	%	Plots	%	Plots	%
Digital Globe	1764	88%	708	42%	349	82%
CNES/ Astrium	242	12%	537	32%	18	4%
Image NASA	0	0%	449	27%	58	14%
Total	2006	100%	1694	100%	425	100%
Temporal distribution						
	Plots	%	Plots	%	Plots	%
2012-2014	1576	79%	1351	80%	176	41%
Pre 2012	430	21%	343	20%	249	59%
Total	2006	100%	1694	100%	425	100%
Seasonal distribution						
	Plots	%	Plots	%	Plots	%
Early	1148	73%	43	3%	33	19%
Mid	0	0%	258	19%	19	11%
Late	428	27%	689	51%	3	2%
Off	0	0%	361	27%	121	69%
Total	1576	100%	1351	100%	176	100%

Source: Authors' calculations.

Part III

The LSMS Methodological Validation Program (MVP)

8. FILLING A KNOWLEDGE GAP THROUGH METHODOLOGICAL EXPERIMENTS

The LSMS team carried out validation studies in three African countries, in which a total of 4158 plot measures were taken with different methods (compass and rope, GPS, and farmers' self-reports).

The existing literature leaves many questions to be answered about use of the various measurement methods in the household survey context. It is evident that self-reported estimates of area have an advantage in terms of time and cost, but the quality of data collected is biased systematically. The use of GPS technology is the frontrunner for objective measurement based on time requirements but the compass and rope technique is historically known for the highest accuracy. However, little systematic evidence exists to help practitioners obtain clarity on issues such as the range of plot sizes within which GPS is an appropriate substitute for compass and rope measurement, the influence of plot and surveying conditions (weather, slope, canopy cover) and enumerators' attributes on the accuracy of measurement with different methods, and ultimately, on how the measurement methodology employed affects the potential policy-informing conclusions drawn from analysis of the data.

In order to address the gaps in the area measurement literature and extend the applicability of studies to the plot conditions common to low-income countries, the LSMS program has prioritized land area measurement in its research agenda. The discussion that follows is based on three methodological validation studies in Tanzania (Zanzibar), Ethiopia and Nigeria have tested different methods for area measurement: farmers' self-reports, compass and rope and handheld GPS devices. The data are briefly described in Box 3.[14]

In what follows, the accuracy of each method is assessed in comparison to the compass and rope method, and the factors contributing to the observed deviations across methods are analyzed using the data collected through the three LSMS methodological validation studies described above. In comparing the GPS and CR measures the following measures of deviation are used:

Bias = GPS – CR

Relative Bias = ((GPS – CR)/CR)*100

The bias is the simple difference between the GPS measure and the CR measure, expressed in acres. The relative bias is the simple difference between the GPS measure and the CR measure, in acres, divided by the CR measure, expressed in percentage terms. The absolute value of both measures is also used in the analysis.

Although the main focus of what follows will be on the deviation of the GPS from the CR measure, measures of deviations of the self-reported (SR) from the CR measure are sometimes performed, employing a terminology analogous to the one just described for the deviation of GPS from CR measures.[15]

[14] The analysis that follows is presented in greater analytical detailed in the companion research paper to this Guidebook (Carletto et al., 2016).

[15] To limit the influence of outliers, 77 observations which fell in the top 1 percent in terms of absolute value of relative bias (for either GPS vs CR or SR vs CR) were dropped from the analysis. One additional observation was dropped from the Nigeria dataset which had a compass and rope closing error of 9.8 percent and was skewing analysis of compass and rope measurements.

The analysis is based initially on a bivariate comparison of the means of the above variables for particular portions of the sample cross-tabulated with a broad range of variables of interest. The second part of the analysis explores the determinants of the different measures of bias. We estimate two main regression models, using the same specification for the various measures of bias described above.

The first model is an OLS regression specified as:

$$(1) \qquad Y_i = L_i + C_i + S_i + SAT_i + T_i + W_i + e_i$$

Where *Y* is one of the four measures of bias defined above for each plot denoted by the *i* subscript, *L* is the measure of the plot taken using CR, *C* is the closing error of the CR measure, *S* is a vector of proxies for the shape of the plot (including the number of corners and the ratio of the perimeter/area), *SAT* is the number of satellites the GPS device was connected to at the time of measurement, *T* is a vector of dummy variables related to tree canopy cover (the reference being no canopy cover), *W* is a vector of dummy variables related to weather conditions at the time of the measurement (the reference being clear or partly cloudy sky), and e is a random error with the usual desirable characteristics.

To focus specifically on plots for which large deviations are observed between GPS and CR, we then estimate a probit model to capture the factors likely to increase the probability that a plot be measured with a relative bias larger than ten percent (in absolute value). We estimate three versions of this model for each experiment, so as to investigate whether under- and over-estimation by large margins are driven by different factors. The model is specified as follows:

$$(2) \qquad Pr\,(Y_i = 1 | X_i) = \Phi\,(X_i\,\beta)$$

where $X_i = (L_i, C_i, S_i, SAT_i, T_i, W_i)$ and Φ is the standard cumulative distribution function. In equation (2), Yi is one of three outcomes: a plot having absolute relative bias greater than 10 percent; a plot having relative bias greater than 10 percent; or a plot having relative bias smaller than -10 percent.

BOX 3 — DESCRIPTION OF THE METHODOLOGICAL EXPERIMENTS IN ETHIOPIA, NIGERIA AND TANZANIA

Data for **Zanzibar, Tanzania** come from the **Measuring Cassava Productivity (MCP) study**. The MCP focused on testing several methods for measuring cassava production, complemented by the measurement of cassava plots using three methods of area measurement. Fieldwork ran from June 2013 through May 2014, with area measurement conducted between August 2013 and January 2014. The study was conducted in two districts, one on Unguja and one on Pemba Island. The enumerators were local agricultural extension officers. The sample consisted of 1,247 households, with 1,932 cassava plots measured for land area. Partners in the study included the Ministry of Agriculture and Natural Resources, Zanzibar, the Office of the Chief Government Statistician, Zanzibar, and the World Bank. The handheld GPS Unit used in the study was a Garmin eTrex 30.

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. Area measurement 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 computer-assisted personal interviewing (meaning some degree of familiarity with technology). Area measurement was conducted from September to December 2013 (post-planting) in 3 zones of the Oromia region in Ethiopia. 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 September 2013. Partners in the study include the Central Statistical Agency of Ethiopia, the World Agroforestry Centre (ICRAF), and the World Bank. This study also used Garmin eTrex 30 units to collect GPS land area data.

The last batch of data comes from the **Nigeria Area Measurement Validation Study**. This study was conducted on a subsample of the General Household Survey panel households. Fieldwork ran from March to May 2013. Four states were selected for inclusion in the study based on safety, location, and previous performance of farmer self-reported area and GPS area. Staff from the head office of the National Statistics Bureau were trained and collected the data in the field. The plot selection was stratified on plot size to ensure a complete range of plot sizes included. In total, 211 households were selected, including 518 plots. The study was implemented by the National Bureau of Statistics, Nigeria, and the World Bank. The GPS Unit utilized for this study was the Garmin GPS Maps 62.

In each of the three studies, the first measure of agricultural plots to be collected was the farmer self-reported estimate, followed by compass and rope, and finally by GPS. The order of measurements was deliberate and great attention was paid to this in the field. Farmer estimation must be recorded prior to any objective measurement so as not to influence the farmer. Enumerators were instructed in all studies *not* to influence the farmer's estimate.

Fieldwork protocols required enumerators to repeat the compass and rope measurement if the closing error was 5 percent or more. In the Ethiopia experiment, the closing error calculation was done on-the-spot by the enumerators, thanks to the computational tool embedded in the computer-assisted personal interviewing software. In Tanzania and Nigeria, the closing error was calculated by the supervisors (sometimes present at the plot at the time of measurement in Nigeria), and in case of error in excess of 5 percent, enumerators had to re-visit the plot in order to take the new measurement during a second visit. The instance of closing error greater than 5 percent was in fact a rare occurrence during fieldwork (in the Ethiopia experiment only 5 percent of fields were measured more than once).

Table 7 — Closing Error and Plot Shape

Plot shape	Ethiopia			Tanzania			Nigeria			Pooled		
	N	Closing error (%)	Bias (GPS-CR, acres)	N	Closing error (%)	Bias (GPS-CR, acres)	N	Closing error (%)	Bias (GPS-CR)	N	Closing error (%)	Bias (GPS-CR, acres)
< = 4 sides	662	2.32	0.01	358	2.03	0.00	71	1.46	-0.01	1091	2.17	0.01
5 - 9 sides	875	2.19	0.00	980	2.00	0.01	215	1.63	-0.01	2070	2.04	0.00
> = 10 sides	228	2.09	0.01	570	1.97	0.01	199	1.68	-0.02	997	1.94	0.01
Total	1765	2.23	0.01	1908	2.00	0.01	485	1.62	-0.01	4158	2.05	0.00

Source: Authors' calculations.

9. ASSESSING THE RESULTS OF THE EXPERIMENTS

The LSMS validation experiments confirm that the respondents' self-reports suffer from large errors and systematic bias. GPS measures are a valid alternative to compass and rope for most practical purposes. Compass and rope is four times more time consuming than GPS and not immune to measurement error.

9.1 COMPASS AND ROPE: HOW GOLDEN IS THE GOLD STANDARD?

Compass and rope constitutes the 'gold standard' in area measurement, but, as is the case with any measurement method, it is not immune from error. To some degree, the error associated with the compass and rope measurement is observable through the closing error. The closing error will not flag circumstances in which the corner points were properly identified (which can only be done through fieldwork supervision), but will ensure that the corners selected and the bearings taken create a full, closed polygon. The average closing error in our data across all measurement is around 2 percent, with the range going from 1.6 percent in Nigeria to 2.2 percent in Ethiopia (Table 7).

Regression analysis aimed at determining the factors that contribute to closing error is presented in Table 8. At the individual country level, only in Tanzania there is a significant negative relationship between plot area and closing error, implying that closing error is smaller on larger plots. When the data from three experiments are pooled, plot size has no significant effect on the closing error. The number of corners on the plot (as measured by the number of vertices captured in the compass and rope measurement) exhibits a negative and significant coefficient in Ethiopia and the pooled data – contrary to the expectation that more corners allows more room for measurement error. Tree cover proves to have little effect on the closing error, as none of the individual experiments exhibit significant coefficients.

Motivated by the observation of plots in which the GPS and CR measurements diverge more than might be expected from the technical limitations of a GPS device alone, we undertook an exercise to try to better understand the sources of error on these plots. For a select number of plots, which were selected based on the error observed and not randomly, the CR measurements were mapped in the same coordinate

Table 8 — Determinants of Closing Error

	Ethiopia	Tanzania	Nigeria	Pooled
CR area (acres)	0.020	-0.291**	0.096	-0.032
CR area^2	0.166	-	-0.005	-
CR area^3	-0.039**	-	-	-
Number of corners	-0.032***	0.006	-0.004	-0.013***
Slope (clinometer)	0.014***	-	-	-
Tree cover:				
Partial	-0.003	-0.052	-0.128	-0.143***
Heavy	0.183	-0.163	0.331	0.021
Weather:				
Mostly cloudy - rainy	-0.014	-0.128**	0.036	-0.048
Constant	2.298***	2.118***	1.597***	2.238***
N	1765	1908	485	4158
R^2	0.015	0.007	0.019	0.008

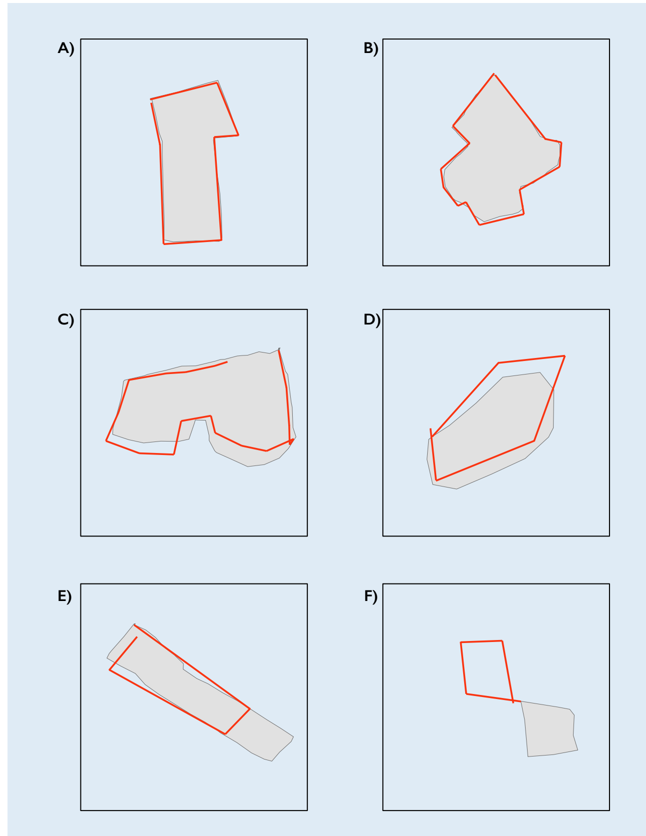
Source: Authors' calculations.

space as GPS outlines by generating shapes using the distance and bearing (which were recorded during the exercise), using the first vertex of GPS as a source point. A simple visual interpretation of of the results can be drawn from Figure 7, where red outlines are constructed from CR measurements and grey shapes are GPS plot outlines. The bias can in essence be mapped to a few stylized groups according to the source of the discrepancy:

- Negligible error: plots A) and B) show a small discrepancy between the two measures, and are included for reference
- Complex shape, high closing error: plot C) is a large plot with 19 sides and obvious closing error
- CR shape simplification: In plot D) the number of vertices in GPS is twice the number of CR corners
- Enumerator/field delineation error: On plot E) the enumerator appears to have gotten one of the two delineations wrong, and simplified the shape when taking the CR measure
- Error in CR bearing: On plot F) the enumerator appears to have switched front and back bearings for the CR measurement

While it is not possible to allocate the respective contributions to total bias from CR vs GPS, these observations do underline the fact that CR is also a complicated process with multiple potential sources of error. The CR method can lead to measurement error generation processes not dissimilar from those associated with competing instruments such as handheld GPS. Ultimately, however, there seems to be little evidence that closing error or error in other components of the CR measurement is systematic. This is comforting for the analysis that follows, as we move to explore systematic sources of error between methods, taking the CR method as the benchmark.

Figure 7 — CR vs. GPS Shapes



Source: Authors' calculations.

9.2 COMPARISON OF COMPETING MEASUREMENTS

9.2.1 COMPASS AND ROPE VS. SELF-REPORTED ESTIMATIONS

Before delving into the differences between CR and GPS measures, we now explore the difference in subjective (self-reported) and objective (CR) measurement.[16] As discussed above, farmer self-reported estimates of area have long been used in household surveys for the convenience and affordability of implementation. Additionally, because there is no field visit required, it is easier to collect self-reported data on all plots. GPS, on the other hand, is often associated with a non-negligible percentage of missing values when survey operations are large. We are not aware of large-scale household surveys that use compass and rope. The benefits of subjective measurement come at a significant cost to data quality, however, as they are subject to several potential sources of error.

Table 9 presents mean plot areas as measured by farmer self-reported estimation and compass and rope for all three methodological experiments. The data is grouped by compass and rope plot size class. The observed differences between self-reported estimation and the CR benchmark is very large in all the experiments, so that the comparability of subjective and objective measurements is immediately questioned. The mean self-reported and compass and rope measurements

Table 9 — Comparison of Self-Reported and CR Measures

Level (CR)	Ethiopia						Tanzania					
	N	SR	CR	Bias	Mean bias / mean CR	Difference in means	N	SR	CR	Bias	Mean bias / mean CR	Difference in means
1 (< 0.05 acres)	352	0.09	0.02	0.07	307%	***	44	0.32	0.04	0.28	661%	***
2 (< 0.15 acres)	392	0.27	0.09	0.18	188%	***	622	0.41	0.11	0.31	288%	***
3 (< 0.35 acres)	351	0.40	0.23	0.17	72%	***	816	0.62	0.23	0.39	173%	***
4 (< 0.75 acres)	316	0.66	0.51	0.15	29%	***	323	0.98	0.49	0.49	100%	***
5 (< 1.25 acres)	179	0.95	0.97	-0.02	-2%	-	63	1.53	0.92	0.61	66%	***
6 (>= 1.25 acres)	99	1.42	1.90	-0.47	-25%	***	20	2.05	1.81	0.24	13%	-
Total	1689	0.47	0.38	0.09	23%	***	1888	0.65	0.27	0.38	143%	***
Level (CR)	Nigeria						Pooled					
	N	SR	CR	Bias	Mean bias / mean CR	Difference in means	N	SR	CR	Bias	Mean bias / mean CR	Difference in means
1 (< 0.05 acres)	-	-	-	-	-	-	397	0.12	0.03	0.09	371%	***
2 (< 0.15 acres)	21	0.15	0.11	0.03	30%	-	1035	0.35	0.10	0.25	247%	***
3 (< 0.35 acres)	73	0.39	0.25	0.14	55%	***	1240	0.55	0.23	0.32	136%	***
4 (< 0.75 acres)	129	0.79	0.53	0.26	50%	***	768	0.82	0.50	0.31	62%	***
5 (< 1.25 acres)	108	1.31	0.99	0.32	33%	***	350	1.16	0.96	0.20	21%	***
6 (>= 1.25 acres)	153	2.56	2.87	-0.30	-11%	-	272	2.11	2.44	-0.32	-13%	**
Total	485	1.38	1.31	0.07	5%	-	4062	0.66	0.44	0.22	51%	***

Source: Authors' calculations.

differ by as much as 143 percent on average (Tanzania). The mean difference is smaller in Ethiopia and Nigeria, at 23 and 5 percent respectively, but still considerably larger than the divergence observed between the objective measurements.[17]

Self-reported measures result not only in higher average deviations, but in dramatically systematic measurement error patterns. In each of the methodological studies, the area of the smaller plots is severely overestimated. In Ethiopia, for plots less than 0.05 acres (as measured by compass and rope), the average farmer estimate of area is 0.09 acres, compared to an average compass and rope measurement of 0.02 acres (307 percent overestimation on average). In Tanzania, the overestimation of small plots is even more pronounced, with an average difference in means for the smallest plots 0.32 acres, or 661 percent overestimation with respect to compass and rope. While the smallest plots are significantly overestimated, the degree of overestimation falls with plot size and eventually, in Ethiopia and Nigeria, the sign of the bias is reversed with farmers on average underestimating the area of the larger plots. This is a matter of concern not only because of the magnitude of the observed bias, but also because the bias is correlated with key variables of interest (such as plot size itself) which will translate into biases at the analysis stage (e.g. in analyses of productivity or land distribution). The scatterplots on the right side of Figure 8 convey the same message in graphic form.

Farmer overestimation of small plots and underestimation of larger plots is not a phenomenon observed only in the controlled environments of the methodological studies. Nationally representative data from the LSMS-ISA Malawi and Tanzania, both for 2010/11, exhibit the same trends in comparison of GPS and self-reported area measurement

[16] Comparing self-reported to GPS yields exactly the same results, even when analyzed using data from the nationally representative LSMS surveys in Malawi (2010/11) and Tanzania (2010/11); therefore, we limit the comparison to self-reported and CR.

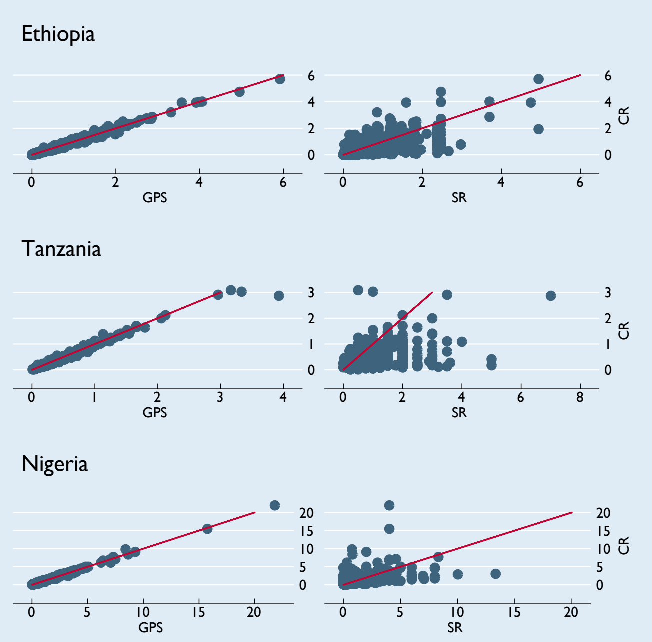
[17] SR and CR measurements are significantly different at the 1 percent level in Ethiopia, Tanzania, and the pooled data. In Nigeria, the SR and CR measurements are not significantly different on average. However, in disaggregating to plot size levels as found in Table 9 the SR and CR measurements are significantly different in levels 3, 4, and 5, all at the 1 percent level.

(compass and rope not available), with the self-reported estimates on the smallest plots over-reported by more than 300 percent (available from the authors). Carletto et al. (2013 and 2015) observe the same trend using LSMS-ISA data from Uganda and Niger, in addition to Malawi and Tanzania. De Groote and Traore (2005) had also reported similar results from Southern Mali. Taken together, these results point to the validity of these conclusions beyond the experiments, and certainly in much of the African continent. More studies will be needed to extend the results to other developing regions.

While Table 9 illustrates the degree to which farmer self-reported estimates differ from compass and rope measurements, it does not offer any explanation as to why the two systematically diverge. For this, we turn to regression analysis. Table 10 presents the results of four OLS regression models as per the discussion in Section 8 above: the first on the measurement bias (farmer self-reported estimate minus CR measured area), the second on the absolute value of this bias, the third on the relative (percentage) bias, and the fourth on the absolute value of the relative bias.

The claim of plot area affecting the direction and degree of error associated with self-reported area estimates is supported by the regression results. The results from the first

Figure 8 — Scatter Plots of Compass and Rope vs GPS (left) and Self-Reported (right) Land Area Measures, Acres



Note: Red line is line of equality between measurements

Source: Authors' calculations.

two specifications (on bias and its absolute value), indicate an increase in the bias with plot size. When looking at the relative bias and the absolute value of the relative bias, the linear term is negative and the quadratic term positive in all countries, indicating that in percentage term the bias declines steeply with plot size.

The regressions further reveal that the bias in self-reporting is systematically related not only to plot size, but to a host of other variables of interest, which is clearly a matter of concern for any analytical use of the data. In Ethiopia self-reported estimates of area diverge more from compass and rope measurements on those plots that are further from the household. Consistent with Carletto et al. (2015), the existence of property rights (proxied here by the possession of a title or certificate of ownership or the ability to sell or use the plot as collateral) has a significant, negative relationship with the relative bias in Ethiopia, suggesting that on plots for which the household has some form of property right, they are better able to estimate the area.

Results from Nigeria and Tanzania (but not Ethiopia) suggest that measurement bias is greater in households with older household heads. Contrary to expectations, the education and literacy status of the household head does not hold consistent results across country. In Ethiopia, the literacy of the household head is associated with reduced measurement bias (in acreage terms), but education has a positive association with bias.

Finally, one key decision point when collecting self-reported area data is whether to allow respondents to use non-standard units, or to force them (or enumerators) to convert responses from traditional to standard units at the moment of the interview. In Table 11, we compare deviations between self-reported and GPS data separately splitting the sample between observations where respondents used traditional and standard units in the Ethiopia and Nigeria sample. When land area is collected using non-standard units, as opposed to forcing respondents or enumerators to perform a conversion to standard units at the time of the interview, data from self-reporting appears to approximate the preferred GPS measures much better. This finding supports the idea that it is best to allow non-standard units to be used at interview time, while organizing complementary collection of adequate conversion factors to translate all the data into a common metric at the data processing stage.

Table 10 — Determinants of Bias (SR – CR)

	Ethiopia				Tanzania			
	SR-CR	|SR-CR|	{Bias/CR} *100	{|Bias|/CR} *100	SR-CR	|SR-CR|	{Bias/CR} *100	{|Bias|/CR} *100
CR area (acres)	0.043	0.278***	-775.385***	-724.752***	-0.070	0.821***	-1208.4***	-1172.4***
CR area²	-0.247***	-	425.846***	408.956***	-	-0.863***	966.7***	942.4***
CR area³	0.038***	-	-56.161***	-54.541***	-	0.264***	-209.4***	-202.0***
Number of corners	-0.011***	0.002	-10.179***	-8.710***	0.027***	0.022***	7.738***	7.490***
Distance from dwelling	0.012***	0.014***	5.047***	4.902***	0.000	0.000	-0.144	-0.153
Number cultivated plots in HH ‡	-0.014***	-0.011***	-4.841*	-3.735	-0.002	0.000	2.129	2.024
Slope (clinometer)	0.001	0.001	-1.865	-1.656	-	-	-	-
Soil quality (SR):								
Fair	-0.090***	-0.076***	-69.345***	-66.665***	-0.032	-0.023	2.226	3.229
Poor	-0.049	-0.057*	-130.936***	-123.089***	0.120	0.102	43.172	42.997
Property rights⁰	-0.012	-0.024	-32.988*	-33.235*	0.010	-0.002	-2.068	-3.612
Tree cover:								
Partial	0.131***	0.094***	124.283***	117.589***	0.064***	0.039*	5.838	3.351
Heavy	0.162***	0.165***	76.105**	74.343**	-0.019	-0.024	-11.779	-12.629
HH head characteristics:								
Female	-0.038	-0.028	-28.272	-28.918	-0.029	-0.019	15.763	15.81
Yrs. education	0.021***	0.016***	9.683**	8.871**	-0.002	-0.001	-1.735	-1.734
Age	-0.001	-0.001	-0.271	-0.249	0.001*	0.001**	0.744	0.776
Literate	-0.102***	-0.114***	-23.008	-23.86	-0.052	-0.051*	-15.767	-15.068
Constant	0.317***	0.231***	456.555***	452.797***	0.158**	0.053	338.02***	335.02***
Includes country dummies	-	-	-	-	-	-	-	-
N	1689	1689	1689	1689	1737	1737	1737	1737
R2	0.231	0.279	0.206	0.183	0.073	0.150	0.170	0.160

(contd.)

Table 10 — Determinants of Bias (SR – CR) (contd.)

	Nigeria				Pooled			
	SR-CR	|SR-CR|	{Bias/CR}* 100	{|Bias|/CR }* 100	SR-CR	|SR-CR|	{Bias/CR }* 100	{|Bias|/CR }* 100
CR area (acres)	0.112	0.454***	-25.308***	-10.551***	-0.014	0.341***	-255.718***	-229.597***
CR area^2	-0.127***	0.017***	0.966***	0.532***	-0.101***	0.022***	42.172***	39.887***
CR area^3	0.004***	-	-	-	0.003***	-	-1.457***	-1.392***
Number of corners	0.048***	0.017	1.968**	1.517**	0.026***	0.014***	-0.110	-0.156
Distance from dwelling	-	-	-	-	-	-	-	-
Number cultivated plots in HH ‡	0.061	0.088***	0.799	2.861	-0.016***	-0.007**	-2.768	-1.726
Slope (clinometer)	-	-	-	-	-	-	-	-
Soil quality (SR):								
Fair	-	-	-	-	-	-	-	-
Poor	-	-	-	-	-	-	-	-
Property rights[0]	0.082	-0.133	8.284	-7.938	0.017	-0.033**	-9.745	-13.003
Tree cover:								
Partial	-0.273***	-0.114	-39.153***	-21.355**	0.03	0.045***	46.016***	45.218***
Heavy	0.518**	0.415**	-9.628	-2.723	0.243***	0.172***	47.628***	43.547**
HH head characteristics:								
Female	0.348	0.117	8.628	-5.546	-0.008	-0.025	-4.621	-6.532
Yrs. education	0.019	-0.002	0.551	-0.059	0.005	0.000	-0.352	-0.558
Age	0.010**	0.003	0.520	0.14	0.001	0.000	-0.102	-0.129
Literate	0.397	0.074	31.090*	9.958	0.024	-0.031	2.714	-1.544
Constant	-1.186***	-0.317	8.794	66.538***	-0.066	0.057	253.352***	270.263***
Includes country dummies	-	-	-	-	Yes	Yes	Yes	Yes
N	485	485	485	485	3931	3931	3931	3931
R2	0.529	0.625	0.111	0.032	0.386	0.510	0.114	0.090

*p<0.1; ** p<0.05; *** p<0.01
‡ In Tanzania, number of plots owned or cultivated.
[0]Property rights defined here as: HH has title or certificate, HH has ability to sell land, or HH can use land as collateral.
Source: Authors' calculations.

Table 11 — Standard and Non-Standard Area Units

Level (GPS)	Ethiopia								
	Standard units				Non-standard units				
	N	SR	GPS	Mean bias/ mean GPS	N	SR	GPS	Mean bias/ mean GPS	Difference in bias
1 (< 0.05 acres)	-	-	-	-	375	0.09	0.02	276.1%	-
2 (< 0.15 acres)	31	0.67	0.09	643.6%	356	0.24	0.10	150.0%	***
3 (< 0.35 acres)	24	1.02	0.25	302.4%	349	0.36	0.23	53.6%	***
4 (< 0.75 acres)	20	1.32	0.52	152.4%	309	0.60	0.52	16.3%	***
5 (< 1.25 acres)	-	-	-	-	163	0.87	0.96	-9.8%	-
6 (>= 1.25 acres)	-	-	-	-	93	1.19	1.71	-30.3%	-
Total	120	1.16	0.63	84.2%	1645	0.42	0.37	12.9%	***
Level (GPS)	**Nigeria**								
	Standard units				**Non-standard units**				
	N	**SR**	**GPS**	**Mean bias/ mean GPS**	**N**	**SR**	**GPS**	**Mean bias/ mean GPS**	**Difference in bias**
1 (< 0.05 acres)	-	-	-	-	-	-	-	-	-
2 (< 0.15 acres)	-	-	-	-	25	0.15	0.11	38.1%	-
3 (< 0.35 acres)	-	-	-	-	69	0.33	0.25	33.9%	-
4 (< 0.75 acres)	28	1.49	0.53	181.4%	112	0.67	0.54	24.4%	***
5 (< 1.25 acres)	25	2.24	1.01	121.2%	71	1.06	0.99	7.3%	***
6 (>= 1.25 acres)	76	3.51	3.24	8.4%	76	1.61	2.51	-35.9%	**
Total	131	2.80	2.19	28.2%	354	0.85	0.97	-12.2%	***

*p<0.1; ** p<0.05; *** p<0.01
Source: Authors' calculations.

9.2.2 COMPASS AND ROPE VS. GPS

Having ascertained the presence of a large bias in subjective measurement, this section explores the relationship between the two primary means of objective measurement: GPS and compass and rope. In the literature, the main reservation regarding the use of GPS measurement in surveys is its performance on small plots. Furthermore, Keita and Carfagna (2009), Schoning et al. (2005), and Palmegiani (2009) all found that GPS tends on average to err on the negative side, i.e. to understate the area with respect to compass and rope.

Table 12 presents descriptive statistics on the GPS and compass and rope area measurements completed as part of the methodological studies. The data is presented in six classes of plot size as measured by compass and rope: level one contains all the smallest plots (less than 0.05 acres) whereas level six includes the largest plots (greater than or equal to 1.25 acres).[18] Mean plot size is small in all countries, ranging from 0.27 acres in Tanzania to 1.31 acres in Nigeria.

The mean difference between compass and rope and GPS measurement is very small, whether expressed in acres or as a percentage of the compass and rope acreage.[19] The sample mean bias in all three countries is +/- 0.01 acre, which translates in a 1-3 percent difference when expressed in relative terms (note that the values are not expressed in absolute value and as such negative and positive differences offset each other on average). Unlike previous studies, the data do not

Table 12 — GPS vs Compass and Rope (CR) Measures

Level (CR)	Ethiopia						Tanzania					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
1 (< 0.05 acres)	390	0.02	0.02	0.00	0%	-	45	0.04	0.04	0.00	-3%	-
2 (< 0.15 acres)	400	0.10	0.09	0.00	2%	***	631	0.11	0.11	0.00	2%	***
3 (< 0.35 acres)	365	0.24	0.24	0.01	3%	***	823	0.23	0.23	0.01	2%	***
4 (< 0.75 acres)	328	0.52	0.51	0.01	2%	***	326	0.51	0.49	0.02	4%	***
5 (< 1.25 acres)	182	0.98	0.96	0.02	2%	***	63	0.94	0.92	0.02	2%	***
6 (>= 1.25 acres)	100	1.91	1.89	0.02	1%	-	20	1.91	1.81	0.09	5%	-
Total	1765	0.38	0.38	0.01	2%	***	1908	0.28	0.27	0.01	3%	***

Level (CR)	Nigeria						Pooled					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
1 (< 0.05 acres)	-	-	-	-	-	-	436	0.02	0.02	0.00	-1%	-
2 (< 0.15 acres)	21	0.11	0.11	-0.01	-7%	***	1052	0.10	0.10	0.00	2%	***
3 (< 0.35 acres)	73	0.24	0.25	-0.01	-4%	***	1261	0.24	0.23	0.01	2%	***
4 (< 0.75 acres)	129	0.52	0.53	-0.01	-2%	**	783	0.51	0.50	0.01	2%	***
5 (< 1.25 acres)	108	0.97	0.99	-0.02	-2%	***	353	0.97	0.96	0.01	1%	-
6 (>= 1.25 acres)	153	2.86	2.87	-0.01	0%	-	273	2.44	2.43	0.01	0%	-
Total	485	1.30	1.31	-0.01	-1%	*	4158	0.44	0.44	0.00	1%	***

*p<0.1; **p<0.05; ***p<0.01
Source: Authors' calculations.s

exhibit any clear trends in terms of GPS underestimating plot size compared to CR, neither on average, nor across the distribution of plot sizes. In Nigeria, GPS underestimates plot size compared to CR, but only slightly, while in Tanzania and Ethiopia GPS averages are somewhat larger than compass and rope measurements. Moreover, the magnitude as well as the sign of the error seem both to be unrelated to plot size, being small in all of the plot size classes.

The concern of GPS accuracy at small plot levels is also discounted. While some literature suggests that plots smaller than 0.5 hectares (1.24 acres) have significantly different GPS and compass and rope measurements with much lower correlation (Schoning et al., 2005), results from the methodological validation experiments suggest otherwise. In the pooled data, the difference between the average GPS measurement and average compass and rope measurement for plots ranging from 0.05 – 0.15 acres was less than 0.002 acres or 2 percent of the average compass and rope area. Even for the smallest plots, those less than 0.05 acres (202.3 square meters or 0.02 hectares), on average the measurements are extremely close. In Ethiopia, the average GPS measurement of 390 plots in

[18] Results for categories in which there are fewer than 20 observations are not reported. The same is true for all tables presented in the paper.

[19] GPS and CR measurements are significantly different at the 1 percent level in Ethiopia, Tanzania, and the pooled data. In Nigeria, GPS and CR area measurements are significantly different at the 10 percent level. Furthermore, in Nigeria the GPS and compass and rope measurements are significantly different at the 5 percent level for all plot size levels reported in Table 12 except for the largest plots (level 6), in which the measurements are not significantly different. Notably, GPS and CR measurements on the smallest plots (level 1) are not found to be significantly different in Ethiopia, Tanzania or the pooled data.

this size range is 0.0216 while the average compass and rope measurement for the same plots is 0.0215 acres.

The small mean relative bias that is recorded does not appear to bear any clear trend with plot size in the grouped data. In Tanzania, the smallest and largest plot classes have the smallest and largest average relative bias, but figures are not large (between -3 percent and 5 percent), and the number of observations in these two classes fairly small (less than 50). The correlation coefficients between GPS and CR measures are in excess of 0.99 in all three studies, and 0.87 or larger in all classes with n larger than 50 (Table 13).

The results presented here suggest that average GPS measures are not much different from compass and rope even for very small pots, and even from fairly small n, and that is despite the difference in enumerator skill levels and plot characteristics of the different studies. This is confirmed by an inspection of the scatterplots in the left side of Figure 8, where GPS measures are plotted against compass and rope with measures tightly clustered around the equality line. This lends support to the argument that GPS is an acceptable substitute of compass and rope measures across the entire range of plot sizes in our samples, at least if the goal is that of estimating average plot size for groups with sufficient numerosity.

From the perspective of survey practitioners and national statistical offices, considerations about accuracy need to be accompanied by considerations related to timing (and hence cost). In survey implementation, time is often the scarcest and most valuable resource, and enumerators' remuneration an important budget item. The reason why the choice of method should matter for survey practitioners is compellingly conveyed by Figure 9, which shows the measurement time for GPS and compass and rope measurements by plot size classes, moving from small plots on the left to large plots on the right. Compass and rope requires significantly more time than GPS, with time increasing exponentially with plot size, while the additional time required for GPS measurement for larger plots of the order of magnitude included in these studies is negligible. In both the Ethiopia and Tanzania experiments,[20] the compass and rope measurement took approximately four times that required for GPS. GPS required 13.9 minutes on average in Ethiopia, while the compass and rope measurement on the same plots required an average of 57 minutes. In Tanzania, the duration averages were 7.4 minutes and 29.3 minutes for GPS and compass and rope respectively. These findings are consistent with previous studies such as Schoning et al. (2005) and Keita and Carfagna (2009) who find that compass and rope takes approximately 3.5 times as long as GPS on average.

To put the time considerations into context, given the sample size and average measurement durations in Ethiopia, the field teams spent a total of 416 hours measuring plots with GPS (1797 plots * 13.89 minutes) and 1,707 hours measuring with compass and rope. Using GPS instead of compass and rope, therefore, saves 1,291 hours of labor: over 160 persons/days (at 8 hours per day)! This estimate of time savings is for a relatively small-scale methodological experiment; savings in nationally representative household surveys would be proportionally larger. The true value comes in the ability of enumerators to complete the interviews of more households per day. With GPS measurement, enumerators are more likely to complete more than one household interview in a single day, allowing mobile field teams to spend less time in a particular area. Minimizing the amount of time required to collect quality land area data can significantly reduce costs and improve the flow of fieldwork.

Table 13 — Correlation Coefficient (GPS & CR)

Level (CR)	Ethiopia	Tanzania	Nigeria	Pooled
1 (< 0.05 acres)	0.95	0.81	-	0.95
2 (< 0.15 acres)	0.91	0.92	0.91	0.92
3 (< 0.35 acres)	0.90	0.95	0.90	0.93
4 (< 0.75 acres)	0.91	0.96	0.87	0.92
5 (< 1.25 acres)	0.93	0.95	0.91	0.92
6 (>= 1.25 acres)	0.98	0.96	1.00	1.00
Total	0.996	0.993	0.997	0.997

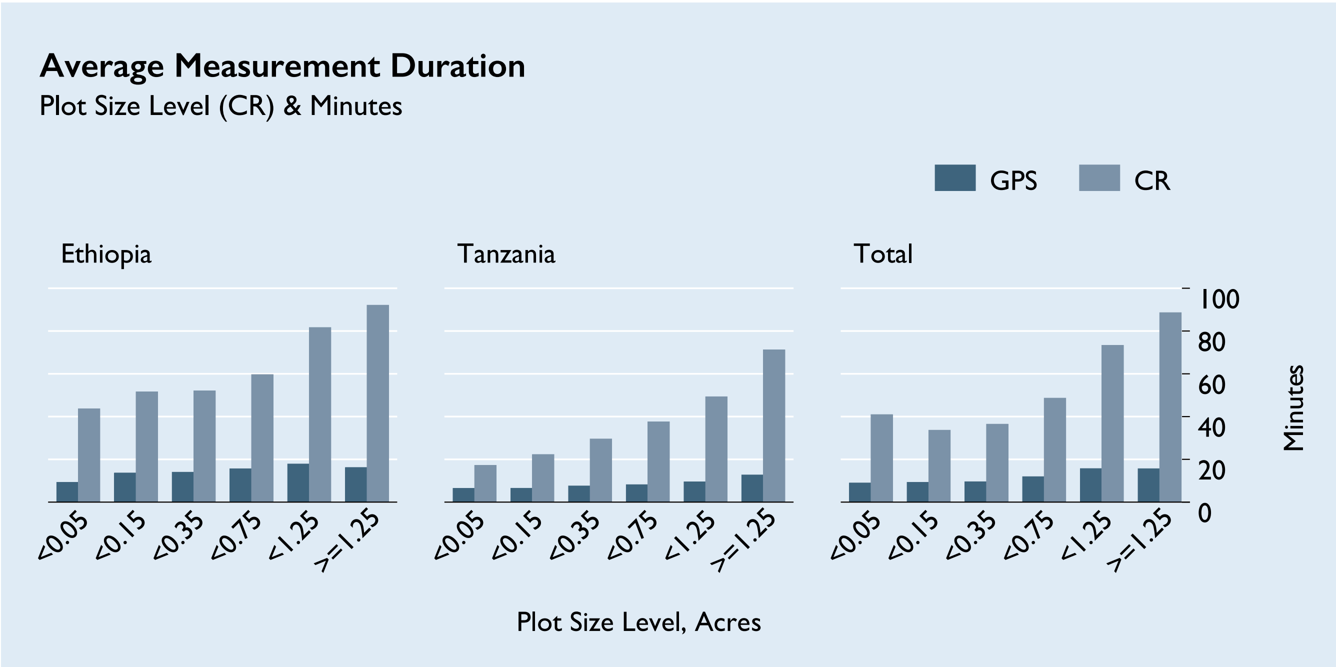
Source: Authors' calculations.

9.2.3 GPS MEASURES: EXPLORING THE DEVIATIONS FROM THE GOLD-STANDARD

As stated earlier in this paper, previous studies have raised the issue of how factors other than plot size (such as number of available satellites, geographic and atmospheric conditions)

[20] Data on measurement duration is not available for Nigeria.

Figure 9 — Time Taken for GPS and CR Measurement by Plot Size (Minutes)



may affect the quality of GPS measures. None of the studies have provided compelling, conclusive evidence on the impact of these factors on measurement quality. Some have explicitly called for further research to systematically investigate this matter. Our data allow us to do that in a systematic manner for a number of factors including plot shape, slope, and tree cover, weather conditions, and number of GPS satellites acquired at the time of measurement. We do this via a comparison of the GPS measurement to the 'gold standard' of CR measurement on the same plots.

The global navigation system requires, at a minimum, the acquisition of four satellites to triangulate the 3D position of the GPS receiver. The acquisition of additional satellites can improve position error.[21] Enumerators in both the Tanzania and Ethiopia experiments recorded the number of satellites fixed at the start of the GPS measurement. In training, enumerators were instructed to wait until at least four satellites were acquired, with further instruction that they must wait until the "GPS accuracy" figure on the GPS device stabilized (therefore allowing time for maximum satellite acquisition). We group observations according to the number of satellites acquired at the time of measurement (less than or equal to 15 satellites, 15 to 19 satellites, and more than 19 satellites), with the thresholds for these classes being based on the characteristics of the distribution, not on any theoretical argument. The mean GPS and compass and rope measurements at the three levels of satellite acquisition are reported in Table 14. As expected, the differences in area measurements tend to decline as the number of satellites increase, even though average differences remain small across all groups. In Ethiopia, the difference between measurements is 1.6 percent (but not statistically significant) on the plots with fewest satellites and 1.2 percent on plots with the most satellites, although the trend is not linear as the middle category has an average of 1.8 percent bias. In Tanzania, the differences are 2.9 and 2.6 percent, respectively.

Various geographic and atmospheric conditions can impact the satellite signal acquisition. Dense canopy cover and weather conditions at the time of measurement have been found or argued to impair the accuracy of the GPS measurement. To address the concern over canopy density and the impact on GPS area measurement accuracy, the methodological validation studies included a subjective measure of canopy density. Table 15 presents the average GPS and compass and rope measurements disaggregated by level of tree cover. Contrary to expectations, the relative difference between the two measurements was slightly higher on plots with no tree cover, with the level of bias decreasing with increasing canopy density. This could be attributable to plot size, enumerator characteristics or other factors, which are not

[21] http://www.garmin.com/aboutGPS/

Table 14 — Bias and Number of Satellites

Number of satellites	Ethiopia						Tanzania					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
<= 15	305	0.23	0.22	0.00	1.6%	-	488	0.31	0.30	0.01	2.9%	***
16 - 19	1204	0.40	0.39	0.01	1.8%	***	1266	0.27	0.26	0.01	2.9%	***
> = 20	256	0.49	0.48	0.01	1.2%	**	154	0.24	0.24	0.01	2.6%	***
Total	1765	0.38	0.38	0.01	1.7%	***	1908	0.28	0.27	0.01	2.9%	***

*p<0.1; **p<0.05; ***p<0.01

Source: Authors' calculations.

controlled for in these simple descriptive statistics. The sections below will further explore the influence of tree cover on measurement.

It was argued above that weather conditions should not influence the precision of GPS point estimates, rather it is higher level atmospheric conditions which can impact the satellite signals and influence the precision of GPS point estimates. However, the literature on GPS measurementst points to weather conditions as a potential source of error. In order to address this discrepancy, all three methodological studies included a subjective measure of weather at the time of measurement, ranging from all clear to rainy. Table 16 presents the mean area measurements and the associated discrepancy by weather condition. In this case, no clear trend emerges in terms of systematic association of the differences between the two measures and weather conditions. In Ethiopia, the relative bias in measurements hovers around 2 percent for plots measured in conditions "mostly clear" or better. The descriptive statistics from Nigeria and Tanzania provide little evidence that weather conditions have an adverse effect on GPS area measurement. It should be noted that the majority of plots were measured in conditions "partly cloudy" or clearer.

Keita and Carfagna (2010) and Muwanga-Zake (1985) explain that plot slope can influence the difference between GPS and compass and rope measured areas, as the GPS

Table 15 — Bias and Tree Cover

Tree cover	Ethiopia						Tanzania					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
None	1245	0.40	0.39	0.01	2.0%	***	858	0.27	0.26	0.01	3.2%	***
Partial	431	0.35	0.35	0.00	0.7%	-	946	0.28	0.27	0.01	2.8%	***
Heavy	89	0.28	0.28	0.00	1.0%	-	104	0.34	0.33	0.01	1.6%	*
Total	1765	0.38	0.38	0.01	1.7%	***	1908	0.28	0.27	0.01	2.9%	***
Tree cover	Nigeria						Pooled					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
None	150	0.92	0.94	-0.02	-2.1%	-	2253	0.38	0.38	0.01	1.6%	***
Partial	278	1.42	1.43	-0.01	-0.6%	-	1655	0.49	0.48	0.00	0.7%	**
Heavy	57	1.66	1.66	0.00	-0.1%	-	250	0.62	0.62	0.00	0.4%	-
Total	485	1.30	1.31	-0.01	-0.9%	*	4158	0.44	0.44	0.00	1.1%	***

*p<0.1; **p<0.05; ***p<0.01

Source: Authors' calculations.

Table 16 — Bias and Weather Conditions

Weather	Ethiopia						Tanzania					
	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means	N	GPS	CR	Bias	Mean bias / mean CR	Difference in means
Clear/sunny	576	0.50	0.49	0.01	1.9%	***	800	0.30	0.29	0.01	3.3%	***
Mostly clear	733	0.33	0.33	0.01	2.0%	***	217	0.28	0.27	0.00	1.3%	**
Partly cloudy	334	0.32	0.31	0.00	0.6%	-	705	0.25	0.24	0.01	2.8%	***
Mostly cloudy	94	0.34	0.34	0.00	-0.1%	-	76	0.22	0.21	0.01	3.1%	**
Completely cloudy	-	-	-	-	-	-	41	0.26	0.25	0.00	2.0%	**
Rainy	-	-	-	-	-	-	69	0.29	0.28	0.01	2.7%	***
Total	1765	0.38	0.38	0.01	1.7%	***	1908	0.28	0.27	0.01	2.9%	***
Weather	**Nigeria**						**Pooled**					
	N	**GPS**	**CR**	**Bias**	**Mean bias / mean CR**	**Difference in means**	**N**	**GPS**	**CR**	**Bias**	**Mean bias / mean CR**	**Difference in means**
Clear/sunny	317	1.31	1.32	-0.01	-0.9%	**	1693	0.56	0.55	0.01	1.0%	***
Mostly clear	101	1.35	1.34	0.01	0.5%	-	1051	0.42	0.41	0.01	1.5%	***
Partly cloudy	62	1.13	1.16	-0.03	-2.6%	-	1101	0.32	0.32	0.00	1.0%	*
Mostly cloudy	-	-	-	-	-	-	174	0.30	0.30	0.00	0.5%	-
Completely cloudy	-	-	-	-	-	-	54	0.25	0.25	0.00	1.3%	-
Rainy	-	-	-	-	-	-	85	0.34	0.33	0.01	2.1%	*
Total	485	1.30	1.31	-0.01	-0.9%	*	4158	0.44	0.44	0.00	1.1%	***

*p<0.1; **p<0.05; ***p<0.01

Source: Authors' calculations.

measures the horizontal plane and traversing measures the surface area. Fermont and Benson (2011) note that plot slopes greater than 10 degrees will result in significantly different measurements. The LASER study incorporated the use of clinometers for slope measurement. Descriptive statistics on the slope and measurement bias are reported in Table 17. For plots of slope of 5 degrees or less, the mean relative difference is 1.3 percent, whereas for plots of 6 – 15 degrees it is 2.2 percent and for plots of slope greater than 15 degrees it is 2.4 percent. Plot slope may play a role in the discrepancy observed between GPS and compass and rope area measurement, but the materiality of the impact is questionable.

Having ascertained that the average difference between GPS and CR is small does not rule out that for individual measurements, there may be observations with errors of significant magnitude. To investigate this issue, we plot the percentage and absolute differences between GPS and CR measures over plot area (Figure 10). A number of considerations emerge from a visual analysis of these graphs. First, the GPS measurement error in percentage terms is often far from negligible, in some instance larger than +/- 50 percent. Second, large percentage errors appear to be roughly equally distributed above or below the zero line, which explains why we do not observe differences in the means for the two measures. Thirdly, the magnitude of the percentage errors is much larger for the small size classes, and decreases rapidly as plot size increase. Those trends are clearly mirrored by the graphs with the absolute bias, which show no clear correlation with plot size and fairly constant dispersion both sides of the zero line, with most values within the plus/minus 5 range. That seems to suggest that it is the inherent imprecision of GPS devices that causes percentage error to matter much more for very small plots. We therefore turn to investigating in greater depth the extent and nature of the errors for 'high-bias' observations, as arbitrarily

Table 17 — Bias and Slope (Measured with a Clinometer)

Plot slope (degrees)	Ethiopia					Difference in means
	N	GPS	CR	Bias	Mean bias / mean CR	
0 - 5	1076	0.36	0.35	0.00	1.3%	***
6 - 15	562	0.44	0.43	0.01	2.2%	***
> 15	127	0.37	0.36	0.01	2.4%	**
Total	1765	0.38	0.38	0.01	1.7%	***

*p<0.1; **p<0.05; ***p<0.01
Source: Authors' calculations.

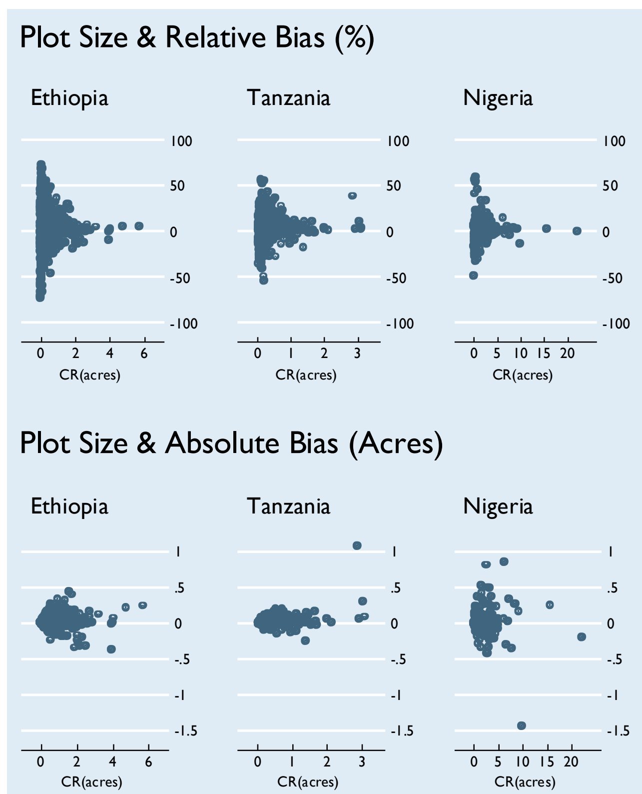
defined using a +/- 10 percent deviation between the GPS and the CR measures.

Table 18 reports on key characteristics of the plots and the measurements, slicing the sample according to whether the bias is below or above the 10 percent threshold, and splitting the latter portion of the sample in observations where GPS over- or under-reports land area. The first thing to observe is that the number of observations with such large errors is far from negligible, ranging from 17 percent in Nigeria to 31 percent in Ethiopia. Again, no strong systematic bias emerges in terms of GPS over- or under-reporting: differences in average acreage between GPS and CR are small even for the high-error portion of the sample in all countries. In two of the three experiments (Ethiopia and Tanzania), there are more GPS observations with large percentage over-reporting compared to under-reporting; in Nigeria, the opposite is true. Desiere and D'Haese (2015) present more optimistic results in their robust sample of over 50,000 parcel-level observations in Burundi, as 90 percent of plots greater than 550 m_2 were measured with less than 10 percent absolute value of relative error.

The table also reports the average values for several of the variables that are expected to influence the quality of GPS measurement. We do not observe any substantial difference for some of the factors that are often cited as important for GPS measurement, such as number of plot corners, number of satellites and tree canopy cover. We do however observe some difference in the perimeter/area ratio, which approximates the complexity of a plot shape. In all three experiments, this is higher in plots that are substantially underestimated by the GPS measure, compared to the plots that are measured with greater accuracy. Ethiopia is the only country for which such a difference, albeit of much smaller magnitude, is also observed for plots with size over-reported by more than 10 percent. Plot shape complexity therefore does seem to affect GPS accuracy, resulting mostly in under-reporting of the plot size. The plot shape, however, also has implications on the accuracy of the CR measurement which we are using as a benchmark for accuracy of the GPS.

One last variable for which there appears to be systematic differences is the magnitude of the CR closing error. In both Ethiopia and Tanzania there is a gradient between plots that are underestimated by a large margin (which have the smallest closing error), plots with error below 10 percent (which have in-between closing error), and plots with large GPS overestimates (with the largest closing error). In Nigeria the plots with larger overestimates are also the ones with the largest closing error, but the ranking of the other two groups is inverted. What we conclude from these observations is

Figure 10 — Scatter Plots of Relative (%) and Absolute (Acres) Bias over Plot Size (Acres)



Source: Authors' calculations.

Table 18 — Descriptive Statistics for High-Bias Observations

	Ethiopia						Tanzania					
	Relative bias > 10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Relative bias < 10%	All plots	Difference in means (>10% bias vs. < 10%)	Relative bias > 10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Relative bias < 10%	All plots	Difference in means (>10% bias vs. < 10%)
N:	542	305	237	1223	1765		388	251	137	1520	1908	
% of total plot sample	31%	17%	13%	69%	100%		20%	13%	7%	80%	100%	
Average:												
CR area (acres)	0.22	0.23	0.20	0.45	0.38	***	0.21	0.23	0.17	0.28	0.27	***
GPS area (acres)	0.23	0.28	0.16	0.45	0.38	***	0.22	0.27	0.14	0.29	0.28	***
Bias (GPS - CR)	0.01	0.05	-0.03	0.00	0.01	***	0.02	0.04	-0.03	0.01	0.01	***
|% Bias|	22.74	23.18	22.18	3.41	9.34	***	16.95	16.61	17.57	4.13	6.74	***
Closing error (%)	2.24	2.31	2.14	2.22	2.23	-	2.09	2.22	1.86	1.97	2.00	*
Number of corners	5.94	5.98	5.89	6.48	6.32	***	8.09	8.25	7.80	8.35	8.30	-
Per : area ratio (GPS)	0.41	0.27	0.59	0.20	0.26	***	0.19	0.16	0.24	0.15	0.16	***
Number of satellites	17.0	17.1	16.8	17.4	17.3	***	16.5	16.6	16.4	16.8	16.7	**
Walking speed (m/min)	37.0	37.8	36.1	43.5	41.5	***	42.1	42.4	41.6	44.3	43.9	***
Tree cover:												
Partial (n)	139	77	62	292	431		207	132	75	739	946	
(%)	26%	25%	26%	24%	24%	-	53%	53%	55%	49%	50%	*
Heavy (n)	39	20	19	50	89		26	16	10	78	104	
(%)	7%	7%	8%	4%	5%	***	7%	6%	7%	5%	5%	-

(contd.)

Table 18 — Descriptive Statistics for High-Bias Observations (contd.)

	Nigeria						Pooled					
	Relative bias >10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Relative bias <10%	All plots	Difference in means (>10% bias vs. < 10%)	Relative bias >v10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Relative bias < 10%	All plots	Difference in means (>10% bias vs. < 10%)
N:	83	30	53	402	485		1013	586	427	3145	4158	
% of total plot sample	17%	6%	11%	83%	100%		24%	14%	10%	76%	100%	
Average:												
CR area (acres)	0.94	1.31	0.72	1.38	1.31	**	0.27	0.29	0.25	0.49	0.44	***
GPS area (acres)	0.96	1.56	0.61	1.37	1.30	*	0.29	0.34	0.21	0.49	0.44	***
Bias (GPS - CR)	0.02	0.25	-0.11	-0.02	-0.01	**	0.01	0.05	-0.04	0.00	0.00	***
|% Bias|	18.96	23.60	16.33	3.93	6.50	***	20.21	20.39	19.97	3.82	7.82	***
Closing error (%)	2.05	2.68	1.69	1.54	1.62	***	2.16	2.29	1.99	2.01	2.05	***
Number of corners	9.17	9.50	8.98	10.24	10.06	-	7.03	7.13	6.89	7.87	7.66	***
Per : area ratio (GPS)	0.13	0.08	0.15	0.09	0.09	***	0.30	0.21	0.42	0.16	0.20	***
Number of satellites	-	-	-	-	-	-	-	-	-	-	-	-
Walking speed (m/min)	58.6	67.5	53.3	61.8	61.3	*	40.7	41.3	39.9	46.0	44.7	***
Tree cover:												
Partial (n)	50	18	32	228	278		396	227	169	1259	1655	
(%)	60%	60%	60%	57%	57%	-	39%	39%	40%	40%	40%	-
Heavy (n)	9	3	6	48	57		74	39	35	176	250	
(%)	11%	10%	11%	12%	12%	-	7%	7%	8%	6%	6%	**

Source: Authors' calculations.

that for the cases in which we observe substantial deviations between GPS and CR measures, part of the explanation is likely to result in noise in the CR measures. In that sense, the inaccuracy in the GPS measures may be somewhat less serious than the prevalence of high bias cases seems to indicate, particularly when recognizing that the gold standard is also bound to be imperfect.

9.2.4 A MULTIVARIATE ANALYSIS OF FACTORS CONTRIBUTING TO DEVIATIONS OF GPS FROM CR

The descriptive statistics presented above are aimed at comparing the two primary objective area measurement options: GPS and compass and rope. In this section, regression analysis is used to explore the determinants of measurement bias, defined here as the difference between GPS measured area and compass and rope measured area, which is used as the benchmark.

The results in Table 19 include four specifications per data-set, the difference among them being the dependent variable, which is: (i) bias (GPS – CR), (ii) absolute value of bias, (iii) relative bias (bias divided by CR area * 100), and (iv) absolute value of relative bias. Recall from the descriptive statistics that the observed error is generally small, and that we found little evidence of systematic variation with many of the factors that are a priori expected to influence GPS measurement precision. It is therefore not completely surprising that the explanatory power of these regressions (as captured by their R2 values) is low, and that a majority of the estimated coefficients are not statistically significant.

The main variables of interests are the set of terms (levels, quadratic, cubic) related to the plot size itself, as measured by CR, graphic representations of which are available in Figure 11. In the first specification, there appears to be a relationship between plot size and measurement error only in Ethiopia, where the shape of the relationship is that of an inverted U, with the predicted bias being positive on very small plots, peaking at about 0.7 acres, and becoming negative for plots larger than about 1.7 acres. The coefficients are small, so that the predicted error is in the +/- 0.02 acres range. In Tanzania, a linear relationship is exhibited in which larger plot size results in larger bias (in terms of acres). In Nigeria and the pooled data, there is no statistically significant relationship between bias and plot size, controlling for other factors.

When the absolute level is considered, in the second specification, the relationship with plot size becomes monotonically positive, with a small curvature (quadratic term is significant) only in Nigeria. Values are somewhat larger, up to about 0.2 acres in the observed plot size range, but still small.

When the percentage bias is considered (third specification), the relationship with plot size becomes an L-shaped quadratic curve (the cubic term is significant only in Ethiopia and the pooled data, tilting the curve up around the 2 acres mark). The last specification has the absolute bias expressed in percentage terms as the dependent variable, with the relationship with plot size being again best characterized as L-shaped.

Taken together these results are in line with the earlier descriptive analysis in that the overall distribution of the bias does not seem to bear much relationship with plot size, as they are largely equally distributed on the positive and negative side. The absolute magnitude of the error does however increase somewhat with plot size, but less than proportionally. For that reason, in percentage terms the bias actually declines fairly rapidly as plot size increase, stabilizing as plot size reaches the 1-2 acres range.

Of the other covariates reflecting physical characteristics expected to affect the quality of GPS measures (cloud and canopy cover, plot slope), hardly any are consistently significant across countries. In Ethiopia and Tanzania, there is evidence that heavy canopy cover does increase relative bias (in absolute value, specification 4).

What appear to matter most are closing error and the perimeter/area ratio. The former reflects inaccuracy in the CR measure, while the latter is a proxy for the complexity of the plot shape which is likely to affect the accuracy of GPS measures, but can in principle also be capturing noise in the CR measure aside from what is captured by the closing error.

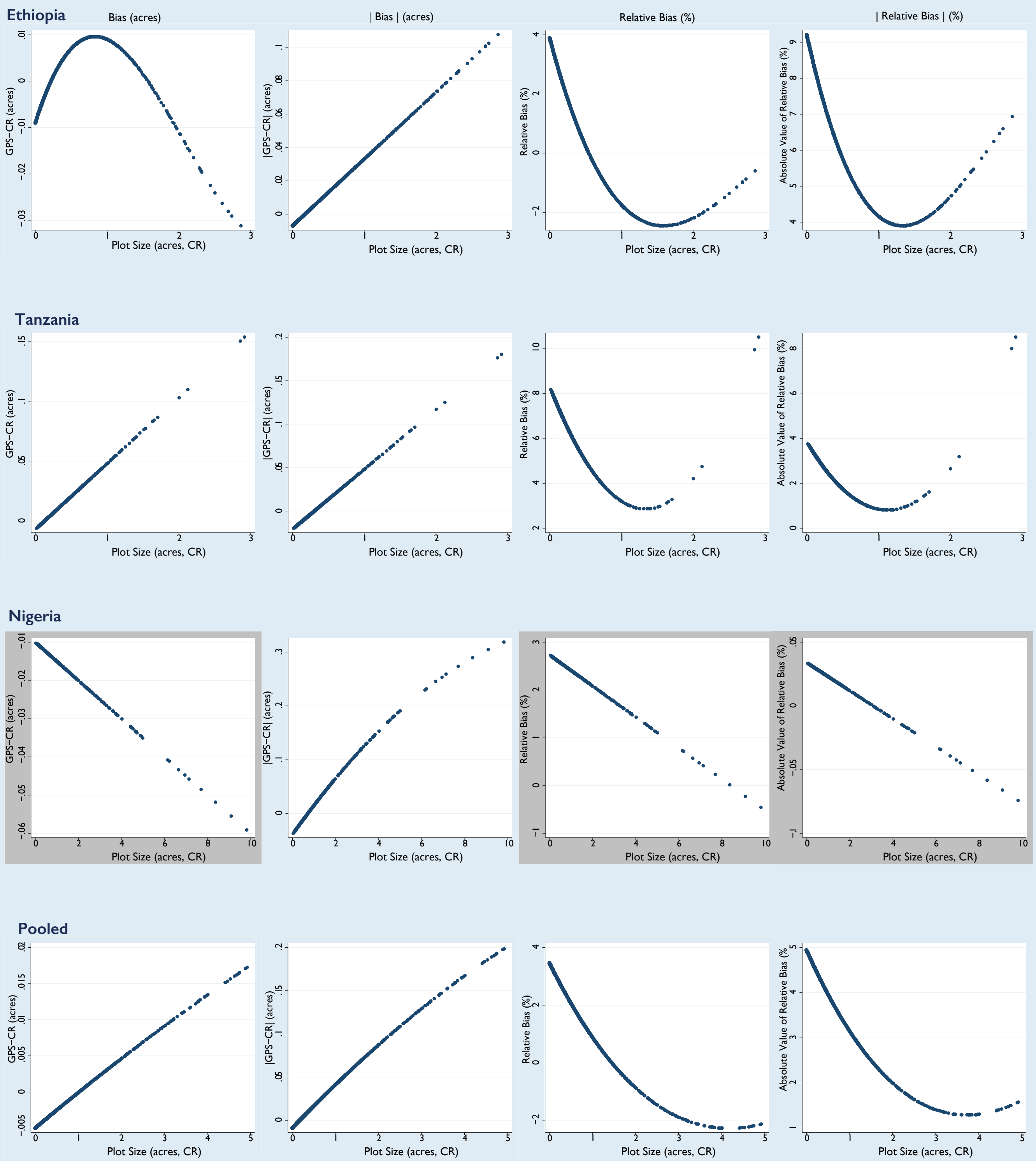
Table 19 — Determinants of Bias (GPS – CR, in acres)

	Bias	|Bias|	{Bias/CR}*100	{|Bias|/CR }*100	Bias	|Bias|	{Bias/CR }*100	{|Bias|/CR}*100
	Ethiopia				Tanzania			
CR area (acres)	0.049***	0.040***	-9.186***	-9.013***	0.055**	0.069***	-8.169***	-5.421***
CR area^2	-0.037***	-	4.025***	4.557***	-	-	3.057**	2.406**
CR area^3	0.006***	-	-0.477**	-0.589***	-	-	-	-
Closing error (%)	0.003**	0.001	0.862***	0.156	0.002*	0.002**	0.494***	0.282**
Number of corners	0.001	0.001	-0.048	0.026	0.000	0.000	0.056	0.090**
Per : area ratio (GPS)	0.002	-0.002	-13.927***	10.551***	-0.003	0.036	-38.537***	12.955***
Number of satellites	0.000	-0.001	0.107	-0.114	0.000	0.000*	0.027	-0.004
Slope (clinometer)	0.000	0.000	0.018	0.045	-	-	-	-
Tree cover:								
Partial	-0.005**	0.000	-0.074	0.318	-0.001	0.002	-0.729*	0.779**
Heavy	-0.006	0.009*	-1.019	3.804**	-0.006*	0.001	-1.339	1.116*
***Weather*:**								
Mostly cloudy - rainy	-0.005**	0.003	-0.085	1.206*	0.001	0.000	0.569	0.527*
Constant	-0.009	0.007	3.897	9.213***	-0.007	-0.021	8.317***	3.867**
Includes country dummies	-	-	-	-	-	-	-	-
N	1765	1765	1765	1765	1908	1908	1908	1908
R2	0.046	0.262	0.117	0.199	0.151	0.263	0.071	0.051
	Nigeria				Pooled			
CR area (acres)	-0.005	0.055***	-0.331	-0.015	0.011	0.050***	-1.898***	-3.344***
CR area^2	-	-0.002***	-	-	-0.001***	-0.002***	0.352**	0.507***
CR area^3	-	-	-	-	-	-	-0.012**	-0.017***
Closing error (%)	0.006	0.019***	1.327***	1.260***	0.003*	0.004***	0.762***	0.370***
Number of corners	-0.001	0.000	-0.101*	-0.009	0.000	0.000	-0.002	0.055*
Per : area ratio (GPS)	-0.13	0.109	-58.831***	43.445***	-0.006	0.001	-13.442***	11.534***
Number of satellites	-	-	-	-	-	-	-	-
Slope (clinometer)	-	-	-	-	-	-	-	-
Tree cover:								
Partial	0.013	-0.004	0.126	0.721	-0.001	0.001	-0.217	0.692**
Heavy	0.023	-0.012	-1.237	0.56	-0.002	0.004	-0.870	2.170***
Weather:								
Mostly cloudy - rainy	-0.029	0.016	-0.274	-0.773	-0.004	0.003	0.219	0.772**
Constant	0.000	-0.033	2.856	0.107	-0.002	-0.008*	3.979***	5.731***
Includes country dummies	-	-	-	-	Yes	Yes	Yes	Yes
N	485	485	485	485	4158	4158	4158	4158
R2	0.017	0.304	0.127	0.136	0.026	0.316	0.095	0.162

*p<0.1; **p<0.05; ***p<0.01

Source: Authors' calculations.

Figure 11 — Graphic Representation of Land Area Coefficients Found in Table 19



*Specifications in which all coefficients on land area are not statistically significant at the 10% level are highlighted in gray.

Source: Authors' calculations.

Table 20 — Determinants of High-Bias

Probit (reporting marginal effects), Error Clustered on Enumerator ID

	Ethiopia			Tanzania			Nigeria			Pooled		
	Percent bias >10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Percent bias> 10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Percent bias >10%	GPS over-reported by > 10%	GPS under-reported by > 10%	Percent bias >10%	GPS over-reported by > 10%	GPS under-reported by > 10%
CR area (acres)	-0.899***	-0.941***	-0.339***	-0.674***	-0.871***	-0.036	0.006	-0.193***	0.008	-0.275***	-0.257***	-0.119***
CR area^2	0.794***	1.056***	0.281***	0.555**	0.642***	-	-	0.060***	-	0.069***	0.100***	0.023***
CR area^3	-0.198***	-0.349***	-0.059**	-0.117*	-0.129**	-	-	-0.005***	-	-0.004***	-0.010***	-0.001***
Closing error (%)	0.003	0.01	-0.007	0.014*	0.018**	-0.005	0.053***	0.038***	0.015**	0.017**	0.021***	-0.004
Number of corners	0.006	0.002	0.004	0.005	0.006*	0.001	-0.001	-0.001	0.000	0.004	0.002	0.002
Per : area ratio (GPS)	0.173***	-0.144**	0.175***	0.428***	-0.911***	0.558***	1.700***	-1.435***	1.696***	0.254***	-0.072**	0.191***
Number of satellites	-0.003	0.001	-0.004	-0.007	-0.003	-0.003	-	-	-	-	-	-
Slope (clinometer)	0.002	0.002	0.000	-	-	-	-	-	-	-	-	-
Tree cover:												
Partial	0.002	0.005	0.003	0.043*	0.014	0.027*	0.052	0.016	0.044	0.029	0.012	0.019
Heavy	0.111*	0.042	0.078**	0.080*	0.031	0.045	0.047	-0.017	0.060	0.081**	0.026	0.055**
Weather:												
Mostly cloudy - rainy	0.026	0.009	0.016	0.044	0.035*	0.012	-0.026	0.007	-0.019	0.035*	0.023	0.012
Includes country dummies	-	-	-	-	-	-	-	-	-	Yes	Yes	Yes
Psuedo-R2	0.096	0.047	0.128	0.050	0.036	0.120	0.106	0.152	0.172	0.076	0.039	0.111
N	1765	1765	1765	1908	1908	1908	485	485	485	4158	4158	4158

Bias = GPS - CR (acres)

*p<0.1; **p<0.05; ***p<0.01

Source: Authors' calculations.

Although the difference between the two objective measurements is relatively small on average, it is worth exploring the problem cases in which the deviation is much larger. Table 20 reports results of a probit model (see equation 2) estimating the probability of a plot being a "problem plot" – defined here as having a relative bias greater than 10 percent (in absolute value). In all countries, we find evidence that the plots with the highest probability of large measurement error are the very small plots. The regressions unveil a cubic relationship between the probability of GPS measures being overestimated by more than 10 percent of plot size. That translates into the probability being highest for very small plots, and decreasing fast as plot size increases, before flattening fairly quickly (and eventually tilting up somewhat) for
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10. CONCLUSIONS

The Guidebook recommends integrating land area data collection with portable GPS devices in household and farm surveys. This should be complemented with farmer self-reports on land area.

This Guidebook strives to combine practical guidance for survey practitioners working on incorporating land area measurement into agricultural or living standards surveys, while at the same time providing them with the science-based evidence necessary to carefully evaluate the trade-offs implied by choosing one measurement method over another. As technology is evolving very quickly, the Guidebook attempts to consolidate the emerging evidence while highlighting areas where it is likely that opportunities may expand in the coming future, such as satellite imagery.

There are several important findings emerging forcefully from this analysis which translate into clear implications for future survey design and implementation. The first result is that experimental data confirm what was already known about the magnitude, direction and determinants of measurement error in farmers' self-reported estimates of land area. While not a novel finding, this is a useful reminder of the urgency to find alternative measures that are both accurate and feasible in the context of large-scale household surveys. GPS measurement is the obvious candidate.

Much of the focus of the paper has, therefore, been on assessing the fitness-for-purpose of GPS measures. In this respect, an important finding of the study is that on average GPS measures return very accurate estimates of plot size, even for very small plots, and even for reasonably small samples. We also do not detect any evidence that GPS systematically under-reports land size, as is the case in earlier studies. That should suffice to make GPS an attractive method for land data collection for most household survey practitioners. This conclusion becomes even more forceful when taken together with the comparison of the time (cost) of GPS compared to CR measurement, with our data showing GPS to lead CR by several orders of magnitude.

This strong message in support of the adoption of GPS in survey fieldwork, is, however, mediated by a number of considerations regarding outstanding challenges with GPS measurement. One that emerges from the analysis is that while the GPS measurement error is almost universally small in magnitude (only 5 percent of observations record a discrepancy with CR of more than 0.09 acres), in relative terms a discrepancy of +/- 10 percent is not uncommon. Considering that GPS measures in large-scale surveys are often plagued by a missingness rate in the range of 15-30 percent, that means that a large-scale dataset of GPS plot measurements can be plagued by as much as 50 percent problem cases. This requires complementing data collection with information that can aid in identifying problem cases, as well as devising field implementation protocols that can help reduce both bias and missingness in GPS measures.

Despite the evidence that subjective measurements can be riddled with problems, farmer self-reported estimates of area should still be included in household surveys, but not as the primary measurement method. Objective measurements come with their own challenges, including time and equipment requirements, questions of accuracy at small-plot levels, and feasibility of full plot sample measurement. Subjective measurements have negligible fieldwork costs, and, more importantly, they can serve as a baseline for imputation where objective measurements may be missing (Kilic et al. 2013). Therefore, we recommend GPS measurement complemented by farmer self-reported estimated area (for all plots). In doing that care should be taken to make sure the self-reported measure should be assessed first, so as not to be affected by the objective measure.

Another ancillary story emerging from the data concerns self-reported data. While confirming all known issues with measurement error in self-reported land data, the analysis presented here provides at least one suggestion for limiting the scope of this error in the future. When land area is collected using non-standard units, as opposed to forcing respondents or enumerators to perform a conversion to standard units at the time of the interview, data from self-reporting appears to approximate the objective measurements more closely. The implication for survey work is to allow the reporting in non-standard units in questionnaires, while focusing on building a library of conversion factors.

Finally, our analysis raises some concerns about the benchmark compass and rope measurement. It appears that much of what we labeled for simplicity as GPS measurement error may in fact be linked to noise in the CR data. This is hardly surprising, since CR does in fact require significant precision that will be hard to reach for survey enumerators that are not professional land surveyors. In terms of specific suggestions for CR measurements, we do observe an increase in discrepancy between CR and GPS when the CR closing error is above 3 percent. Translated into recommendations for survey work, this indicates that 3 percent may be a good rule of thumb for instructing enumerators to re-take CR measurement.

As technology advances and satellite imagery becomes available at increasing frequencies and resolutions, and at a more affordable cost, area measurement via remote sensing imagery has the potential to become the standard. For now, particularly in the developing country context where agricultural plots are often small and irregularly shaped, area measurement via GPS complemented by self-reported estimates offers the best balance between implementation feasibility and measurement accuracy.

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ANNEXES

Annex 1

Key definitions used in the Uganda National Panel Survey 2011/12

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 parastatals.

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 is 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 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 non-agricultural land in general and residential land in particular irrespective of the location is collected in the socio-economic 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.

Source: Uganda Bureau of Statistics, Interviewer's Manual of Instructions for Uganda National Panel Survey 2011/12 – Agriculture Module.

Annex 2

Example Protocol for GPS Measurement

Below is an excerpt from an LSMS training manual for measuring cultivated plots with a Garmin eTrex 30.

GPS AREA MEASUREMENT AND COORDINATES

A GPS uses the information from satellites to find the geographical position on the earth surface by longitude and latitude. The position is found by a continuous measurement of the time a satellite signal takes to reach your GPS from a satellite in the sky. With clear signals from at least 4 satellites, the GPS is able to calculate the geographical position with a sufficient accuracy. The better sight to a large part of the sky a GPS has, the more signals and clearer signals are received. Shadows of buildings and even large trees should be avoided while using the GPS in the field.

BEFORE calculating the area with the GPS:

1. Complete all other sections of the Post-Planting Questionnaire, including section PP5: Field Roster in which you obtain the respondent's self-estimates of the areas of each of their fields. The In-Field Measurement section is the last section of the post-planting questionnaire.

2. Walk around the field with the respondent in order to determine the field boundaries. Clear any obstructions that may block your path, so that you have a clear, unobstructed path around the boundary of the field. This should have been completed prior to the compass and rope measurement.

3. Mark your **starting point** with a ranging pole so you can identify the point when you return. The starting point should be the northwest corner of the field, the same point where you started with the compass and rope measurement.

4. Wait for the device to fix on at least **4** satellites.

5. To preserve the battery, set the backlighting on the GPS as low as possible. To do this, do the following:

a) While the device is on, click the power button once (do not hold it).

b) Move the Thumb Stick to the left to decrease the backlighting. You should decrease the backlight as much as possible in order to save the batteries.

c) Exit this page by pressing the BACK button.

PROCEDURE FOR AREA MEASUREMENT USING GPS

1. Enter the time you are starting in the In-Field Measurement Questionnaire, question 12.

2. Proceed to the start of the field where you have marked it with a ranging pole.

3. Turn on the GPS device by holding the power button until an image appears on screen. The GPS will then seek to acquire satellite signals. This may take up to 3 minutes. From the main menu, navigate to highlight SATELLITE and press the Thumb Stick. The green and blue bars at the bottom of the screen show the satellites that have been found. Wait until **at least 4 satellites** have been acquired.

On the left side, you will see the GPS accuracy in meters. This number will fluctuate as satellites are acquired. **Wait until this number is steady before moving on.**

4. Press the MENU button twice to return to the main menu. You may also push the BACK button repeatedly until you arrive at the main menu. Select the AREA

CALCULATION page by highlighting and clicking the center of the Thumb Stick.

5. START will appear on the screen. When you are ready to begin, click the Thumb Stick. Now the GPS has started recording the track. You will see CALCULATE on the screen (NOTE: do NOT click this until you are finished).

6. Walk slowly clockwise around the perimeter of the field. You should hold the GPS flat in your hand and stretch your hand slightly forward. You MUST walk on the edge of the field (NOT a meter outside the plot). At every corner, you MUST stop for 5 seconds (counting slowly 1001, 1002, 1003, 1004, and 1005) and then continue walking. You MUST walk all the way around the field until you have returned to the location of the ranging pole, with the GPS facing the direction in which it started the area calculation.

7. When you reach the ranging pole, CALCULATE should still be seen on the screen. Click CALCULATE by pressing the Thumb Stick. The GPS will display the area measurement directly in SQUARE METERS. You should then record the results with TWO decimals. If the area is not displayed, it means you have not clicked the Thumb Stick straight. You must press the back button until you see CALCULATE on the screen and then press the Thumb Stick again.

8. Save the track you have just recorded by highlighting SAVE TRACK and pressing the Thumb Stick. Delete the default track name and enter the name as "HHID-ParcelID-FieldID". For example, if the HHID is 1234 and the parcel ID is 02 and the field ID is 01, enter the track name as 1234-02-01. Highlight DONE and press the Thumb Stick.

9. To review the track, view the outline on the map, or determine the distance of the perimeter, return to the main menu and navigate to the TRACK MANAGER. Press the Thumb Stick. Highlight the track you would like to review and press the Thumb Stick. From there, select VIEW MAP. This will show you the length of the perimeter in meters (called "distance").

DEVICE OVERVIEW

① Zoom keys
② Back key
③ Thumb Stick™
④ Menu key
⑤ Backlight key

⑥ Mini-USB port (under weather cap)
⑦ Battery cover
⑧ Battery cover locking ring
⑨ Mounting spine

USING THE ETREX KEYS

- Move the Thumb Stick up, down, left, and right to highlight menu selections or to move around the map.
- Press the center of the Thumb Stick to select the highlighted item.
- Press **back** to move back one step in the menu structure.
- Press **menu** to display a list of commonly-used functions for the current page. Press **menu** twice to access the main menu from any page.
- Press ▲ and ▼ to zoom in and out on the map.

Source: Garmin eTrex 30 Owner's Manual, http://static.garmin.com/pumac/eTrex_10-20-30_OM_EN.pdf

10. Turn off the GPS device by holding the power button.

PROCEDURE FOR SAVING WAYPOINTS (COORDINATES) USING GPS

1. For **FIELD** GPS Coordinates:

a. Stand at the start of the field where you have marked it with a stick or ranging pole. This should be the north-west corner and the same point you used for the area measurement.

b. Press the MENU button two times to arrive at the main menu.

c. Highlight MARK WAYPOINT and press the Thumb Stick. The coordinates will be listed under the heading "Location". Record these on the questionnaire.

d. Rename the waypoint to match the "HHID-ParcelID-FieldID". Use the Thumb Stick to highlight the waypoint name which is located at the top of the page next to the flag icon. Press the Thumb Stick, delete the number that is filled in automatically and enter the "HHID-ParcelID-FieldID". For example, if the HHID is 1234 and the parcel ID is 02 and the field ID is 01, enter the waypoint name as 1234-02-01. Click DONE when you have entered the name.

e. Click DONE again to return to the main menu.

2. For **HOUSEHOLD** GPS Coordinates:

a. Stand outside the Northwest Corner of the house.

b. Press the MENU button two times to arrive at the main menu.

c. Highlight MARK WAYPOINT and press the Thumb Stick. The coordinates will be listed under the heading "Location". Record these on the paper form.

d. Rename the waypoint to match the "HHID". Use the Thumb Stick to highlight the waypoint name which is located at the top of the page next to the flag icon. Press the Thumb Stick, delete the number that is filled in automatically and enter the HHID as it appears on the questionnaire. Click DONE when you have entered the HHID.

e. Click DONE again to return to the main menu.

Annex 3

Example Protocol for Compass and Rope Measurement

Below is an excerpt from an LSMS training manual for measuring cultivated plots with the compass and rope method (using an Excel program for computation of area).

COMPASS AND ROPE AREA MEASUREMENT

To conduct the compass-and-rope measurement, the **enumerator** and the **Crop Farmer/Crop Farm Manager** should first walk along the edges of the field to identify the boundary and obstacles. The enumerator will need assistance from a local guide. It is best to have a team of three (3) people if possible.

The materials that you will need for use in this exercise are:

- In-Field Measurement Questionnaire (on CAPI)
- Prismatic Compass
- Ranging Poles (3)
- Measuring Tape
- Writing Materials e.g. Pen, Pencil, etc.
- Pre-printed scratch paper
- Excel compass and rope area calculation program

In-Field Measurement Questionnaire: This is designed for recording field measurement via the compass-and-rope method as well as GPS units, soil sample details and crop-cutting area information.

Prismatic Compass: This is a device used for capturing geographic bearings in degrees (0^0). The model type of this device has a flip cover with a pinhole through which the bearing is read.

Ranging Poles: The minimum number of poles required is three (**3**). The first pole should be erected (positioned) at the **starting point (position A). This first pole must not be moved until the measurement is complete.** The second pole should be positioned at first bend point (position B). The third pole should be stationed at the second bend (position C). Both the 2^{nd} and 3^{rd} poles can be removed after use and put in the positions of measuring distance and degree between the following two interval-points, until arrival at original position A.

Measuring Tape: This is a distance-measuring instrument marked in metric-units (segments).

Writing Materials: These materials can include pen, pencil, etc.

Pre-printed scratch paper: The enumerator will be given scratch paper to record the compass and rope measurements on paper before entering them in the In-Field Measurement Questionnaire. Only measurements with less than 5% closing error will be recorded in the In-Field Measurement Questionnaire.

Compass and Rope Area Calculation Program: This is a program in Excel for computing field area and closing error after capturing distance measurements (meters) and bearings (degree) of a plot. This program is downloaded on your CAPI tablet.

PROCEDURE FOR AREA MEASUREMENT USING COMPASS AND ROPE

The enumerator will need the assistance of a field guide. A team consisting of 3 persons is preferred, so if possible, a household member or supervisor may assist. Two persons are needed to hold the edges of the measuring tape respectively and take the bearing and distance measurements, while a 3rd person may ensure that the tape is held straight by clearing any obstacle/obstruction in the way.

1. Walk around the field with a household member, preferably the farmer of the field, to determine the field boundaries and clear any obstacles.
2. Enter the time you are starting in the In-Field Measurement Questionnaire, question 3. This should be the time after you have completed step 1 above.
3. Identify your starting point and call it point A. Point A should be the northwest corner of the field. Firmly plant one ranging pole at point A and proceed clockwise around the field to the next corner. This is point B and the second ranging pole should be placed at that point. At this stage, a person is stationed at both point A and B. Facing each other with the ranging poles in front, the person at point A should use the compass to line up the pole at point B and look through the pinhole to take reading. This reading should be recorded on the scratch paper in the column marked 'Front Bearing' on the row for point A-B on the form.
4. Now extend the measuring tape from point A to point B with the zero mark held against pole A. When the tape is held straight and taut, read the distance to B and enter this figure in meters in the column marked 'Distance' on the row for point A-B. You should record 2 decimal places (for example, 15.27m).
5. Now, the team member at point A moves (leaving the pole in position) to point B and lines the compass up with the pole at point A and take reading. Record this reading in the column marked 'Back Bearing' on the line for point A-B on the scratch paper.
6. Take the 3rd ranging pole and place it at the next corner of the plot after point B: this is point C. Proceed to measure the front compass bearing, the distance and the back bearing from B to C in the same way that you measured them from point A to point B. Enter the results in the appropriate columns for the line marked B-C on the scratch paper. When you are done with the side B-C, remove the pole at point B and take it to the next corner after C: this is point D. Continue in this way from point to point (corner to corner) until you have returned once again to point A, the corner where you started.
7. Make sure all your readings are entered on the scratch paper.
8. Finally, this data should be entered into the area measurement program for the computation of field area, perimeter, and closing error (refer to example in Figure A3). If the closing error is 3% or more, then this indicates that the measurement was not done properly and the field must be re-measured. If the closing error is less than 5%, you will go on to answer questions 4-9 on the In-Field Measurement Questionnaire. To use the Excel program:
    a. On the CAPI tablet, open the file called "Area of Polygon Final.xlsx."
    b. Delete any data found in the first three columns of the table. The table must be empty before you begin calculating the area of a new field.
    c. Enter the front bearing, back bearing and distance (in meters) for all sides of the field into the table as seen below. The program will automatically calculate the perimeter, area, and closing error but do not record the numbers until you have entered all sides in the table.
    d. If the closing error is less than 3%, go ahead with completing the in-field measurement questionnaire. If the closing error is 3% or more, the field will need to be re-measured. Remember, the difference between the front bearing and the back bearing should be near 180 degrees. If you check this as you are measuring the field, you will likely complete the first measurement with a low closing error.

Figure A3 — Example of Excel-Based Compass and Rope Area Measurement Computation Tool

Instructions: Enter values in Front bearing and Distance. The computations are on the right in RED					
When finished, delete entries under Front Bearing and Distance					
Front Bearing	Back Bearing	Distance	Perimeter (m)	Area (m^2)	Closing Error (%)
124.0	305.0	12.3			
59.0	242.0	27.8			
134.0	310.0	14.3			
219.0	39.0	13.1			
211.0	9.0	7.1			
250.0	70.0	18.6			
327.0	147.0	25.7	118.9	623.2	3.1

Source: LSMS

Annex 4

Glossary of Terms

Bias In this document, bias refers to the simple difference between an area measurements and another measure taken as a benchmark (usually the CR measure), in acres.

Bounding Extent In this context, the bounding extent refers to the full geographic coverage of an enumeration area in which all households and plots are enclosed.

Closing error Also referred to as closure error. Closing error is a measure of the gap between the reported start and end points of a polygon constructed via CR measurement. The closing error is computed as a ratio of the distance between the reported start and end points to the perimeter of the plot, and expressed in percentage terms.

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).

Gpx A .gpx file is a GPS exchange file. It is an xml formatted file which contains data directly from the GPS unit. A .gpx file may include waypoints and/or track outlines.

Kml Keyhole Markup Language (KML) files contain geographic data that can be readily loaded on a map, such as in Google Earth.

Map datum A map datum is a tool used to identify the shape and size of the Earth, as well as identify a reference point for coordinate systems. A common map datum is WGS 84.

Multispectral data Data corresponding to a particular range of wavelengths on the electromagnetic spectrum. Objects reflect and absorb varying amounts of radiation at different wavelengths, creating a spectral signature.

Non-standard unit Units of area that are not readily converted to known, standardized units such as acres or hectares. Non-standard units often vary with geographic location.

Ortho-rectification The process of ortho-rectification removes the effects of image perspective and terrain, rendering the rectified image planimetrically correct (with a constant scale).

Panchromatic images Single band images generally displayed as shades of gray.

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).

Relative bias The bias expressed as a percentage of the benchmark measure (usually, in this document, the CR measure).

UTM Universal Transverse Mercator refers to a Coordinate Reference System based on cylindrical projection typically used with zone-specific parameters in local areas for large scale mapping.

Waypoint Also referred to as geographic coordinates. Waypoints, or coordinates, identify the position of a single point in terms of a designated coordinate system.

WGS 84 World Geodetic System 1984, used in reference to both a Coordinate Reference System and an earth-centric datum. For more detail see EPSG code 4326 at http://www.epsg-registry.org/

LIVING STANDARD MEASUREMENT STUDY RESOURCES ON LAND AREA MEASUREMENT

The Living Standard Measurement Study team, part of the World Bank's Development Data Group, has developed a substantial methodological research program on land area measurement. The program benefitted from generous funding from UK Aid and the Bill and Melinda Gates Foundation, and from close collaboration with the Research Component of the Global Strategy for Agricultural and Rural Statistics.

The datasets for all LSMS surveys and from the methodological experiments, and the program's publications are available via the LSMS website at www.worldbank.org/lsms. To date the program has produced the following outputs:

Carletto, G., Gourlay, S., Murray, S. and Zezza, A. (2016). Cheaper, Faster and More Than Good Enough: Is GPS the new gold standard in land area measurement? World Bank Policy Research Working Paper, 7759. Washington, D.C.: World Bank Group.

Carletto, G., Gourlay, S., and Winters, P. (2015). From Guesstimates to GPStimates: Land Area Measurement and Implications for Agricultural Analysis. Journal of African Economies, 24 (5), 593–628. (Also available in the World Bank Policy Research Working Paper series.)

Carletto, G., Savastano, S., and Zezza, A. (2013). Fact or artifact: The impact of measurement errors on the farm size–productivity relationship, Journal of Development Economics, 103(C), 254–261. (Also available in the World Bank Policy Research Working Paper series.)

Dillon, A., Gourlay, S., McGee, K., andOseni, G. (2016). Land measurement bias and its empirical implications : evidence from a validation exercise. World Bank Policy Research Working Paper, 7597. Washington, D.C.: World Bank Group.

Kilic, T., Zezza, A., Carletto, G., and Savastano, S. (2013). Missing(ness) in Action: Selectivity Bias in GPS-Based Land Area Measurements. World Bank Policy Research Working Paper 6490. Washington, D.C.: World Bank Group.

Kilic, T., I. Yacoubou Djima, and C. Carletto. (2016). Is Predicting Missing GPS-Based Land Area Measures Mission Impossible in Household Surveys? Exploring the Promise of MI. World Bank Policy Research Working Paper, forthcoming. Washington, D.C.: World Bank Group.

World Bank and ONE. (2014). Levelling the Field. Improving Opportunities for Women Framers in Africa. Washington, D.C.: World Bank Group.

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