Making Measurement Great Again: The Use of Sensors and Scanners for Rapid, High-Quality Data on Land

Sydney Gourlay[‡], Adriana Paolantonio [†], John Ilukor [††][1]

Abstract

In a world with increasing climate change and intensifying food insecurity, agricultural productivity is central to development. Increasing agricultural productivity requires a detailed understanding of cultivated land and its limitations, and how these shortcomings can be addressed. In this regard, both land *quality* and *quantity* play a critical role. The ability to appropriately estimate the degree to which these inputs positively or negatively affect production is dependent on accurate measurement. With an evolving technological landscape, the menu of tools available to potentially measure land quality and quantity, particularly in cost-effective and scalable ways, is expanding. Through a methodological survey experiment implemented in Uganda, we set out to validate innovative approaches for measuring area (land quantity) and soil health (land quality) and assess their feasibility for implementation in household survey contexts and project operations, as well as the policy-relevant implications of their use.

Preliminary draft prepared for submission to the 2024 World Bank Land Conference. Not for citation.

---

[1] [‡] Senior Economist, Living Standards Measurement Study (LSMS), Development Data Group, World Bank, Rome, Italy. sgourlay@worldbank.org; [†] Economist, Living Standards Measurement Study (LSMS), Development Data Group, World Bank, Rome, Italy; [††] Economist, Living Standards Measurement Study (LSMS), Development Data Group, World Bank, Kampala, Uganda.

1. Introduction

In a world with increasing climate change and intensifying food insecurity, agricultural productivity is central to development. Increasing agricultural productivity requires a detailed understanding of cultivated land and its limitations, and how these shortcomings can be addressed. In this regard, both land *quality* and *quantity* play a critical role. The ability to appropriately estimate the degree to which these inputs positively or negatively affect production is dependent on accurate measurement. With an evolving technological landscape, the menu of tools available to potentially measure land quality and quantity, particularly in cost-effective and scalable ways, is expanding. Through a methodological survey experiment implemented in Uganda, we set out to validate innovative approaches for measuring area (land quantity) and soil health (land quality) and assess their feasibility for implementation in household survey contexts and project operations, as well as the policy-relevant implications of their use.

Validation of improved methods for measuring these elements in a survey context requires the implementation of a study in which each of the elements is measured using multiple methods, with the study designed for direct comparison of the methods to each other and to benchmark measure, where relevant. With support from the 50x2030 Initiative, the Korea Green Growth Trust Fund, and the Korea-World Bank Partnership Facility, the World Bank's Living Standards Measurement Study Unit has partnered with the Agriculture and Food Practice Group of the World Bank and technical and institutional partners, to implement a methodological survey experiment designed specifically to validate new tools for the measurement of land area and high-resolution data on soil health, with an eye for data quality, cost-effectiveness, and scalability.[2]

Land area, specifically the area of an agricultural parcel or plot, can be measured in a number of ways, including traversing (also known as the compass and rope method), by handheld GPS unit, and by farmer self-reported estimate. Each of the abovementioned methods possesses unique costs and benefits. While experience suggests that traversing is time-intensive, it also produces some of the most accurate figures and has therefore often been used as the benchmark in comparative exercises (as in Keita et al. 2010, for example). Farmer self-reported estimates fall on the other end of the spectrum requiring minimal resource expenditures as a trade-off for precision, with significant evidence of systematic bias in these farmer estimates. More recently, the use of handheld GPS devices has been validated vis-à-vis traversing (for example, Carletto et al. 2017), and has been integrated in numerous household and agricultural survey operations worldwide. Despite the successful adoption of handheld GPS measurement in survey operations, new tools offer potential for smoother, more cost-effective measurement of land area at potentially similar levels of accuracy. Often the hurdles for adoption of handheld GPS measurement are procurement of these separate devices and the merging of data from the survey instrument and the separate GPS device. The 50x2030 Initiative has supported the development of new features in the World Bank's Survey Solutions CAPI program, that allows for a perimeter-pacing approach to area measurement, like the approach of handheld GPS-based measurement. This new tool requires validation in smallholder agricultural contexts but has the potential to eliminate the need for the separate GPS device resulting in lower equipment costs and cleaner data.

---

[2] The study also has an emphasis on the measurement of high-resolution data on climate using community-level weather sensors, but this is not included in the scope of this paper.

Analysis of soil health through objective tests can reveal levels of soil nutrients and crop-specific soil constraints to productivity. Soil monitoring conducted at the plot-level as part of household or farm surveys has the added benefit of integrating data on soil properties with farm management practices, input use, and agricultural outputs, as well as household socio-demographics, allowing for a thorough understanding of the implications of soil health on key development outcomes. Household and farm surveys, however, often rely on subjective soil health data which have been found in research conducted by the World Agroforestry Centre (ICRAF) and the Living Standards Measurement Study (LSMS) to be poor predictors of objective measurements of soil attributes and are subsequently limited in their ability to accurately identify soil constraints and their productivity implications. Technological advancements in spectral-based modeling and instruments offers the potential for relatively rapid, low-cost soil analysis vis-à-vis traditional lab-based methods, while at the same time the scope and resolution of geospatial-based soil data is improving. Building on previous work undertaken by the World Bank in partnership with ICRAF and the community at large, we seek to validate these recent innovations for objective soil measurement and/or improve subjective soil assessment, in an effort to transform the way soil is measured in household and agricultural surveys.

This draft paper, prepared specifically for the 2024 World Bank Land Conference, presents initial results from the methodological study, with an emphasis on the comparison of methods for measuring land area (namely, Garmin handheld GPS units, tablet-based measurement in Survey Solutions, and tablet-based measurement in Survey Solutions with the use of a Garmin Glo GPS-booster) and soil health (namely, AgroCares in-field scanner, in-country analysis with Palintest kits, and conventional and spectral laboratory-based analysis). Section 2 discusses the data in more detail as well as the methods employed, while Section 3 discusses the preliminary results. Section 4 concludes.

2. Data & Methods

The Uganda Climate, Land Area, and Soil Study (CLASS) was implemented in 75 rural communities across 5 districts in Eastern and Northern Uganda (Apac, Dokolo, Kamuli, Kaliro, and Buyende).[3] The study, which included three household visits (after planting, during harvest for crop-cutting of maize, and after harvest) to each of the 900 randomly selected maize-growing households, tests multiple approaches to measuring land area and soil health side-by-side, i.e., on the same plots of land, to allow for direct comparison. In each household, one maize plot was randomly selected for crop-cutting, land area measurement, and soil health measurement.[4] In addition to the measurements of land area and soil health, each sampled enumeration area also hosted a community-level weather sensor.

With respect to land area, we seek to answer the following key questions: (i) How accurate is land area measured through the new Survey Solutions perimeter-pacing feature for area measurement (details here) in a smallholder context, relative to handheld GPS devices?; (ii) Can this accuracy be increased through the use of a GPS boosting tool?; and (iii) What are the trade-offs in terms accuracy, cost, and scalability between the new Survey Solutions feature and handheld GPS devices?

---

[3] Fieldwork implementation was conducted by EDI Global.

[4] In one-third of households, a second plot was randomly selected from the same parcel as the first selected plot, for soil analysis using the AgroCares Scanner only, to allow for assessment of intra-parcel heterogeneity. This second plot is not utilized in the analysis in this paper.

To answer these questions, on the randomly selected maize plot in each household, the following measurements were undertaken: (i) measurement via handheld GPS unit (Garmin eTrex30), (ii) measurement directly in the CAPI tablet (Samsung Galaxy T580) using the newly developed Survey Solutions feature for automatic area measurement and boundary recording via perimeter pacing; (iii) measurement directly in the CAPI tablet using the newly developed Survey Solutions feature for area measurement and boundary recording via perimeter pacing with GPS enhancement through the use of a Garmin Glo; and (iv) respondent estimation of plot area. Plot boundaries were collected and stored both from the handheld GPS measurement and the tablet-based measurements.

There are a number of research questions that underlay the soil health component of this study, with the primary questions being: (i) Can in-field soil scanners, sensors, or other tools be implemented in a scalable manner to produce high-quality, high-resolution soil data in the context of an agricultural/household survey?; (ii) What are the trade-offs between analytical value, cost, and scalability, and are there "low tech" interventions that could complement or substitute these more sophisticated methods?; (iii) Do publicly-available geospatial soil data products, such as SoilGrids or iSDAsoil, adequately measure the values and spatial variability of key soil properties at the plot level?; and (iv) How can imputation approaches be best utilized to improve soil data in agricultural/household surveys in a scalable manner?

We attempt to answer these questions by implementing, on the same plot of land which was selected for area measurement, the following measurement methods: (i) in-situ near infrared (NIR) spectrometer (AgroCares Scanner); (ii) Palintest SKW500 kit implemented in regional laboratories by Jabba Engineering; (iii) low-cost digital pH meter; (iv) subjective and observational questions; (v) conventional wet chemistry and lab-based spectral analysis implemented by the World Agroforestry (ICRAF) in Nairobi; and , (vi) post-facto comparison with publicly available geospatial soil data, such as SoilGrids and iSDASoil, leveraging georeferencing of ground-based samples. At the time of the conference, the soil samples are still being analyzed at ICRAF labs, and are therefore excluded from the analysis at this stage.

The data collected through the Uganda CLASS study will allow for comparative analysis of the different measurement methods identified above. In the section below, we present findings from the direct comparison of the different measurement methods that shed light on the appropriateness of the given approaches, considering data quality in terms of accuracy vis-à-vis benchmark measures and implementation considerations such as cost and scalability. These comparative findings will ultimately be complemented by the potential policy implications for relying on one method vis-à-vis another, for example, on estimating crop productivity.

3. Preliminary Results

Land Area

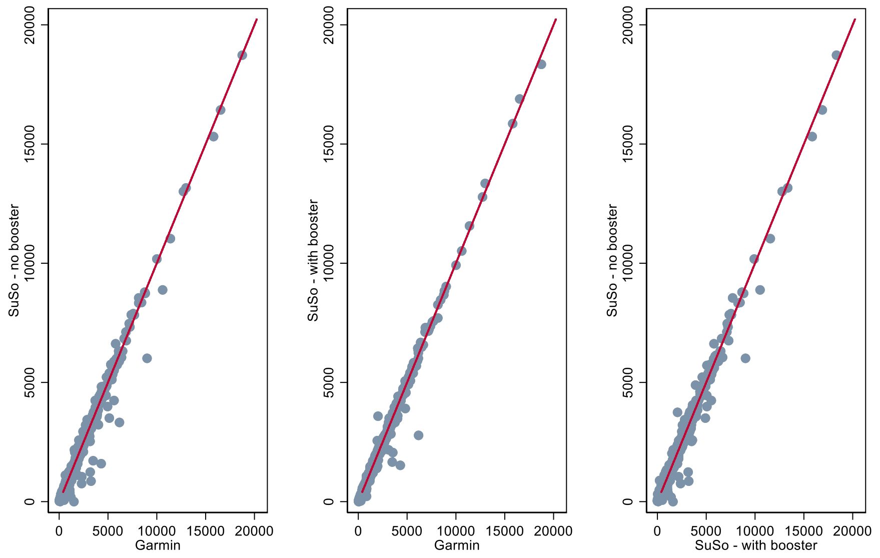
Comparison of the Garmin handheld GPS unit and the Survey Solutions, both with and without the GPS booster, reveals similar but statistically different area estimates. Table 1 presents the mean area measurements from these methods. The tablet-based measurements are statistically different from the Garmin handheld, which we consider the benchmark, though the magnitude of the difference may not be substantial for agricultural analyses. When looking at the measurement *bias*, defined here as the tablet-based measurement minus the Garmin handheld, is on average -42m^2 for tablet-based measurements with a GPS booster and -29m^2 for the tablet-based measurement without a booster. Though the bias appears to be greater for the booster, when we look at the absolute value of the bias, and the absolute value of the bias in percentage terms, we find that the measurement error is slightly smaller when using the booster (though the difference in means between the measurement with the booster and without is not statistically different from zero). The correlation of the measurements across all three methods is high, as illustrated in the scatterplots in Figure 1. The correlation coefficient between the Garmin and the boosted tablet is 0.994, between the Garmin and the non-boosted tablet is 0.990, and between the two tablet measurements is 0.991.

Table 1. Comparison of Means - Land Area

	Mean (m2)	Bias (SuSo-Garmin)	| Bias |	| % Bias |	T-Test (X=Garmin)*	T-Test (boosted= nonboosted)*
Garmin handheld	1670.27	-	-	-	-	-
SuSo with booster	1628.25	-42.02	94.73	10.53	0.000	0.166
SuSo no booster	1641.06	-29.21	126.71	12.05	0.003	

Notes: N=869; * p-values from two-sided t-test reported

Figure 1. Scatterplots - Land Area Measurements (m^2)



By disaggregating the comparative analysis by plot size, we uncover an apparent relationship between plot size and measurement error, present both when using a GPS booster and when using the tablet without any GPS assistance. The left panel of Figure 2 illustrates that the absolute value of the relative bias, that is the absolute deviation from the Garmin GPS measurement as a percent of the Garmin area, is decreasing with plot size. While looking at the absolute value allows us to observe the deviation from the Garmin measurement, there is also value in understanding the degree of over- and under-estimation relative to the Garmin measurement. The right panel in Figure 2 presents the relative bias, allowing for visualization of the over-and under-estimation. Both tablet-based measurements illustrate under and over estimations, though the tablet with the booster appears to underestimate area more commonly than the non-boosted tablet, especially on plots in the smallest plot area quintile.

Comparison of plot boundary outlines collected from with the Garmin handheld, the tablet with the booster, and the tablet without the booster reveals differences in the plot shapes in addition to the observed differences in areas. Figure 3 illustrates differences in plot outlines from select plots. The extent to which these differences in plot outlines could impact remote-sensing based applications, such as yield estimation, will be explored.

Figure 2. Measurement Error by Plot Size Quintile (absolute value of relative bias (%) on left; value of relative bias (%) on right)

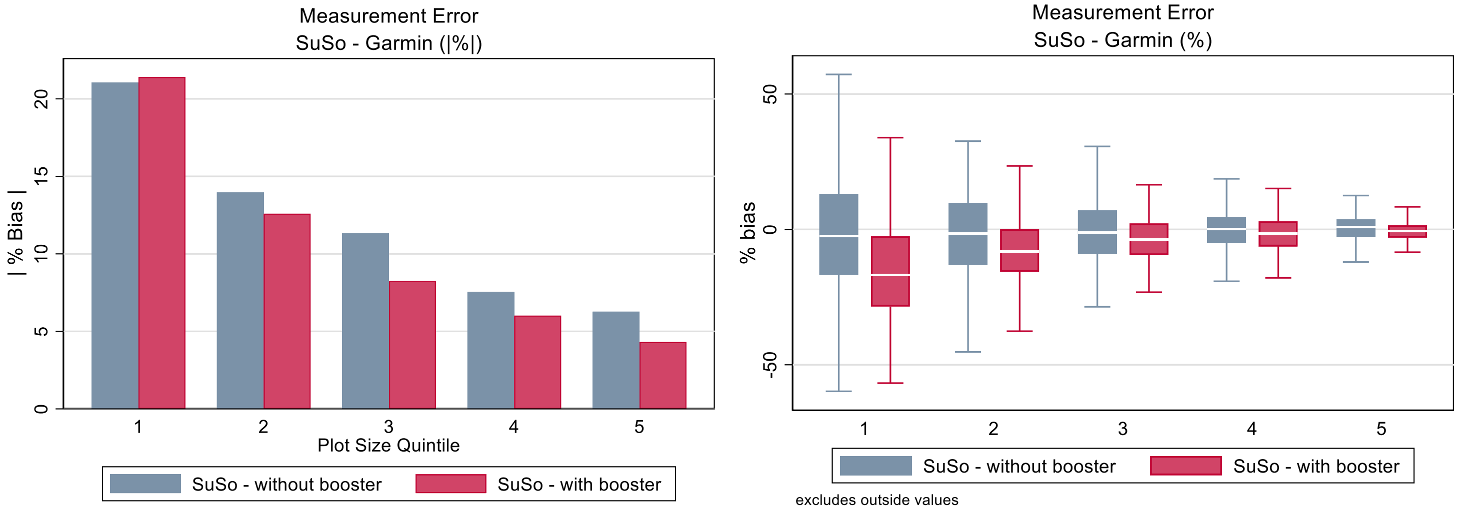
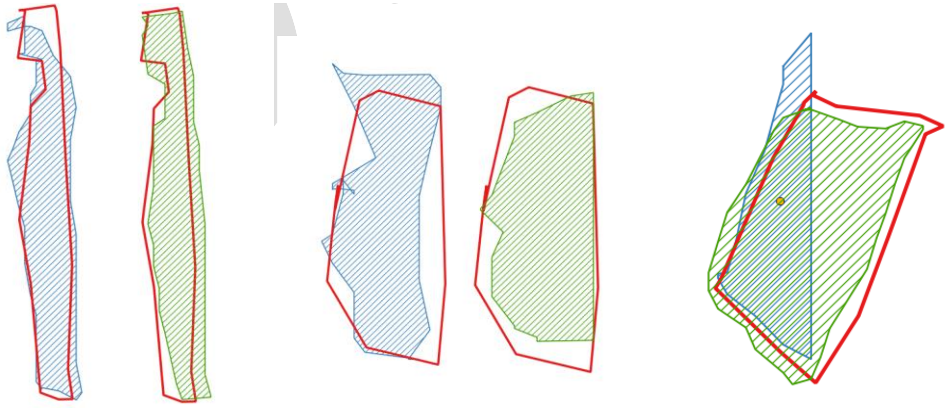


Figure 3. Plot Outlines, by Method



Red = Garmin GPS; **Blue = SuSo without booster**; **Green = SuSo with booster**

Soil Health

With the benchmark measure of laboratory-based conventional and spectral soil analysis underway, results are limited at the time of writing. An initial comparison of measurements from the AgroCares Scanner taken directly in the field, and the Palintest kit conducted in regional laboratories in Uganda is presented below, though without the benchmark measure against which to compare it is premature to draw conclusions on the relative accuracy of the measures.

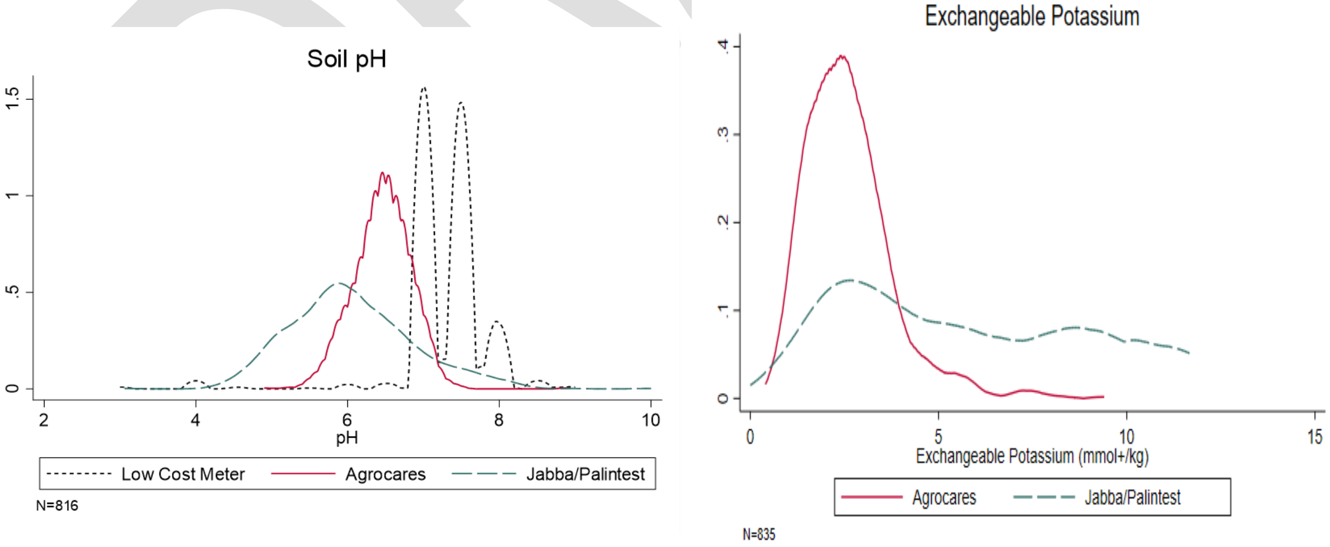
Table 2 presents the mean values for key soil parameters as measured by the AgroCares Scanner, the Palintest kit by Jabba Engineering, as well as pH measured by the low-cost meter. The means are significantly different across methods for all key parameters reported, with the exception of phosphorous. Kernel density plots, found in Figure 4, illustrate differences in the distributions of measurements for soil pH and exchangeable potassium.

Table 2. Comparison of soil parameters across methods (means)

	AgroCares	Jabba	Low-Cost Meter	T-test AC = Jabba*	T-test LC = Jabba*	T-test LC = AgroCares*
pH (w/low cost meter)	6.46	6.05	7.28	0.000	0.000	0.000
pH	6.47	6.04	-	0.000	-	-
Clay (%)	44.68	7.04	-	0.000	-	-
Potassium (mmol+/kg)	2.60	5.79	-	0.000	-	-
Phosphorous (mg/kg)	2.91	2.48	-	0.199	-	-
Calcium (mmol+/kg)	85.82	80.53		0.004		

* p-values from two-sided t-test reported

Figure 4. Distributions of Soil pH and Exchangeable Potassium



Soil parameters will also be compared with data from geospatial soil products, such as SoilGrids2.0 and iSDAsoil, upon receipt of the benchmark laboratory data. We will also assess the relevance and implication of the measurement error associated with the different methods in agricultural analyses such as agricultural productivity.

4. Conclusions

The Uganda Climate, Land Area, and Soil Study (CLASS) was designed and implemented to validate innovative methods for improving the quality, scope, and efficiency of data collected through agricultural and rural household surveys. By employing a variety of methods to assess land area and soil health, the study aims to determine the accuracy, cost-effectiveness, and scalability of these tools in a smallholder agricultural context. The preliminary phase of the CLASS study has laid the groundwork for a comprehensive understanding of the trade-offs involved in adopting new technologies for land and soil measurement, with the potential to inform and transform agricultural policy and practice.

With respect to land area measurement, we find statistically different means across methods, but with extremely high correlations, which suggest that tablet-based measurements may be a reasonable alternative to handheld GPS measurement, though additional analysis is needed (and ongoing) in order to understand whether the differences observed across methods have substantive and significant implications for agricultural analyses. In the domain of soil health, preliminary results highlight the importance of measurement method, with statistically different means in several key soil parameters when using the AgroCares in-field scanner and local lab-based analysis with a Palintest kit. These measures will be compared with what we consider the benchmark, laboratory testing at ICRAF using conventional and spectral methods, when that data becomes available.

For both domains, further analysis will be conducted to understand the relevance of the observed measurement error for agricultural analysis and policy, which will in turn inform recommendations for best practices going forward. The methodological validation may also be replicated in a different context, to support the validity of the findings.

References

Carletto, C., Gourlay, S., Murray, S., & Zezza, A. (2017). Cheaper, faster, and more than good enough: is GPS the new gold standard in land area measurement?. In *Survey Research Methods* (Vol. 11, No. 3, pp. 235-265).

Keita, N., Carfagna, E., & Mu'Ammar, G. (2010). Issues and guidelines for the emerging use of GPS and PDAs in agricultural statistics in developing countries. In *The Fifth International Conference on Agricultural Statistics (ICAS V)*, Kampala, Uganda