Precision Agriculture for Development

1. *Introduction*

In developed countries, precision agriculture technologies are transforming agricultural production by allowing farmers to better target inputs to local conditions, thus increasing yields and reducing environmental impacts from input overuse. Precision agriculture technologies include new sensors, such as distributed soil and yield monitors, as well as new processing techniques for data from existing sensors: for example, new spectroscopic techniques make it possible to measure growth stages and nutrient deficiency from satellite imagery.

Three technological innovations have created new scope and opportunities to improve the reach and quality of advisory services for farmers in developing countries. First, measurement technologies associated with precision agriculture make it possible to learn more about local conditions in developing countries. For instance, detailed weather forecasting data, soil type mapping, and the use of remote sensing yield-monitoring devices are increasing the scope to fine-tune recommendations for farmers. Second, machine-learning techniques make it possible to tailor expert knowledge at scale to conditions revealed in existing and new sources of data. These techniques can additionally be trained with a feedback loops with users to continuously improve predictions. Third, the widespread adoption of mobile phones makes it possible for information to be collected from and delivered to farmers inexpensively.

2. *Emerging evidence on the importance of local agricultural information*

Research on agricultural technology adoption has increasingly pointed to the value of carefully targeted, external sources of information for smallholder farmers:

Information can increase farmer income at low cost. One demonstrated channel is by allowing farmers to improve their farming operations. For instance, a simple rule-of-thumb "color wheel" to guide appropriate fertilizer use resulted in a 7 percent yield increase and an 8 percent reduction in use of fertilizer, with a 9:1 benefit-to-cost ratio for Bangladeshi smallholders;[1] providing Indonesian seaweed farmers with information on the relationship between practices and yields led to the take-up of improved practices;[2] Kenyan farmers who used ½ teaspoon of fertilizer per maize plant had a mean rate of return of 70% on an annualized basis, whereas higher fertilizer use had negative mean returns.[3] A second demonstrated channel involves farmers' improved position as market participants. In India, market kiosks that provide daily agricultural price information to farmers increased the average prices that they received, which led to increases in soy cultivation;[4] in Ghana and India, increased information flows have been shown to help farmers with spatial arbitrage—decreasing price dispersions, transaction costs, and product waste.[5,6]

Localized information is most valuable. Farmers face great heterogeneity in local soil type, agroclimatic characteristics and market conditions. The profitability of specific inputs or management practices depends on all of these.[7] For instance, the yield response to some types of inorganic fertilizers depends on the soil's pH levels and its organic content,[8] which can vary as much across fields as across agro-ecological zones.[9] Farmers might find it difficult to target these deficiencies, since these characteristics are difficult to observe. In Ivory Coast, local heterogeneity in environmental conditions (pests, soil and rainfall) explained most differences in rice output among farmers[10] and in Kenya, farmers' valuation of agronomic recommendations increased when the advice was based off soils closer to their farms.[11] Spatial and temporal heterogeneity in prices can also be large. A fraction of Zambian farmers faced unprofitable returns to adopting the nationally recommended fertilizer application rate, partly because the cost of fertilizer at their local market was higher than the cost used to create those recommendations.[12] Heterogeneity in individual or household socio-demographic characteristics also matter.[13,14]

Farmers are willing to spend resources on information. In some contexts, farmers already realize the value of acquiring information. For instance, a study with small-scale Sri Lankan farmers found that searching for information represented 11% of the total cost of agricultural production.[15] In Western Kenya, maize farmers were willing to pay for local soil test results.[16]

3. Why market and policy failures hamper the creation and flow of such information

Generating useful information independently is often prohibitively costly. In developed countries, large farms make use of technologies such as sensors and soil and yield monitors, allowing farmers to precisely target inputs to individual farm needs. In developing countries, smallholder farmers might find that collecting such information is expensive or inaccessible. Even simpler technologies, like soil analyses, might be well beyond their means. For instance, in Western Kenya, the average individual willingness to pay for a local soil test result was not sufficient to cover the cost of the test. However, aggregate willingness to pay by area was higher than the cost of creating that information.[17] Additionally, experimenting with inputs by oneself can be difficult because individual results are noisy, and/or because individuals may not know along which dimensions to experiment.[18] Since many agricultural conditions and opportunities are spatially correlated, and many people can share this information, it should not be necessary for each farmer to generate his or her own knowledge. However, this creates the need for functioning institutions.

The private sector is not very good at creating and diffusing useful information in low-income contexts. Information has properties that make it difficult to market. First, information is difficult to sell to buyers since they may be uncertain about its value. They are often also cash constrained, and contracts to recover the benefits of information through later yield increases are difficult to enforce. Second, self-interested actors can provide biased information. For instance, input dealers may recommend farmers to use too much pesticide.[19] Third, information may be costly to produce and distribute, but is cheap to reproduce, making it difficult for any producer of information to recover costs.

Public sector agricultural extension efforts tend to be dysfunctional. In theory, as a public good, governments should provide or subsidize information generation. However, while many developing country governments spend heavily on agricultural extension, they are often hobbled by poorly functioning bureaucracies and limited accountability.[20] Existing recommendations are usually developed on experimental stations at which researchers seek to maximize yields. Meanwhile, farmers' adoption decisions are not only driven by the agronomic benefits of practices (yields), but also by their costs (inputs and time) and risk exposure.[21]

4. How technology has started to address these barriers

The dramatic increase in mobile phone penetration in rural areas, coupled with advances in information and communication technologies (ICT), have led to a number of innovations. These can be largely classified into three groups:

Agricultural skills building. The overarching idea here is to build improved knowledge on agronomic practices. They include e-Extension services by the ministries of Agriculture in Kenya, Ghana, and Paraguay, which provide extension workers with tablets and/or smartphones; the Community Knowledge Worker model by the Grameen Foundation in Uganda, which aims to do the same through community members; generalized agricultural tips via SMS (e.g. Airtel Kilimo Kenya) or voice (e.g., Green Sim India); and websites with specific agronomic recommendations (e.g., mbeguchoice.com on seeds). Icow Kenya, which allows farmers to track the gestation of their livestock and has 180k reported active users. Digital Green encourages the production and screening of agricultural videos.

Resolution of farmer concerns. A variety of private and public ICT approaches have emerged to address specific questions and concerns of farmers. Avaaj Otallo allows Indian farmers to record questions that peers and staff can answer. A number of organizations, such as Grameen Uganda, Senekela Mali, and Tigo Kilimo Tanzania, have established farmer hotlines. Farmers' Club, established by Esoko and Vodafone Ghana, offers free-calls between members. There are also diagnostic tools on pests and diseases (e.g. plantwise.org).

Timely local information. This includes data on market prices (e.g., Esoko Ghana, National Livestock Marketing Information System Kenya) and weather forecasts (e.g., MKisan India).

5. Shortfalls of programs implemented thus far

ICT for agriculture has promise. An evaluation of the mobile based service Esoko finds that farmers who had access to the service sold yams at 11% higher prices than those without access.[22] Cole and Fernando (2014) show that farmers who received frequent reminders to use a toll-free cellphone-based agricultural consulting service, changed agricultural practices and experienced increases in yields for cumin and cotton, consistent with evidence of increases in profits.[23] They estimate that a $1 investment in the system generates a return of more than $10 (when offered the opportunity purchase the service for a six-month period, farmer's average willingness to pay was $1.70, below the cost of providing the service).[24] Two trials were conducted in Kenya of an SMS-based extension service with contract farmers of Mumias sugar, a large outgrowing company. While one trial measured no significant gains, the second trial increased plot yields by 8.5-11.5 percent relative to the control group.[25] The SMS-based system also allowed farmers to report delays or delivery failures, which significantly improved input application. These benefits spilled over to neighboring farmers who did not participate in the service.[26] In an ongoing evaluation of tablet-enabled extension services in Northern Ghana, researchers have found high demand for the service, and significant impacts on farming knowledge and practice.[27]

Farmers are willing and capable to engage with ICT. For instance, in India there was a high level of trust in the aforementioned consulting service, with the "typical" farmer using the service, both to receive information, and to ask specific questions. By the end of two years, 80% of a representative sample of cotton farmers that was offered access to the service had engaged with it. The free access hotline information service that provides agronomic information run by Ethiopia's Agricultural Transformation Agency logged over 4 million calls and registered 460k farmers in a year.[28] The mobile system 'Senekele' that offers price information has reached over 154 thousand users in 2 months.[29]

The shortage of context-relevant, localized, customized information is a central impediment. To date, the cost-effectiveness of ICT solutions is more associated with their low cost than their outsize effectiveness. Few systems have scalable mechanisms for local information creation. As a consequence, most systems provide advice that is too coarse, not well suited to the agronomic or socio-demographic conditions faced by farmers. Policymakers acknowledge this as one of the biggest challenges in making ICT useful for farmers.[30]

6. Complementary innovations to improve results

The following innovations may improve the effectiveness of these programs:

Two-way communication and information aggregation: ICT can be used to crowd-source information about local conditions, farmers' backgrounds, and experiences with inputs and practices, at a very low cost. Farmers themselves are an untapped source of information that can (i) be used to learn more about individual customer needs, and (ii) be aggregated across farmers to help solve the local information creation problem.

Personalized, automatized recommendation: Once information is aggregated, computational techniques could predict optimal local farming practices given a participant's crops, local soil and weather conditions, socioeconomic characteristics, labor supply, access to inputs, and other variables.

Iterative learning: When best practices are not known, local information creation entails direct experimentation with famers. For example, by recommending fertilizer usage plans to a randomly selected subset of farmers, one could track which types of farmers are able to follow these practices and in what settings they are more likely to increase yields. Constant experimentation can also help optimize techniques for customer engagement and test behavioral nudges for adoption.

A long history of quantitative field research has created the experience needed to establish a system that encompasses all of these innovations.

7. Our solution

We propose to develop a low-cost, high quality, easily scalable, customized agricultural advice service, aiming to significantly and sustainably increase farm income and reduce negative environmental impacts.

The system, a new model for agricultural extension, will provide farmers with personalized agricultural advice through mobile phones. The recommendations will be tailored to optimize input and management practices to local agro-climatic and market conditions and taking into account farmers' demographic profiles. For instance, input recommendations could be customized based on soil nitrogen content, moisture, and local weather forecasts; local availability of inputs and access to markets; and farmers' education, access to seasonal labor, and ability to take on risk.

We will use a hybrid model of data generation. Initially, the system will be trained on expert recommendations based on current best practices. These recommendations will be tailored to individual farmers using agronomic models and data from remote sensing technologies as well as from soil samples. However, what distinguishes this platform is that the system will allow for a two-way flow of information with farmers that will continually refine our knowledge of best practice. The recommendation system will be continuously trained as it collects data about farmers' background, farming experiences, and results. This will allow it to better predict optimal agricultural practices for other farmers with similar characteristics and similar conditions.

The system will allow constant experimentation and learning by generating a large and rich database linking agricultural practices to yields and a platform for facilitating experimentation. When best practices are not known, the platform can conduct hundreds or thousands of experiments (i.e., A/B testing) virtually without cost. For example, by recommending advanced fertilizer usage plans to a randomly selected subset of farmers, we could then track what type of farmers are able to follow these practices and in what settings they increase yield. Similarly, the service will constantly experiment to learn the optimal ways to request information and guarantee its reliability. To maximize the value of the information we receive, we will use machine learning techniques to dynamically prioritize the questions that are most discriminating for the advice a farmer will receive, and the questions that provide the most learning benefit to the system. These priorities will shift as conditions change and as the system learns new relationships.

8. Our approach

The initial development and testing is planned for multiple locations and settings, with three main activities. First, PAD plans to implement and operate directly with appropriate on-the-ground partners, responsible for all or most pieces of the value chain. Second, PAD plans to engage in/support the development of components of a customized advisory service such as setting up smart two-way communication systems. Third, PAD may support high potential (impact and scale) agricultural advisory systems by providing services, e.g., on research, data analytics and evaluation design. As such PAD will not only be an implementer but also contribute to field building. The system described above may *de facto* be a combination of different systems with PAD having different levels of involvement and ownership for different subsystems.

In year one we will start direct operations in two locations: 1) In India, building on prior work done with Awaaz De, and 2) in Western Kenya, doing initial development and testing for a subsystem that focuses on maize farmers, leveraging existing local research and networks. We may also explore more indirect involvement e.g., by supporting individual components or providing support and services for systems designed and implemented by such organizations as CABI in India and ATA in Ethiopia.

9. Planned activities in India

While India is the second largest producer of cotton in the world, it's global productivity in cotton production ranks 78th. In previous research work Cole and Fernando (2015) found that the introduction of a low-cost, mobile-based extension system had positive effects on yields and efficient input use in the cultivation of cotton. We plan to scale up a similar system, integrating additional PAD features, to over 50,000 farmers in Gujarat, India. To reach these farmers PAD will partner with Sajjata Sangh, a network of 17 NGOs engaged in natural resource management, with a reach of at least 900,000 beneficiaries, comprising farmers, livestock owners, small rural entrepreneurs and rural youth. We will employ the already proven mobile phone-based technology that allows farmers to call a hotline, ask questions and receive responses from agricultural scientists and local extension workers. To diversify and orient our content towards maximum scale and impact, we plan to investigate the potential for our systems to cover rice cultivation, a staple of Indian agriculture that accounts for nearly 20% of global rice production but remains 23% below the global average productivity.

Initially the systems will collect and aggregate data from farmers at sign-up. Farmer queries and phone calls to a random subset of farmers will yield data on input management practices, agricultural outcomes and current damage from pests. Recommendations will be generated based on this data (on pest attacks, crop cycles, weather, etc.), and some will be individualized based on individual farmer profiles. This information will be shared with farmers via push calls and direct responses to specific questions. Finally, as farmers implement recommendations, they will be surveyed by phone to improve future analysis through machine learning techniques.

The pilot will be designed to answer micro and macro questions about how successfully-piloted technology can be scaled, and incorporate new elements (e.g., two-way information flows and machine learning algorithms). Lines of inquiry will include:

- How to acquire customers at minimum cost
- Most cost-effective and accurate methods for collecting data from farmers and additional useful data (remote sensing/satellite/drone/etc.)
- Refining the user interface and optimizing system to facilitate farmer use
- Assessing demand for information for other crops (e.g., paddy)
- Assess active use as system is scaled to 50,000 farmers
- Effectiveness of different content framing
- Optimal targeting for viral spread

Once a refined product is developed, we will conduct a randomized control trial to evaluate the overall impact of the system on farmers' income, productivity and input use.

10. PAD Organization

Organizationally, PAD will initially work through a fiscal agent with US nonprofit status, Global Development Incubator, a nonprofit incubator with global orientation such as. In the second phase, PAD will seek its own nonprofit status with the establishment of a Boston based 501(c)3 organization. In implementation countries PAD will likely first work under the umbrella or locally accredited research agencies such as IPA in Africa and IFMR in India. At a later stage PAD may set up its own local organizations. In places where nonprofits may not be allowed to charge any fees or earn any income, we may choose to incorporate as for-profit organizations but owned by the US nonprofit. While we are looking to find ways to eventually be able to offer services that can sustain themselves, we expect that PAD will continue to be dependent on philanthropic contributions and thus require nonprofit status.

11. PAD Team

Michael Kremer

Michael Kremer is the Gates Professor of Developing Societies in the Department of Economics at Harvard University and Senior Fellow at the Brookings Institution. He is a Fellow of the American Academy of Arts and Sciences, a recipient of a MacArthur Fellowship and a Presidential Faculty Fellowship, and was named a Young Global Leader by the World Economic Forum. Kremer's recent research examines education and health in developing countries, immigration, and globalization. He and Rachel Glennerster have recently published Strong Medicine: Creating Incentives for Pharmaceutical Research on Neglected Diseases.

Shawn A. Cole

Shawn Cole is the John G. McLean Professor of Business Administration in the Finance Unit at Harvard Business School, where he teaches and conducts research on financial services and social enterprise topics. Much of his research examines corporate and household finance in emerging markets, with a focus on insurance, credit, and savings. He has also done extensive work on financial education in the US and emerging markets. His recent research focuses on designing and delivering advice and education over mobile phones, with an emphasis on agricultural and financial management.

He has worked in China, India, Indonesia, South Africa, and Vietnam. He is an affiliate of the National Bureau of Economic Research, and the Bureau for Research and Economic Analysis of Development. He is on the board of the Jameel Poverty Action Lab, as the co-chair for research.

Heiner Baumann

Heiner Baumann has served as Director of Global Programs at Barr since the programs' inception in 2010. Over the past twenty years, he has helped design, build, and manage outcome-oriented philanthropic and social-change organizations, including New Profit Inc. and The Children's Investment Fund Foundation. These focused primarily on health, education, livelihoods, and environment with programs in Africa, South Asia, North America, and Europe. Prior to this work, he spent five years with McKinsey & Company, where he supported a range of corporate clients and also helped build the firm's nonprofit practice.

Heiner's writings on the topics of innovation and capacity building in the nonprofit sector have appeared in the Harvard Business Review and Alliance magazine, and he has been a speaker in multiple countries on venture philanthropy. He has served on the boards of directors of several local and international nonprofit organizations and is currently on the Executive Committee of Big Bang Philanthropies, a funder collaborative tackling poverty in developing countries.

Dan Bjorkegren

Dan Bjorkegren is an Assistant Professor of Economics at Brown University. He studies the process of economic development using new sources of data, including records generated by mobile phones and has worked in China, India, Indonesia, South Africa, and Vietnam. He is an affiliate of the National Bureau of Economic Research, and the Bureau for Research and Economic Analysis of Development. He is also on the board of the Jameel Poverty Action Lab, as the co-chair for research.

Robert On

Robert has a background in EECS and Statistics and is a PhD student at the School of Information, Berkeley. His areas of research cover ICTD and Development Economics. Robert is interested in the procurement, implementation, use, and evaluation of information systems for social and economic development with the motto: Try a lot, fail a lot, but measure everything. In a previous life he was working at Google as a software engineer doing data-driven economics research.

Raissa Fabregas

Raissa Fabregas is a doctoral candidate at Harvard University. She has experience working on impact evaluation of agricultural interventions in Africa and has engaged with donors, governments, and researchers to design and implement randomized control trials. She is currently investigating how much farmers learn from different extension approaches in Kenya.

A. Nilesh Fernando

Nilesh Fernando is a Post-Doctoral Research Scholar at Harvard University. He received a Ph.D. in Public Policy from Harvard University in 2015 and previously worked and as a Research Associate at Harvard Business School and the Centre for Microfinance in Gujarat, India for two years working on field experiments related to agriculture. His dissertation research includes understanding the effects of providing mobile phone-based agricultural extension to farmers in Gujarat.

Niriksha Shetty

Niriksha is a Senior Research Associate at IFMR-Lead. She graduated with a double major in Economics and Mathematics from Franklin and Marshall College in Lancaster, PA. Niriksha was previously involved in the implementation of the 'Avaaj Otalo' system in Madhya Pradesh and subsequent analysis of data collected in this research project.

Olga Rostapshova

Olga Rostapshova is a Technical Director at Social Impact and has led a range of impact evaluations in Africa and Asia. She holds a PhD in Public Policy from Harvard University, where she was the recipient of the National Science Foundation Graduate Fellowship and a Kauffmann Fellow. Olga earned her BS in Engineering and BA in Economics, with minors in Environmental Studies and Public Policy from

Swarthmore College. She previously worked at Ernst & Young's Quantitative Economics and Statistics group, and consulted for the World Bank, MIT and Harvard.

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