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Targeting conservation agriculture in the context of livelihoods and landscapes

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ABSTRACT

Development programs have typically neglected uncertainty and variability in terms of outcomes and socio-ecological context when promoting conservation agriculture (CA) throughout sub-Saharan Africa. We developed a simple Monte Carlo-based decision model, calibrated to global data-sets and parameterized to local conditions, to predict the range of yield benefits farmers may obtain when adopting CA in two ongoing agricultural development projects in East Africa. Our general model predicts the yield effects of adopting CA-related practices average -0.60 ± 2.05 (sd) Mg maize ha^{-1} year^{-1}, indicating a near equal chance of positive and negative impacts on yield. When using site-specific, socio-economic, and biophysical data, mean changes in yield were more negative (-1.29 and -1.34 Mg ha^{-1} year^{-1}). Moreover, practically the entire distributions of potential yield impacts were negative suggesting CA is highly unlikely to generate yield benefits for farmers in the two locations. Despite comparable aggregate effects at both sites, factors such as land tenure, access to information, and livestock pressure contrast sharply highlighting the need to quantify the range of livelihood and landscape effects when evaluating the suitability of the technology. This analysis illustrates the potential of incorporating uncertainty in rapid assessments of agricultural development interventions. Whereas this study examines project-level decisions on one specific intervention, the approach is equally relevant to address decision-making for multiple interventions, at multiple scales, and for multiple criteria (e.g., across ecosystem services), and thus is an important tool that can support linking knowledge with action.

1. Introduction

Perhaps more than any other agricultural intervention, development programs promote conservation agriculture (CA)—the combination of minimum or zero soil disturbance, continuous soil cover, and crop rotations—to combat the deteriorating environmental conditions and increasing social pressures threatening smallholder farmers' livelihoods in sub-Saharan Africa (SSA) (Andersson and Giller, 2012). The suitability, utility, and impact of CA for smallholder farming systems in SSA are far from certain, however. Although CA has been shown to increase and stabilize yields, conserve soil moisture, increase soil carbon stocks, and improve soil physical and chemical properties in many situations (Chivenge et al., 2007; Rockström et al., 2009; Thierfelder and Wall, 2009; Thierfelder et al., 2012), using CA does not always produce positive outcomes for the farmer, soil or wider landscape (Affholder et al., 2010; Govaerts et al., 2009; Paul et al., 2013). Environmental and social factors affecting the farming enterprise—such as mean annual precipitation, soil type, land tenure, labor availability, crop residue management, access to markets, amongst others—determine the direction (positive or negative) and magnitude of impacts derived from practicing CA (Giller et al., 2011, 2009; Knowler and Bradshaw, 2007; Rusinamhodzi et al., 2011). Variable results, in research trials and in the field, suggest CA should not be regarded as the panacea oft prescribed (Giller et al., 2009). Its use needs to be carefully targeted to favorable areas or tailored to match production conditions (Baudron et al., 2012; Giller et al., 2011).

Development programs rarely consider uncertainty and variability, in terms of either socio-ecological context or sustainable development outcomes, prior to promoting CA throughout SSA. This neglect contributes to the variable results often seen on the ground, heightens the risk of unintended consequences, and can threaten the livelihoods of the intended beneficiaries. Rapid, rigorous, and objective approaches that can evaluate CA and other potential agricultural management interventions while accounting for systematic uncertainty are needed to support effective

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development programs. Probabilistic modeling and Monte Carlo analysis may be well-suited tools for this purpose (Jeuland and Pattanayak, 2012). This approach simulates the range of potential outcomes based on the variability and uncertainty of model parameters. It, therefore, forecasts both the most likely effects as well as extreme ones, allowing decision makers to understand the diversity and likelihood of possible impacts. Despite pervasive use in the private sector, Monte Carlo approaches are practically absent from programmatic decision-making in agricultural development.

Here, we test the utility of Monte Carlo approaches for targeting CA in SSA. First, we develop a decision model, calibrated to available data and including uncertain factors, to predict the range of yield effects a farmer might experience when switching from conventional cultivation practices to CA for rain-fed maize. We then parameterize the model for social and environmental conditions at two development project sites in East Africa that are considering or actively promoting CA in order to evaluate the likelihood CA would be a sound intervention selection.

2. Materials and methods

2.1. Decision model

We built a model to predict yield changes when converting from conventional rain-fed maize production practices to CA. The model's parameters were selected based on the review by Giller et al. (2011) and include both biophysical and social factors that influence CA adoption and yield. Yield effects (Δ yield) were expressed as:

$$\Delta\text{yield} = \text{sl} + \text{so} + \text{bio} + \text{prec} + \text{in} + \text{fs} + \text{ts} + \text{ls} + \text{m} + \text{i}$$

with the parameters standing for the effects of slope (sl), soil (so), biomass production (bio), precipitation (prec), nitrogen input (in), farm size (fs), tenure security (ts), livestock density (ls), access to markets (m), and access to information (i). A simple linear model structure was used to ensure that all important site factors included in the current scientific discourse on CA received representation. Inclusion of interactions between factors would have required a very complex model structure, in which estimates of virtually all parameters would have been difficult to constrain. Without including interactions, the model cannot account for positive and negative feedbacks inherent to farming systems. Variation in the magnitude of predicted impacts among parameters is captured in the range distributions used for each parameter. Quantitative information on the distribution (90% confidence intervals) of effects of the majority of biophysical parameters was estimated from a recent meta-analysis by Rusinamhodzi et al. (2011). It is important to note that the meta-analysis focuses on yields of rain-fed maize under no-till, with and without rotations and other management and environmental criteria. The management system is not precisely equivalent to CA and thus utilizing these data as input for developing calibrated probabilities of CA introduces a source of uncertainty. Moreover, use of effect estimates derived from the meta-analysis required the scale of our analysis to conform to the one used by its authors, who evaluated maize production across a range of different production regions of the world. Thus, our results need to be placed in this context and reported yield changes should be considered relative to the level of production in the meta-analysis. For reference, global maize yields averaged 5.0 $\text{Mg ha}^{-1}\text{ year}^{-1}$ for the ten years from 2003 to 2012 (FAO, 2013) and therefore a predicted decrease in yield in this study of 1.3 $\text{Mg ha}^{-1}\text{ year}^{-1}$ represents approximately a 25% decline in production.

For many socio-economic parameters in our equation, quantitative information was not readily available. Since it has been shown, however, that these factors significantly influence the prospects for CA introduction (Knowler and Bradshaw, 2007), we were sure that their impact is not negligible and that they must not be omitted from simulations. We therefore included in the model our best estimates of 90% confidence intervals for the respective parameters. In estimating these values, we followed procedures proposed by Hubbard (2010) for self-calibration. While some readers may disagree with our choice of lower and upper bounds for the confidence intervals, we consider them adequate for describing prior distributions in a Bayesian sense; i.e., they constitute assumptions about the effects of the various factors that seem reasonable in the absence of actual measurements.

All parameters were assumed to be normally distributed across the 90% confidence intervals listed (Table 1). For some variables, the data compilation by Rusinamhodzi et al. (2011) indicated that different distributions should be chosen depending on the general setting of the site. For instance, yield effects of CA tend to be more positive for coarse than for fine textured soils. The model reflects such categorical differences. For deciding on the category that a farm site fell in, samples were drawn from a uniform distribution describing the mix of site conditions encountered at or assumed for the study sites. After this case decision, the exact value of each effect was then determined by sampling from the normal distribution constructed from the confidence intervals. Monte Carlo simulations ($N = 10{,}000$) generated distributions of mean yield effects of CA over a ten-year time horizon. Ten-years were selected to account for maturation time of some CA impacts (Six et al., 2004), yet it should be considered that smallholder farmers tend to take decisions over shorter time horizons.

We modeled four cases. The base case assumes no prior knowledge of target population, location or socioeconomic context of the farming systems. It simply defines the entire range of possible outcomes based on the estimated dataset. Then we parameterized the model for site-specific data collected near Kaptumo, Kenya and Kolero, Tanzania (described in Section 2.2). Lastly, we created an 'ideal' scenario that reflects a near best-case scenario for CA and smallholder farming in SSA (Table 1).

2.2. Study sites and data collection

Two sites of ongoing development programs served as study sites. The first site, Kaptumo, Kenya, is situated in the South Nandi district in the Western Highlands of Kenya, at elevations between 1800 and 2000 m (35.084°E, 0.044°N). Mean monthly temperature ranges between 16 and 31 °C, with mean annual precipitation between 1500 and 2200 mm. Natural vegetation of the region was originally forest, but it has undergone conversion from its natural forest state starting around the turn of the 20th century. Today, the Kaptumo area consists of mixed crop-livestock farms that produce dairy and tea and a few staple crops for subsistence, primarily maize, and sorghum. The second site, Kolero, Tanzania (37.756°E, −7.212°S) sits in the Uluguru Mountain range, which is part of the Eastern Arc Mountains of Tanzania, where agriculture occurs on steep, unterraced slopes. Monthly mean temperatures range between 22 and 33 °C, with mean annual precipitation above 1800 mm. The natural vegetation was tropical rainforest, but no original forest remains within the study site. Slash and burn is the common land management strategy. Cultivation of staple grains—maize, upland and paddy rice, and cassava—dominates agricultural fields.

Socioeconomic and biophysical data collection in the Kaptumo and Kolero regions took place between October 2011 and December 2012. Socioeconomic surveys were administered to 357 and 333 households, respectively. Surveys asked questions about household assets, such as land size and ownership, and details of the primary farming enterprises including such factors as access to market and