Farmer Participatory Research Advances Sustainable Agriculture: Lessons from Michigan and Malawi

Sieglinde S. Snapp,* James DeDecker and Adam S. Davis

ABSTRACT
Sustainable production for field crops has proved to be a challenging proposition. Farmer participatory research (FPR) is an important approach to help ensure relevance and define locally adapted solutions for enhanced adoption of sustainable agriculture (SA) technologies. The mother and baby trial (MBT) design has proved effective as a FPR approach to address challenges on smallholder farms. The MBT systematically links long-term “mother” trials, where slow and erratic processes can be monitored, to “baby” trials led by farmers to capture a wide range of farm practices and environmental contexts. Communication and learning is facilitated through MBTs as well. This distributed FPR approach documents the performance of technologies in diverse contexts and provides multiple opportunities for joint planning, observation, and reflection. We describe two MBT case studies, one within a developing country context (Malawi) and the other representing a novel application of MBT within an intensive agriculture context (Michigan). To explore tradeoffs in SA performance, multiple domains (productivity, environmental, and economic) are presented via radar charts as a visualization tool. In both FPR experiences, farmer perspectives and a wide range of practices were revealed. In Malawi, a mesic site was associated with steep SA tradeoffs compared with a marginal site. In Michigan, diversity in tillage practices, field crop performance, and soil health were found to be conditioned by the environment. Overall, the MBT approach supported the development of SA technologies adapted to local conditions.

Core Ideas
• Sustainable agricultural technologies are needed for environmental services.
• Agricultural learning communities support joint learning and on-farm adoption.
• Case studies from Michigan and Malawi illustrate the mother and baby trial approach.
• Farmer participatory research enhances stakeholder communication and adaptations.

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 onc-farm research and participatory colearning approaches have been proposed as tools to ensure relevance in agricultural research for many years (Carberry, 2001; Clinton, 1913). These methods are intended to bridge the divide between research and practice by engaging farmers as partners in the research process and by sampling the wide variation in environmental contexts and farm practices (Farrington and Martin, 1988). Farmer participatory research builds upon action research theory and the methods developed by social scientists acting as change agents to solve problems with stakeholders (Lantz et al., 2006). An iterative process is central to FPR: problems and potential solutions are identified by farmers in collaboration with educators and scientists, “best bet” options are tested through on-farm research, observations are made by all parties, results are synthesized and discussed, and an iterative process of fine-tuning continues (Kanyama-Phiri et al., 1998). This planning–action–reflection cycle supports the adaptation of technologies to specific agroecological contexts (Bellon, 2001; Snapp and Heong, 2003). Farmer participatory research has generally been conducted within developing country contexts, involving small-scale farmers. There is need to expand this model to other contexts such as intensive field crop systems in the United States.

Traditional research and extension, which follows reductionist component research approaches, have proven inadequate at times to address site-specific, complex, and value-laden challenges involved in environmentally sound, sustainable production. Farmer participatory research generates locally relevant solutions and adaptation capacity, both of which are important for minimizing environmental harm from agriculture (Grabowski et al., 2018). Sustainable agriculture technologies such as conservation tillage and integrated organic and inorganic nutrient management often face steep barriers to adoption, such as the need for specialized knowledge, capital, and labor requirements and the potential for reduced crop yield, at least in the short term (Kassie et al., 2015; Wade et al., 2015). Collaborative research processes are uniquely suited to addressing SA challenges through recognition of different types of knowledge including that of “experts”
and farmers’ experiential or indigenous knowledge (Lobry de Bruyn et al. 2017; Mapfumo et al., 2016). In this way, FPR generates relevant solutions to problems by testing out alternatives on-farm and empowering farmers to innovate and adapt (Bezner Kerr et al., 2007; Wortmann et al., 2005).

Farmer participatory research approaches remain uncommon, partly because of the perceived challenges and pitfalls relative to traditional agronomic research. Chief among these are questions regarding whom should be asked to participate, in which phases of the research and extension process, and in what ways (Bellon, 2001; Lantz et al., 2006). In striving for local relevance, FPR projects often reach a relatively small number of farmers compared with traditional methods (Farrington and Martin, 1988). Furthermore, FPR has been criticized as “soft” science, seemingly ad hoc, or lacking in rigor (Snapp and Heong, 2003). We concur with the need to document and systematize FPR to answer these questions and critiques (Carberry, 2001).

Many examples of FPR to improve agricultural productivity and sustainability have arisen within the context of underdeveloped countries and low-input agriculture (Bezner Kerr et al., 2007; Farrington and Martin, 1988). At the same time, farmer–researcher partnerships clearly exist in North America and Europe with successful outcomes in terms of expanding the role and effectiveness of farmers’ own experimentation (Delate et al., 2017; Wortmann et al., 2005). There are a growing number of examples in the literature on intensified agriculture representing the continuum of FPR approaches (Lyon et al., 2019; Vogl et al., 2015).

One FPR approach is the MBT technique. According to Small and Raizada (2017), the MBT approach has been “widely adopted in the field of participatory agronomy and plant breeding research with farmers around the world.” The MBT approach is a systematic design that samples variation across space and time by promoting the involvement of large numbers of farmers through baby trials (single replicates of subsets of technologies chosen by farmers) systematically linked to mother trials, where all technologies are evaluated in a replicated manner within-site (Isaacs et al., 2016; Lyon et al., 2019; Snapp, 2002). This has been used in many cases for participatory variety selection but also lends itself to documentation of slow processes that are often key to sustainable production, such as soil organic C accrual; this can be evaluated in mother trials established in controlled environments over the long term while the network of baby trials supports joint learning among farmers, extension staff, and researchers. The MBT approach also provides opportunities for researchers to investigate how farmers’ management practices and the environment interact to influence SA performance (Snapp et al., 2002). A recent innovation in MBTs is to conduct a concurrent survey that documents farmers’ preferences and field practices, along with typical crop yields and soil properties. This provides a systematic documentation of farmers’ adaptations and adoption (Mungai et al., 2016; Fig. 1).

**STUDY OBJECTIVES**

The overall goal is to document how FPR can be used to facilitate adaptation of SA technologies in field crops with farmers from contrasting contexts, from Malawi in Southern Africa to Michigan, in the North Central United States. Objective 1 is to present case studies of the MBT approach to participatory research, conducted within a limited resource vs. an intensified production context. Objective 2 is to demonstrate a method of visualizing FPR results, including potential the tradeoffs between production and environmental performance associated with SA technologies applied along environmental gradients, from mesic to marginal.

**Case Study One: Sustainable Agriculture with Malawian Smallholders**

Malawian agriculture is dependent on highly weathered and nutrient-depleted soils; this is typical of farms across East and Southern Africa (Kanyama-Phiri et al., 1998; Tittonell et al., 2005). Economic resources and access to fertilizers are highly limited, particularly among smallholder farmers. This requires an integrated approach that utilizes organic resources as well as inorganic fertilizers (Kanyama-Phiri et al., 1998). Efforts to understand soil fertility and production potential have often floundered on the heterogeneity of soil parent material, household topology, and soil amendments can vary at the scale of 1, 10 or 100 m (Tittonell et al., 2005). Not only do natural resources vary; farmers’ goals and market orientation are also highly variable (Humphries et al., 2015; Grabowski et al., 2018).

The United States Agency for International Development-sponsored Feed the Future initiative in Malawi ‘Africa RISING’ has facilitated the development of FPR approaches to address the site-specific problems of environmental and food insecurity. Combined with on-farm monitoring to understand yield gaps and the relevance and profitability of SA technologies, the Africa RISING team seeks to fine-tune recommendations and understand the interaction of climate, soil type, and market goals to support the adoption of SA technologies (Mungai et al., 2016; Snapp et al., 2018). Farmer participatory research is being carried out in three Malawi administrative units, called Extension Planning Areas (EPAs) (Fig. 2). The research sites were chosen via a stratified random approach to be representative of three agroecological zones, from marginal to mesic. Thus the findings can be assumed to address low and high potential
areas of smallholder agriculture in Central Malawi and beyond. The sites were as follows:

i. Linthipe EPA: Relatively high rainfall, high elevation (1000–1200 m asl) with high agricultural potential,

ii. Kandeu EPA: Medium rainfall and medium elevation (800–900 m asl) with intermediate agricultural potential, and

iii. Golomoti EPA: Low effective rainfall resulting from high evapotranspiration and low elevation (550–650 m asl) and high temperature and marginal agricultural potential. This area is associated with flash flooding because of the low-lying flat terrain and is characterized by poor rainfall distribution.

The Malawian FPR Approach

In 2012, a MBT approach was implemented at the three EPAs. We established a dozen mother trials to test a full suite of SA technologies over the longer term (Fig. 1). Groups of about 30 farmers were engaged at each mother trial site and supported through training and seed access to try out technologies on his or her farm as a baby trial. Georeferenced mother trial and baby trial locations are shown in Fig. 2. Sustainable agriculture technologies were variations in legume crops \(\text{(Phaseolus vulgaris L.), cowpea (Vigna unguiculata [L.] Walp.), peanut (Arachis hypogaea L.), pigeonpea (Cajanus cajan [L.] Millsp.), and soybean (Glycine max [L.] Merr.)}\) diversification of maize \(\text{(Zea mays L.)-based systems through integrated nutrient management (Snapp et al., 2018). In mother trials, this included judicious doses of N and P fertilizer at the recommended rate of 69 kg N ha\(^{-1}\) and 9 kg P ha\(^{-1}\) for sole maize, with reduced rates based on stringent accounting for organic nutrient sources in other treatments. No fertilizer was supplied in the case of baby trials, which allowed exploration of the farmers’ own amendments. A full description is presented in Snapp et al. (2018).}

Fig. 2. Overview of farmer participatory research (FPR) sites in Malawi at three agroecologies: Linthipe, Golomoti, and Kandeu. The inset shows a close-up of the Kandeu site, with panel field sites (brown), baby trial sites (yellow), and mother trial sites (green) indicated. Note that the panel field sites include overlaps with the farmers conducting baby trials and the nearby control farmers and distant control farmers.

Overall, MBTs served as a platform for colearning regarding which technologies performed well. Over 5 yr, the MTBs engaged over 1000 farmers. The research team collaborated with Malawian extension staff to document farmers’ ratings of technologies and adaptation to local conditions, leading to improvements such as plant spacing arrangements, fertilizer combinations, and local management practices (e.g., ratooning) (Rogé et al., 2016). Additional tools included crop modeling and socioeconomic surveys carried out as a panel series (repeated visits to the same farm households) to expand the inference zone of research (Wang et al., 2019; Smith et al., 2016; Fig. 1). In addition to surveys of participating and nonparticipating farmers, preferences regarding technologies were documented through short semiquantitative surveys conducted at field days and other demonstration events (Snapp, 2002). A novel SA technology that proved to be of interest to many farmers was the doubled-up legume rotation. This involved an early maturing grain legume (e.g., peanut or soybean) grown as an understory with a late maturing pigeonpea crop, sequenced in rotation with maize. Other SA technologies included maize grown as an intercrop with a locally selected improved pigeonpea variety, and maize sequenced in a rotation with peanut crop at a high population density and judicious fertilizer doses (Chimoyo et al., 2019).

Statistical Approaches in the Context of Malawi

Econometric regressions of the survey data collected at our sites have found value in the FPR approach, compared with conventional linear extension (Wang et al., 2019). The adoption of three SA technologies was assessed: (i) intercropping maize with a grain legume, (ii) amendment with compost, and (iii) a multipurpose legume, pigeonpea. A probability model assumed that adoption of the technologies was independent of each other and that the error terms were not correlated. Next, this assumption...
Mixed cropping with complementary change adaptation sustainable production of maize technology that supports soil fertility and Agroforestry is a sustainable agriculture tially a weakness in that little is known about the preferences the practicality of time and funding constraints. This is poten-
tigated to farmers who are engaged with the extension staff, given and Heong, 2003). It can thus be inferred that FPR is often lim-
ition and gender, farmers' perceptions of risk, and the environ-
errors. Finally, the results of the two approaches were compared out via an unrelated regression to allow for correlation of the
was relaxed and a regression on all the technologies was carried robustness. Adoption was shown to be high among farmers engaged in the FPR process (Wang et al., 2019).
The performance of SA technology on MBT plots has also been assessed at our sites via ANOVA combined with additive main effect and multiplicative interaction models (Chimonyo et al., 2019). Means, SDs, and t-test characterization along with visualization through radar charts have also proven useful (Snapp et al., 2018). Such simple characterization has formed the basis for discussing the performance of SA technology with a wide range of stakeholders in Malawi, where SA tradeoffs have been shown to vary depending on the farmers' household position and gender, farmers' perceptions of risk, and the environ-
mental context (Bezner Kerr et al., 2018; Sirrine et al., 2010).

### The FPR Process in Malawi

Farmer participatory research involves an iterative process, initiated by a planning phase, followed by action, observation, and reflection; these phases are repeated over time to refine the technologies (Bellon, 2001). This can lead to technologies that are acceptable to farmers over time (Table 1). The planning phase is influenced by site selection and who is engaged in choosing the research objectives and approaches. This depends on the recruitment and roles of researchers vs. farmers or other stakeholders. As described above, the sites were chosen in a stratified random manner to represent varying yield potential from marginal to mesic (Mungai et al., 2016). Village meet-
ings were held to introduce the project in conjunction with Malawian extension staff; this resulted in some sites with a high representation of farmers who knew the extension educators. Farmer participatory research is often enhanced through building on relationships already in place and on farmers' interest in SA technologies. This is critical to trust and communication, the bedrock of quality relationships in the FPR process (Snapp and Heong, 2003). It can thus be inferred that FPR is often limited to farmers who are engaged with the extension staff, given the practicality of time and funding constraints. This is potentially a weakness in that little is known about the preferences and practices of other farmers. At the same time, it builds social capacity, as indicated by the persistence of farmers' engagement with colearning groups facilitated by MBTs at earlier research sites in Malawi (Bezner Kerr et al., 2007, 2018).

In the action and observation phases of FPR, researchers and extension educators seek to collaborate with farmers and other stakeholders to evaluate alternative technologies and systems (Snapp et al., 2002; Vogl et al., 2015). The MBT process used in this study and in an earlier project in Northern Malawi are two examples of how SA knowledge can be generated through FPR, including identification of complementary combinations of crops and integrated soil fertility management recommendations (Table 1). At our Africa RISING study sites, female farmers were asked to rate technologies separately from male farmers, with some-
times divergent results: women often placed a high value on legume grains relative to men (Hockett and Richardson, 2018). This preference was not always reflected in market prices, which highlights the unique insights that can be revealed through engaging farmers in testing out technologies for themselves (Snapp et al., 2018).

Another finding was the first reports for Central Malawi of farmers’ interest in ratooning in pigeonpea (Table 1). This is the practice of cutting branches after harvest to initiate a second cycle for a second harvest from the same plant (Rogé et al., 2016). In contrast, Malawian agronomic recommendations only consider annual management of pigeonpea and strongly recommend extra-early varieties that neither ratoon nor produce stems for fuel wood and provide little vegetation for soil fertility amelioration (Ministry of Agriculture and Food Security, 2012). Farmer participatory research can thus generate new management options outside the scope of current extension recommendations.

The reflection phase of FPR brings researchers and stakeholders together to evaluate the research outcomes, consider how new information can be applied or shared, and identify persistent knowledge gaps that could be addressed (Bellon, 2001). This phase makes the iterative nature of FPR explicit by acknowledging that on-farm results often represent incomplete solutions, where new questions arise along with adaptations to try out (Table 1). In this way, the next planning—action—reflection cycle is initiated.

In Malawi, radar charts provided a means to visualize and reflect on the results together in annual meetings of researchers, extension staff, and farmers (Fig. 3). To facilitate understanding, the results were translated into local languages and a range of

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<th>Initial research hypotheses</th>
<th>Findings and adaptations</th>
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<tr>
<td>Agroforestry is a sustainable agriculture technology that supports soil fertility and sustainable, rain-fed production of maize</td>
<td>Agroforestry with mixed maize–legume trees markedly increase yields and fertilizer efficiency. Risk perceptions by farmers, along with labor requirements, limit the adoption of agroforestry to nil.</td>
<td>Kanyama-Phiri et al., 1998; Mhango et al., 2013; Phiri et al., 1999; Sirrine et al., 2010</td>
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<td>Legume crop diversification enhances soil N through biological N fixation for sustainable production of maize</td>
<td>Highly valued legumes tend to be early maturing and produce income. Legumes that enhance soil fertility tend to be late maturing or ratooned with modest yields and have uncertain or delayed value.</td>
<td>Bezner Kerr et al., 2007; Mhango et al., 2013; Rogé et al., 2016</td>
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<td>Drought-tolerant crops are key to climate change adaptation</td>
<td>Early maturing crops are adapted to droughts but sensitive to poor soils. Late maturing crops are adapted to droughts and to poor soils.</td>
<td>Bezner Kerr et al., 2018</td>
</tr>
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<td>Mixed cropping with complementary growth types will enhance fertilizer efficiency and resilience</td>
<td>Maize yields at half fertilizer rates are sustained through rotation with mixed legume systems. Farmers often prefer crop types that grow well in mixtures and select for such plant architectural traits.</td>
<td>Chimonyo et al., 2019; Mhango et al., 2013; Snapp et al., 2018</td>
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Table 1. A review of Malawian farmer participatory research FPR literature, including initial hypotheses and colearning that resulted in findings informed by farmer insights and adaptations.
graphics were used to make scientific concepts and measurements compatible with the local context, beliefs, and experience. Furthermore, as agricultural recommendations were derived and fine-tuned, a farmer-engaged assessment of the extension guides was carried out so that codevelopment and iterative improvements could be continued.

An early iteration of the FPR process was conducted in Northern Malawi over 2000–2010, which providing initial findings that helped design the technologies assessed in this project (Bezner Kerr et al., 2018). Through a reflection process facilitated by FPR and sharing the results with stakeholders, it became clear that interest in some technologies, such as fertilizer trees, was almost nil (Table 1). Such SA options were associated with steep tradeoffs in terms of labor and risk (Sirrine et al., 2010). What proved to be more acceptable to farmers were crop diversification options; these included extra early maturing crop genotypes and the opposite growth habit: very long duration late maturing crop types (Bezner Kerr et al., 2018; Snapp et al., 2018). In our study, a pigeonpea–maize intercrop was a promising SA technology, as a technology with minimal maize yield tradeoffs and a number of environmental benefits such as extended soil cover and an organic N source (Fig. 3).

Other findings obtained through FPR included the poor performance of some modern varieties that were not suited to growing on degraded soil (Table 1) and the sometimes steep tradeoffs in maize yield area reduction necessitated by small fields, which proved to be a barrier to the adoption of peanut–maize rotations.

Case Study 2: Sustainable Soybean Production in Michigan

The FPR study in Michigan addresses the adaptation of conservation tillage systems to enhance the sustainability of soybean production. Farmers have followed expert recommendations in the United States to reduce tillage in an effort to produce field crops in an environmentally sound manner (Wade et al., 2015), with generally lower production costs (Weersink et al., 1992) and enhanced soil health (Robertson et al., 2014). One long-term experiment in Southwest Michigan has demonstrated that soybean yields can be superior under no-till, given the right conditions (Robertson et al., 2014). However, other research and farmers’ experiences suggest that reduced tillage systems can compromise the establishment and yield of soybean in cooler climates in the Upper Midwest region, especially on poorly drained soils and where large amounts of crop residue are present at planting (DeFelice et al., 2006). Farmers in Michigan, individually and through the Michigan Soybean Promotion Committee industry group, have frequently expressed concerns about the variable performance of no-till soybeans and interest in local adaptation of tillage practices for improved outcomes.

In Michigan, we chose FPR as means to investigate potential the tradeoffs between reduced tillage and plant performance, including soybean establishment and grain yield (Vanhie et al., 2015). Specifically, we were interested in contextualizing tillage recommendations and testing the inference space of previous research such as a southwest Michigan cropping systems experiment that was established in 1990 as part of the Long-Term Ecological Research (LTER) network (Robertson et al., 2014). This is a modified form of MBT, with the main LTER site being
Each farm was subsequently asked to choose two soybean fields and motivations and deterrents for using tillage and posed questions about relevant variables to one another and our team. Farmers shared their experience with various tillage systems and the challenges of tillage decision-making for soybeans were discussed. We termed the Northeast, Central, and Southwest agro-environments of 2016 from three distinct geographic areas of Michigan, as crop yield, profit, and soil health (Baker et al. 2007).

Background of the Michigan Case Study

We recruited 35 commercial soybean growers in the spring of 2016 from three distinct geographic areas of Michigan, which we termed the Northeast, Central, and Southwest agricultural learning communities (ALCs) (Fig. 4). Farmers were asked to participate on the basis of their expressed interest in tillage practices and soil health. Most of the growers had previously collaborated with Michigan State University Extension, other public agencies like county conservation districts, or the Michigan Soybean Promotion Committee. Our sample transected the geographic range of soybean production in Michigan, separated by latitude and soil properties (Fig. 5). Two low-latitude environments with generally coarse textured soils and lower soil organic C concentrations (Clusters C and E) supported high yields under no-till soybean production. The LTER site is situated with Cluster E, and no-till management over the last decade has been associated with approximately 20% higher soybean yield than conventional tillage (Robertson et al., 2014). Conversely, the remaining three environments, characterized by higher latitude and fine textured, poorly drained soils with relatively large amounts of SOC of interest in 2016 and again in 2017, identified as “Good” or “Bad” according to growers’ experiential knowledge of historical soybean performance. Six years of in-depth management history information was collected for each field via a written survey. To address intrafield variation, fields were divided by predominant soil series into two or three zones, each at least 1 ha in size, with the US Soil Survey Geographical database accessed through a mobile app called FarmLogs, which was available to both researchers and farmers. Soil zones were considered as our experimental unit (n = 273). Three quadrats were randomly established in each soil zone shortly before soybean planting to allow soil and plant observations.

Weather, soil, and plant parameters were monitored during four visits to each field per year. Monitoring of the variables soil temperature and soybean cyst nematode abundance was added to our sampling protocol in line with growers’ input early in the study. Monitored properties provided information about each field’s environmental context (temperature, precipitation, soil texture, pH, and organic matter) and more rapidly changing management-dependent variables (soil residue cover, plant population density, soil labile C, aggregate stability, and compaction) thought to influence soybean yield. Soybean yield was measured in 1- by 1-m quadrats at crop maturity. Gross returns to soybean production, less tillage costs, were also calculated from a previous survey of Michigan producers to estimate the average cost of tillage operations, including equipment, fuel, and labor (Battel and Stein, 2018).

Statistical Approaches in the Context of Michigan

Initially, we shared data reports at annual meetings with our learning communities by region, through a statistical characterization (means and SD) of plant and soil data in an anonymous manner, where fields were identified by numeric codes. Tillage intensities were quantified via the STIR formula from the NRCS RUSLE2 model (NRCS, 2008) to classify tillage regimes by field into three categories: no-till, conservation tillage, and conventional tillage. Next, K-means clustering was implemented, with location, weather, and soil health data being used to group cases into agroenvironments (RStudio, https://resources.rstudio.com/rstudio-conf-2019, accessed 20 Aug. 2019), which could be used as the basis for extension recommendation domains in the future (Fig. 5). This approach accounted for differences in yield potential across environments, considering performance in terms of yield gaps within clusters (Patrignani et al., 2014). A yield gap was defined as the difference between the highest yield observed over the study for a given environment or cluster and the yield recorded for each soil zone in that cluster (Patrignani et al., 2014). The clusters delineated five distinct agroenvironments for soybean in Michigan, separated by latitude and soil properties (Fig. 5). Two low-latitude environments with generally coarse textured soils and lower soil organic C concentrations (Clusters C and E) supported high yields under no-till soybean production. The LTER site is situated with Cluster E, and no-till management over the last decade has been associated with approximately 20% higher soybean yield than conventional tillage (Robertson et al., 2014). Conversely, the remaining three environments, characterized by higher latitude and fine textured, poorly drained soils with relatively large amounts of SOC.
Clusters A, B, and F, showed a significant yield penalty for no-till soybeans, a yield gap that could be closed by increasing tillage intensity to various degrees. Thus agricultural performance was markedly influenced by the environmental context.

Michigan’s FPR Process

The planning phase of FPR in Michigan involved discussions with ALCs, where a paired-field experimental design was discarded according to farmers’ input. Instead, we followed an observational research approach designed to capitalize on the diversity of tillage practices in use, as well as local experiential knowledge and interest in management within a relevant environmental context. This observational study design did not directly test new tillage technologies but provided opportunities for codesign of what was monitored and social learning through facilitated discussions of on-farm observations. This occurred during report-back sessions held several times per year in each of the three ALC regions (Fig. 4). Furthermore, participants selected which fields would be sampled on the basis of their experiential knowledge and implemented their customized “treatments” by maintaining their current tillage practices.

In the action phase of the FPR approach, researchers decided which variables to monitor after in-depth discussions with participants, considering farmers’ interest in various SA indicators and logistical advice on monitoring (e.g., where and when to access fields). We felt that this approach helped ensure data availability and quality. Although it was not as highly participatory as some FPR models, we maintain that there is value in the entire spectrum of on-farm participatory research and extension models. In this case modest participation was achieved, we directly addressed a key concern of soybean farmers, and we took the tremendous variability in growing environment and management practices that affect SA outcomes into account.

Reflection in Michigan regarding on-farm findings was facilitated in two ways: through customized data reports for each farmer as described above, and through radar visualizations of performance by cluster and by tillage system (no-tillage, conservation tillage, and conventional tillage) for a range of environmental, production, and economic properties (Fig. 6; Smith et al., 2017). This allowed the presentation of tradeoffs among tillage systems within each cluster, such as the substantial reduction in soybean yield associated with no-till fields relative to other tillage systems in Clusters A, B, and F and an apparent tradeoff with soil health, as indicated by soil aggregate stability, which was high for no-till fields in these clusters. The coded information allowed farmers to examine the performance of their fields confidentially and to benchmark their fields against others in their cluster. The customized data reports and radar charts thus supported social learning, and we actively elicited farmers’ experience to contextualize and help explain the observed data trends. Finally, we included data from the LTER site in Southwest Michigan as a no-till and conventional till comparison that provided a mother trial opportunity to assess performance under researcher-managed conditions for over a decade (Robertson et al., 2014). Thus slow processes such as soil C accrual could be discussed with farmers, where the longevity of the response at the LTER provided unique insights.

Tillage recommendations (no-till, conservation tillage, or conventional tillage) were developed for each cluster, for review by ALC growers (Fig. 6). No-till was recommended for zones in Clusters C and E, conservation tillage was recommended in Clusters A and B, and conventional tillage was recommended...
Fig. 6. Radar chart visualizations of soybean production and economic performance and soil health properties associated with sustainable agriculture (SA) technologies (no-till, conservation tillage, and conventional tillage) in five agroenvironmental zones across Michigan.
in Cluster F. Radar chart visualizations were useful in extension messaging as a means to consider multiple dimensions of performance and potential tradeoffs. For example, production attributes (stand establishment and yield) can be compared with economic returns (gross profit less tillage costs) and soil health indicators (soil residue cover, aggregate stability, total C, and active C). Performance was conditioned by location (Fig. 6). Consider the fields in Cluster F: Conventional tillage is recommended for this cluster in order to maximize yield and profitability; however, conventional tillage in this cluster is also associated with low values for soil C and aggregate stability (relative to other tillage systems in Cluster F). Visualization allows the participants to consider tradeoffs based on their personal values and understanding of the potential benefits relative to less tangible properties (e.g., soil health) relative to soybean yield and profitability. In our review of the literature, very few on-farm studies considered the tradeoffs associated with tillage practices and the associated crop performance and soil health properties. A pioneering observational study in Illinois is an exception, where, similar to our findings, environmental context mattered and conservation tillage practices were associated with variability in a wide range of soil properties including soil C (Needelman et al. 1999).

In 2017, we conducted a short survey of ALC participants to gauge farmers’ learning and interest in the cluster-specific tillage recommendations. Twenty-one farmers responded, 90% of whom reported that participation in the project increased their knowledge of soil management for soybeans (52% ‘a great deal’ and 38% ‘moderately’); 86% indicated that they intended to change their soil management practices based on what they learned. Further, farmers’ interest was evident in how tillage intensity interacted with other management practices, such as manure application, as well as the key role played by environmental context. Overall, the FPR process enhanced knowledge and extension communication with farmers about tradeoffs and the importance of context for understanding the performance of conservation tillage practices.

**Comparison of Malawi’s and Michigan’s FPR Experiences**

Overall, we found that the variations in MBT approaches presented here from Malawi and Michigan both provided important opportunities for researchers, extension staff, and farmers to interact systematically and to enhance knowledge of context-specific patterns in SA technology performance. An important aspect in both contexts was the consideration given to and observations of multiple dimensions of sustainability (e.g., productivity, environmental, and economic) (Fig. 3 and Fig. 6; Smith et al., 2017). Key to this, structured surveys, on-farm monitoring, and scheduled report-back sessions all added depth and richness to our research and increased relevance for farmers (Farrington and Martin, 1988; Snapp et al., 2002). Visualization tools such as radar charts, structural equation modeling, and adaptability analysis have been key to interpreting complex findings in MBT approaches conducted in Southern Africa, as well as the United States (Chimonyo et al., 2019; Smith et al., 2014). This is in concurrence with a recent report on MBT variety selection with vegetable growers in the United States (Lyon et al., 2019).

In both contexts, reflection on the performance of technologies involved a holistic assessment shared with farmers, with metrics related to economic, environmental, and agronomic aspects that were visualized as radar charts (Fig. 3 and Fig. 6). Interdisciplinary research produces complicated outputs and it is important to visualize tradeoffs and synergies in an accessible manner (Bouma, 2015; Grabowski et al., 2018). In the SA performance visualizations presented here, grain yield depended on technology × environment interactions and technologies therefore varied markedly in terms of economic and environmental services. In the intensive Michigan field crop production context, soybean productivity (1–3 Mg ha\(^{-1}\)) was high relative to the limited-resource environment of Malawi (0–0.9 Mg ha\(^{-1}\)). Interestingly, gross returns were in the range of $0 to $300 ha\(^{-1}\) in both contexts, although the very small farm size (often less than 1 ha) in Malawi markedly limited income per farm family and there are serious risks to food security associated with crop failure, with no safety nets such as farm insurance. The social aspects of SA performance were prioritized in Malawi to a greater extent than in Michigan, including a survey that documented female as well as male farmers’ perceptions of technologies.

Similar to other FPR approaches, we found value in reporting the descriptive characteristics of technology performance to farmer groups, including radar charts, and documenting farmers’ perspectives through simple tools such as short surveys conducted at meetings and field demonstrations (Snapp, 2002). Farmers’ responses, field practices, and adaptations all provided novel insights into potential tradeoffs in SA, explaining why farmers might or might not adopt SA technologies. Importantly, farmers often innovated and altered recommended practices in both contexts (Table 1). The MBT approach provided unique insights in that it facilitated documentation of farmers’ adaptations and performance across a wide range of agroecological environments and simultaneously provided a means to benchmark on-farm properties relative to one or more long-term monitoring sites. In Michigan, insights into slow processes such as soil C accrual were strengthened by the presence of an LTER agricultural site as the mother trial. This reinforces the value of long-term observational networks in agroecosystems (Kleinman et al., 2018) and, at the same time, calls for consideration of the need for contextualization through MBT or other FPR approaches.

**CONCLUSIONS**

Farmers have unique perspectives and deep knowledge of how to integrate complex cropping systems for multiple gains at minimal costs. Despite widespread acknowledgement that farmers have unique knowledge on offer, there are remarkably few examples of engaged colearning with farmers, whereby researchers and farmers work together as peers to address challenging SA problems associated with ensuring sufficient production at minimal environmental cost. We found tremendous value in the formation of agricultural learning communities to conduct FPR, from the Upper Midwest United States to southern Africa. We acknowledge the challenges associated with implementing FPR and achieving the ideal of farmer engagement and participation. One aim of this paper is to provide road maps and to make the case that whether the level of stakeholder engagement is shallow or deep, there is great value in ALC engagement to communicate about SA tradeoffs. Although the investment in human resources and time required to reach a modest number of farmers is significant, it is unlikely that the farmers
we encountered in Michigan and Malawi would have been exposed to the same range of alternatives or relevant data via a conventional linear diffusion approach. Indeed, achieving SA in agriculture has often floundered because of limited relevancy and difficulty in extending research findings to practitioners. We contend that the MBT as an FPR approach should not be overlooked as a means to understand technology performance within heterogeneous contexts, to enhance the capacity for adaptation among farmers, and to systematically benchmark performance on-farm relative to long-term observation sites.

CONFLICT OF INTEREST DISCLOSURE
The authors declare that there is no conflict of interest.

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