A Co-Produced Roadmap for Future Research at the KBS LTAR Site

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January 2026

Long-Term Agricultural Research (LTAR) at the Kellogg Biological Station (KBS) aims to advance the design of row crop systems of the upper Midwest via the Aspirational Cropping Systems Experiment (ACSE), co-produced by scientists and stakeholders to advance the potential for cropping systems to provide important ecosystem services. These include, most prominently, profitable yields, clean water, healthy soil, biodiversity benefits, climate resilience, and social well-being (Robertson et al. 2024). Stakeholders have expressly stated that they expect KBS LTAR to "*bridge the gap between agricultural systems needed by present and future generations*." Long-term, systems-level research that extends from plots to farms is crucial for meeting this challenge.

The ACSE, implemented in 2022 at both plot and field scales, is an Aspirational (ASP) vs. Business-as-usual (BAU) cropping system contrast (Fig. 1) that is part of the LTAR Network's Common Experiment. The ASP system incorporates many of the principles embedded in regenerative agriculture (Charles et al. 2024), an approach to farming that promotes positive environmental, economic, and social outcomes using practices appropriate to individual operations. Currently the ASP is a five-crop rotation that includes cover crops, continuous no-till, precision inputs, and biodiversity conservation patches (prairie strips). Crops include corn, soybean, winter wheat, winter canola, and a multi-species forage mix. Prairie strips are planted only in consistently unprofitable portions of fields. The BAU system, in contrast, reflects prevailing practices in Michigan (Guo et al. 2023, NASS 2024): a corn-soybean rotation, chisel plowed, without cover crops, and with inputs uniformly applied across fields. Both systems are periodically updated to reflect

Please cite as: Robertson, G.P., T.C. Ulbrich, B.J. Wilke, B. Basso, H. J. Burrack, T. Butcher, L.Campbell, C. Charles, J.E. Doll, C. Forestieri, N.M. Haddad, R. Heinze, L.T. Johnson, C. Klein, A.N. Kravchenko, D. LaBar, S.T. Marquart-Pyatt, H. Miller, M. Mills, E. O'Halloran, K. Poley, A.Z. Polverento, S. Reed, A.P. Reimer, M. Shaw, A. Smith, C.D. Sprunger, J. Stegink, B. Wickerham and L. Woodke. 2026. A Co-Produced Roadmap for Future Research at the KBS LTAR Site. Zenodo. https://doi.org/10.5281/zenodo.18226702

changing technologies, practices, markets, and social norms.

From the ACSE's inception in 2022, researchers and stakeholders have collaborated to design, analyze, interpret, and refine the experiment. Stakeholders include all participants in the agricultural value chain, including producers and other agricultural professionals, conservationists both NGO- and agency-based,

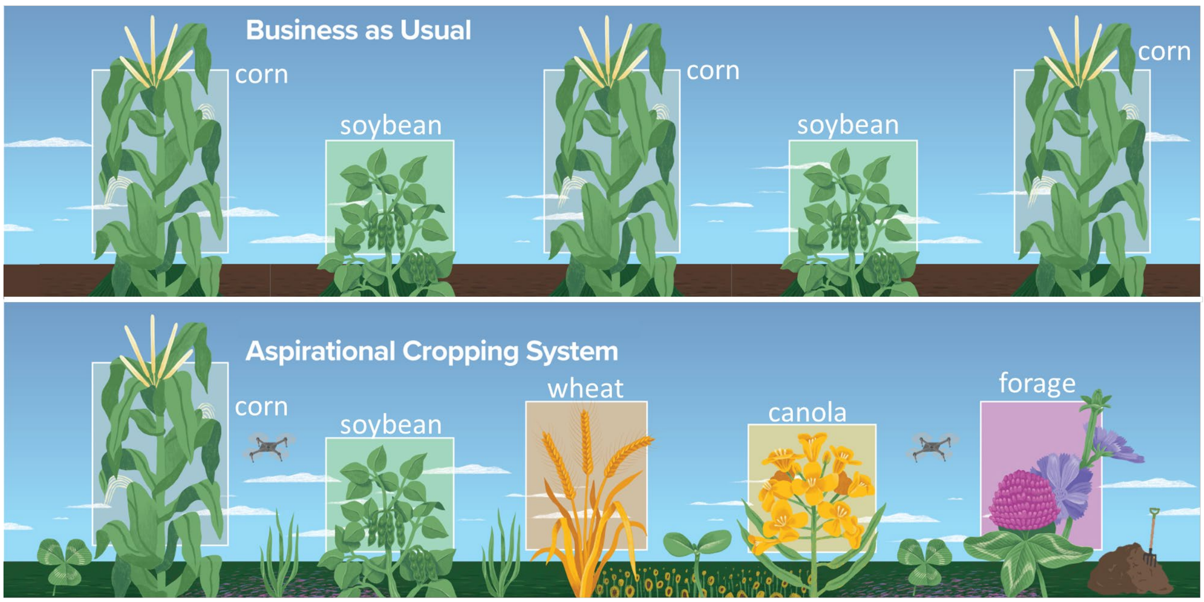

Figure 1. The KBS LTAR Aspirational Cropping System Experiment (ACSE) contrasts a 5-crop Aspirational system (bottom panel) against a Business-as-usual corn-soybean system (top panel) that represents prevailing regional practices.

policy leaders from farm and commodity organizations and government agencies, commodity buyers, and consumer-facing retailers. Following the establishment of the ACSE, collaborative workshops have refined its direction and priorities. For example, an 80-participant metrics workshop in July 2022 deliberated the metrics needed to evaluate success, and a researcher-stakeholder summit in January 2024 identified short- and long-term research priorities, further refined in a summer 2024 joint advisory boards workshop and then the 2025 researcher-stakeholder summit. This whitepaper is the result of these discussions.

Three considerations provide over-arching context for KBS LTAR research priorities. First is our participation in the national LTAR Network, which includes multiple crop- and grazing-land sites across the U.S. (Liebig et al. 2024). As part of this broader network we are committed to asking questions and assembling the biophysical and socioeconomic metrics most likely to capture differences between BAU and ASP systems nationally (Spiegal et al. 2018), thereby contributing to the success of U.S. agriculture in

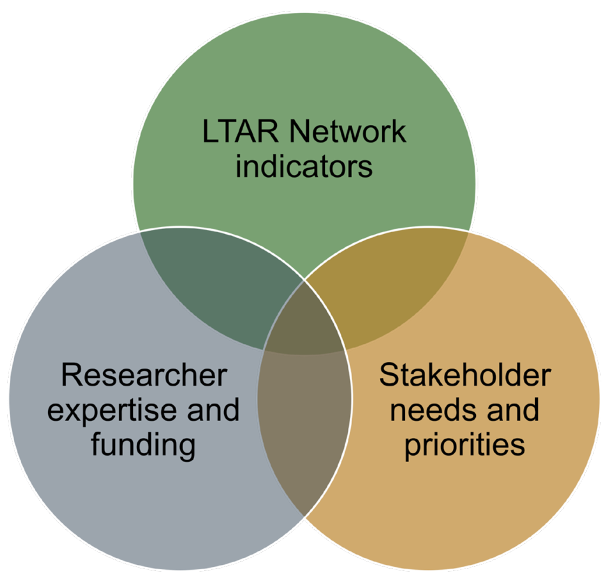

Figure 2. Questions addressed by KBS LTAR research are derived from three overlapping sources.

general. Second is our transdisciplinary, cross-sector approach, informed by a wide range of expertise, to a) test system-level impacts rather than the effects of one or two factors alone, b) be relevant to farmers and farming systems of the region, and c) be long-term in order to reveal both slow-changing and episodic responses of our cropping systems. Research is also influenced by available expertise and funding, providing a third consideration (Fig. 2).

Based on these influences, our overall portfolio comprises six research themes organized by practice and outcomes to deliver sustained productivity and profit, clean water and air, biodiversity conservation, weather and climate resilience, and social well-being. Priority themes include: 1) crop diversification; 2) nutrient cycling and livestock integration; 3) tillage management; 4) precision inputs and conservation; and 5) soil health. Systems integration, a 6th theme, underpins all: how different parts and processes of the system interact to affect long-term outcomes.

1. Crop Diversification

Diversified crops—more complex rotations that also include cover crops—are central to regenerative agriculture, known to provide a suite of benefits ranging from yield stability to pest and disease protection (Bowles et al. 2020). Despite known benefits, however, diversifying row crops away from simple corn-soybean rotations in the upper Midwest has been a major challenge for farmers. In Michigan, for example, only ~30% of cropland diverges from corn-soybean or continuous corn (NASS 2024), and only 10-27% of row crop acreage includes winter cover crops (Guo et al. 2023). Diversification is even lower in the larger region; in neighboring states corn-soybean rotations comprise 82-93% of total cropland, and winter cover crops are grown on only 4-22% of cropland acres.

Stakeholders and researchers identified four priority questions related to diversification:

- What metrics, including profitability and input efficiencies, best identify the ecosystem services delivered by diverse rotations?
- To what extent does diversification affect the quality of produced feed, food, fuel, and fiber?
- What information is needed by farmers and policy makers to enhance the adoption of cover crops?
- How can regional markets for diverse crops best be promoted, created, and stabilized?

2. Nutrient Cycling and Livestock Integration

Tight nutrient cycles, wherein nutrients such as nitrogen and phosphorus are highly conserved and recycled to the greatest extent possible, provide economic savings and protect water and air quality. Water quality is a particular concern of KBS LTAR stakeholders, as is the impact of farming on air quality, including greenhouse gas emissions. Because manure is a major nutrient source in Michigan, livestock integration provides the potential for its more efficient use while also providing marketing and soil health benefits. Two major questions emerged from researcher-stakeholder discussions:

- How do different nitrogen sources and their interactions with management affect water quality, nitrous oxide emissions, microbe-plant interactions, soil organic matter, and plant nitrogen availability?
- How can grazing and manure be best integrated into diverse crop rotations, and what factors most influence their scalability and impact on soil health, water quality, and profitability?

3. Tillage Management

Tillage, used historically for weed control, has well-recognized consequences. Some are positive: accelerated nutrient turnover releases nitrogen and other nutrients from soil organic matter to growing crops, and spring tillage can help to warm and dry soil prior to planting. Other consequences are not: tillage compromises soil structure, which slows infiltration and reduces soil water holding capacity, leading to nutrient runoff and erosion; accelerated microbial activity forces soil carbon loss and harms soil health; and excess soil nitrogen turnover stimulates microbes to generate more nitrate and nitrous oxide, contributing to poor water and air quality. No-till management can ameliorate many of these impacts. Notably, erosion resistance and infiltration rates can improve quickly following no-till initiation, but a decade or more may be needed for crop yields to consistently benefit (Cusser et al. 2020) or for soil carbon and its benefits to accumulate appreciably (Córdova et al. 2025). Resuming tillage may quickly reduce or even eliminate these gains (Ruan and Robertson 2013). Research is needed to identify how different tillage intensities affect yield and other benefits of no-till. A recent MSU Extension Bulletin highlights the challenges (Charles et al. 2025).

KBS LTAR stakeholders and researchers identified three major tillage management questions of topical interest:

- To what extent do different intensities and frequencies of reduced tillage such as strip tillage, vertical tillage, and rotational no-till affect the long-term benefits of continuous no-till, including profitability?
- How does continuous no-till affect biodiversity and downstream water quality?
- How can continuous no-till be implemented to fit into diversified farm approaches and crop rotations?

4. Precision Input Management and In-Field Conservation

Uniform pesticide and fertilizer applications apply inputs to entire fields despite the presence of subfield areas that may not require them. Weeds, for example, tend to be heterogeneously distributed, often in identifiable patches, making herbicides unnecessary elsewhere (Gerhards et al. 2022). Likewise, soil factors related to topography or other landscape features can consistently depress yields in some areas of a field, leaving applied nutrients such as nitrogen little used and thus more susceptible to loss (Basso et al. 2019). Precision or variable rate input technologies allow for cost-saving environmental benefits so long as areas of pest pressure and low yields can be reliably identified.

In many cases low-yielding subfield areas cannot produce enough yield to pay for even reduced inputs; in these cases it can make more economic sense to convert such areas to biodiversity conservation via prairie strips (Schulte et al. 2017, Basso 2021, Kemmerling et al. 2023). Well designed patches are comprised of diverse perennial forbs and grasses that can support pollinators, beneficial insects, and grassland birds, thereby providing valuable biodiversity benefits.

Three questions were identified by stakeholders and researchers related to precision input and conservation management:

- What is the short- and long-term Return On Investment (ROI) for applying fertilizers and pesticides at variable rates?

- What are the biodiversity benefits and drawbacks of precision conservation, including potential spill-over impacts on adjacent cropland?
- What information do farmers and policy makers need in order to advance the adoption of precision conservation on individual farms?

5. Soil Health

Healthy soils are foundational to regenerative agriculture, and essential to achieving its economic and environmental benefits, and also important for farmer well-being (Friedrichsen et al. 2021). Healthy soils combine physical, chemical, and biological soil attributes to create conditions conducive to vigorous, fast-growing crops and economic success. Best indicators of soil health vary with soil type and climate, but common to most are soil organic carbon concentrations as a proxy for soil organic matter and improved water holding capacity, aggregate stability as a measure of soil structure, and soil respiration as a measure of biological activity (Bagnall et al. 2023).

There are many co-benefits of soil health, including soil carbon sequestration with its implications for erosion control, water availability, and climate change mitigation, and soil biodiversity with its implications for nutrient cycling and pest and disease suppression. Indicators that are sensitive to management are particularly useful for choosing management practices that will provide long-term benefits. Biological attributes like nematode community structure (Martin et al. 2022) as well as chemical attributes like POX-C (Wade et al. 2020) show promise, but consensus on how to best integrate early indicators is lacking (Sprunger and Martin 2023), and while farmers understand the importance of soil health they express frustration at how to manage for it (Ulbrich et al. 2025). Identifying indicators that inform the soil health outcomes that farmers most value may also increase their willingness to adopt regenerative management practices in general.

Stakeholders and researchers identified the following priority questions regarding soil health:

- Which soil health indicators can most quickly and reliably predict improved ecosystem function to inform management decisions?
- How do different management practices interact to benefit or harm soil health in different Michigan soils?

6. System Integration

Weaving together the suite of practices most likely to provide desirable outcomes—productivity, economic, social, and environmental—requires a systems-level understanding of interacting components (Robertson et al. 2014). It is not enough to implement no-till or cover crops for their expected soil carbon benefits, for example, without considering their potential impacts on profitability (both short- and long-term), farmer and community well-being (including the time and stress required to manage novel practices), and unexpected environmental consequences (like the potential for additional nitrous oxide emissions and dissolved P losses). In some cases, we don't know even the direction of change when several conservation practices are implemented at the same time, let alone when multiple practices are stacked within a single management plan. Furthermore, the sequence of practices could also impact their success and outcomes. In many cases we must rely on quantitative models to predict the effects of practice interactions (e.g., Basso and Ritchie 2015), but lack appropriate studies for model validation.

Stakeholders and researchers identified a single question that captures the need to understand the integrated system:

- How do different practice combinations (crop diversity, no-till, manure, precision technology, and biodiversity conservation) impact economic and ecosystem service outcomes?

7. Summary

The research priorities noted above represent a range of topics that, over time, the KBS LTAR will seek to address through multiple avenues: within the current Aspirational Cropping Systems Experiment; via adjacent research projects led by MSU and other collaborators; through social science approaches; and by hosting events that facilitate networking and learning with experts across the agricultural supply chain. We will also collaborate and coordinate with other LTAR sites to identify how answers to similar questions elsewhere might scale to our region, and vice versa (Liebig et al. 2024).

A database with the specific topics and questions that stakeholders and scientists generated at recent KBS LTAR Scientist-Stakeholder Summits will be updated at future Summits. Within the database are individual research questions that touch on different management practices and outcomes, as well as their potential for being addressed by ACSE research, adjacent projects, social science, or special events. Periodically revisiting priorities in the context of future challenges and results will provide an important means for keeping priorities relevant.

8. Acknowledgements

KBS LTAR is supported by the USDA-ARS Long-term Agroecosystem Research (LTAR) program and by MSU AgBioResearch.

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