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Special Section: The USDA LTAR Common Experiment—Research to Support a Sustainable and Resilient Agriculture

The LTAR Common Experiment: Facilitating improved agricultural sustainability through coordinated cross-site research

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Abstract

Long-term research is essential for guiding the development of agroecosystems to meet escalating production demands in a manner that is environmentally sound and socially acceptable. Research must integrate biophysical and socioeconomic factors to provide geographically scalable knowledge that involves stakeholders across the research-education-extension-policy spectrum. In response to this need, the Long-Term Agroecosystem Research (LTAR) network developed a "Common Experiment," which seeks to develop and disseminate multi-region, science-based information to enable implementation of visionary agricultural innovations while simultaneously promoting food security, well-being, environmental quality, and climate adaptation and mitigation. The core design of the Common Experiment contrasts prevailing and alternative/aspirational production systems, with the latter including novel innovations hypothesized to advance sustainable intensification in locally appropriate ways. Treatments in the Common Experiment represent a diversity of production systems under cropland, grazing land, and integrated crop/grazing

Abbreviations: ABS-UF, Archbold Biological Station-University of Florida; ARS, Agricultural Research Service; CAF, R.J. Cook Agronomy Farm; CMRB, Central Mississippi River Basin; CPER, Central Plains Experimental Range; ECB, Eastern Corn Belt; GACP, Gulf Atlantic Coastal Plain; GB, Great Basin; JER, Jornada Experimental Range; KBS, Kellogg Biological Station; LCB, Lower Chesapeake Bay; LMRB, Lower Mississippi River Basin; LTAR, Long-Term Agroecosystem Research; NP, Northern Plains; PR–HPA, Platte River–High Plains Aquifer; SP, Southern Plains; TG, Texas Gulf; UCB, Upper Chesapeake Bay; UMRB, Upper Mississippi River Basin; USDA, United States Department of Agriculture; WGEW, Walnut Gulch Experimental Watershed.

land management. Where possible, treatments are evaluated at multiple spatial scales (e.g., from plot to enterprise) and are designed to evolve over the course of the experiment with stakeholder input. A common assessment framework guides data collection for the experiment and is complemented by metric-specific protocols and an emerging data management infrastructure. Currently, there are large differences among sites in the application of the experimental framework and degree of stakeholder engagement; differences largely grounded in pragmatic issues related to land access, site expertise, and resource availability. The full potential of the LTAR Common Experiment may be realized with strategic investments in network capacity.

1 | INTRODUCTION

Agriculturalists are challenged to meet increasing demands of food, fuel, and fiber for a growing human population actively striving for improved quality of life (Khanna et al., 2018). Increased societal demands on agriculture are also occurring at a time of unprecedented planetary change (Richardson et al., 2023), where the effects of human activities directly impact the continued delivery of critical ecosystem services necessary for agricultural production (Keys et al., 2024). Developing agroecosystems that meet increasing global demand for agricultural products in a manner that is environmentally sound and socially just is a significant undertaking requiring a systems-level understanding of biophysical and socioeconomic processes in space and time (Rockström et al., 2017).

Long-term agricultural research will play a central role in meeting this challenge (Robertson et al., 2008). Field-based experimentation in agriculture has a rich history in providing valuable insights into the long-term performance of agroecosystems (Johnston & Poulton, 2018; Parolini, 2015). The development of modern statistics accelerated the knowledge gained from long-term field experiments (Fisher, 1992; Norris et al., 2023; Sandén et al., 2018), but a necessary focus on a limited number of experimental treatments has constrained systems-level understanding. Moreover, agricultural field experiments are often beset by constraints in spatial coverage, inflexible treatment structures, narrow disciplinary focus on biophysical metrics, an absence of stakeholder input, and limited linkages to other ongoing experiments (Peterson et al., 1993). These significant drawbacks highlight the need for a new paradigm in long-term field experimentation for agriculture (Harrison, 2008; Li et al., 2023; Lacoste et al., 2022; Robertson et al., 2014).

In 2008, a bold proposal articulated a framework for long-term field experimentation in the United States that directly addressed these drawbacks (Robertson et al., 2008). The framework called for the creation of a long-term field research network at the federal level that would improve understanding of agriculture from a systems perspective by (1) integrating biophysical and socio-economic domains in assessments of performance, (2) providing knowledge that would be geographically scalable, and (3) directly engaging with stakeholders across the research-education-extension-policy spectrum. The foundation of the network would be strengthened by leveraging existing federal research infrastructure throughout the United States, including ongoing agriculture-oriented sites within the Long-Term Ecological Research network (e.g., Kellogg Biological Station (KBS) and Jornada Basin; Hobbie et al., 2003).

The proposal conceptualized by Robertson et al. (2008) was put into action in 2012 by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) through the development of the Long-Term Agroecosystem Research (LTAR) network (Kleinman et al., 2018; Tsegaye et al., 2024). As the US Government's primary in-house agricultural research agency, USDA-ARS is well-positioned to lead the network with established long-term research sites distributed across the continental United States (Walbridge & Shafer, 2011), along with a documented capacity for conducting cross-site research using established infrastructure to address national-scale problems (Duriancik et al., 2008; Shafer & Jawson, 2012).

The portfolio of research activities within the LTAR network emphasizes coordinated efforts across LTAR sites, which include ARS facilities, universities, and private research institutions (USDA-ARS, 2024a). A long-term "Common Experiment" is an integral component of these network-wide research efforts, as it directly contributes to the LTAR mission of conducting long-term, transdisciplinary, networked research to develop innovative tools and practices that are regionally tailored, along with evidence-based multi-site knowledge supporting sustainable and resilient agriculture (Tsegaye et al., 2024).

Here we provide an overview of the LTAR Common Experiment. Our intent is to complement individual descriptions within this special volume by providing background on the experiment's purpose, objectives, and design. Key attributes of the Common Experiment as it is currently implemented are also shared, along with opportunities and challenges associated with network-level research.

2 | NETWORK APPROACH TO COORDINATED EXPERIMENTAL RESEARCH

Sites included in the LTAR network are expected to conduct research in a coordinated manner to provide novel scientific information with national impact (Kleinman et al., 2018). Network sites represent a diversity of agroecosystems across the conterminous United States (Kumar et al., 2023), with sites broadly categorized as cropland, grazing land, and integrated crop/grazing land systems that include both pastureland and grazed cropland (Tsegaye et al., 2024). Collectively, current LTAR sites represent US agricultural lands that account for 49% of cereal production, 30% of forage production, and 32% of livestock production (Kleinman et al., 2018).

Participation in the long-term Common Experiment is a core component of the network, with site personnel engaging with stakeholders in the design, implementation, and refinement of treatments in the experiment, as well as collecting necessary data on core performance indicators. In addition to the publication of research findings, collected data and metadata from the experiment are to be shared as publicly available, high-quality datasets following FAIR principles and USDA guidelines (USDA-NAL, 2024; Wilkinson et al., 2016). Finally, articulating the value of the LTAR Common Experiment to stakeholders and the broader public is essential, requiring tailored communication efforts across the spectrum of available media.

The goal of the LTAR Common Experiment is to develop and disseminate multi-regional, science-based information to enable the implementation of visionary agricultural innovations that promote food security, social well-being, environmental quality, and climate adaptation and mitigation. Supporting objectives are to (1) develop and evaluate production systems that promote the sustainable management of agricultural land, (2) identify, quantify, and understand mechanisms underlying tradeoffs and synergies among economic, environmental, and social outcomes, and (3) use long-term measurements and experimental observations to model how ecosystem services from agricultural practices will respond to future projections of climate variability and change. The breadth of these objectives is such that collaborations among participating scientists will naturally develop, contributing to multi-site or network-wide projects exploring topics of shared interest that may embed within the LTAR Common Experiment structure or lead to the establishment of complementary field studies.

Core Ideas

- The Common Experiment is an integral component of coordinated research efforts in the Long-Term Agroecosystem Research network.
- The Common Experiment includes cropland, grazing land, and integrated systems across the contiguous US.
- The Common Experiment compares prevailing production systems with systems needed to meet future demands.
- Outcomes are assessed by measurements related to common production, socioeconomic, and environmental indicators.
- Maximizing the impact of Common Experiment outcomes may be enhanced by strategic investments in network capacity.

3 | EXPERIMENTAL FRAMEWORK

The LTAR Common Experiment uses a simple experimental design to maximize participation, longevity, and comparability across sites. The core design compares two treatments, a prevailing or business-as-usual production system versus an alternative or aspirational production system hypothesized to advance sustainable intensification in locally appropriate ways (Spiegal et al., 2018). Framed temporally, the design contrasts contemporary production systems with those expected to be needed to meet future production and ecosystem service demands. Both treatments are intended to be dynamic, in that they are anticipated to change over the course of the experiment. Shifts in predominant management practices within LTAR regions will require adjustments to the prevailing production system treatment (Bean et al., 2021), while the alternative/aspirational production system treatment will evolve with new technologies, markets, and social expectations.

As the experiment matures, agricultural innovations present in alternative production systems will ideally be integrated into commercial production systems across LTAR regions; such transitions could serve as a measure of network impact. Other factors influencing the dynamic nature of treatments include external stressors (e.g., drought and excessive moisture) as well as changes in the agricultural markets and policies. Adapting to conditions in management-appropriate timescales may require experimental treatments to be highly dynamic.

Experimental scale is an important aspect of the Common Experiment. Traditional experimental plots are typically much smaller than producer-managed fields, generating concerns regarding the applicability of plot-based research to

TABLE 1 Recommended design attributes for cropland sites in the Long-Term Agroecosystem Research (LTAR) Common Experiment, with preferred and minimum criteria.

Experimental scale	Attribute	Preferred	Minimum
Plot	Replication	4–6	3
	Size (ha)	1	0.1
Field	Replication	4–6	1.5[a]
	Size (ha)	≥16	10
Both	Start dates	>1	1

[a]One of two Common Experiment treatments is replicated, with treatment choice arbitrary.

larger enterprises (Lacoste et al., 2022; Robertson et al., 2007). Conventional cropping practices have been found to be more resilient to field-scale challenges than alternative practices, as the latter are frequently dependent on timely management interventions (Kravchenko et al., 2017). Accordingly, conducting research across a range of spatial scales is important for the LTAR Common Experiment, recognizing that site infrastructure will dictate what is feasible, and if necessary, whether on-farm or on-ranch sites are needed to address questions at larger spatial scales.

Deployment of treatments at multiple spatial scales is a vital component of the experimental framework. For cropland and integrated sites, plot and field scales are recommended (Table 1), whereas grazing land sites—some of which tend to be managed as semi-natural systems—utilize spatial scales that best represent their respective regional agroecosystems. Many of the economic and social indicators of sustainability are expressed at the enterprise level, and findings from plot and field scale experiments will inform possible outcomes at the farm and ranch scale, and as well as landscape, watershed, and regional scales.

Sites utilizing crop rotations in their Common Experiment are expected to have each crop phase of the rotation present every year. This allows comparisons among treatments to be made year-to-year, rather than waiting for specific rotation phases of each treatment to align, which could be years apart depending on different rotation lengths. To ensure statistical validity, four to six replications are recommended at both spatial scales (plot and field) for croplands (Table 1). Recognizing this may not be possible at sites constrained by available land and other resources, minimum recommendations of three replications at the plot scale and 1.5 replications at the field scale are acceptable (with 1.5 implying that one of the two Common Experiment treatments at the field scale is replicated). Plots are recommended to be 1 ha in size (with 0.1 ha considered minimum), of consistent shape, and carefully blocked during establishment by taking into consideration edaphic features of the site. Recommended field size is ≥16 ha, thereby allowing for the inclusion of significant soil and topographic variability while also accommodating field-scale monitoring equipment such as eddy covariance towers (Table 1).

Grazing land sites do not follow strict guidelines regarding experimental design compared to cropland and integrated sites. Pasture sizes, topography, soils, and degree of variability in plant species composition differ considerably across grazing land sites. Common Experiment treatments at grazing land sites are typically conducted at field (pasture) or enterprise (ranch) scales and are expected to employ robust experimental designs, allowing for statistical validity at each site.

The LTAR Common Experiment is designed to be conducted for at least 30 years. Evaluations spanning decades are necessary to thoroughly understand agroecosystem performance under a range of environmental conditions, inclusive of episodic events. Moreover, long-term research allows for the accurate detection of slow-to-change attributes (Cusser et al., 2020), while facilitating the development, calibration, and validation of models to forecast such changes (Walbridge & Shafer, 2011). Given the longitudinal approach of the Common Experiment, a staggered start to treatment deployment is recommended (Table 1). Use of staggered starts in field research can separate random variation due to “year” from variation due to “time” (Pagliari et al., 2022), thereby allowing for the detection of treatment establishment effects on the trajectory of performance indicators (Tejera et al., 2019).

4 | THE LTAR COMMON EXPERIMENT: CURRENT STATUS

The LTAR Common Experiment was formally introduced in 2018 in a review of sustainable intensification strategies deployed across the network (Spiegal et al., 2018). The review provided valuable insights into commonalities across site experiments and explored both concerns with prevailing agricultural practices and barriers to adopting more sustainable forms of management. At the time of publication, the LTAR Common Experiment was in a nascent phase; some sites had yet to start their Common Experiment, while nearly all were still adjusting initial treatment components. Given that this experiment is inherently dynamic with respect to the expression of applied treatments, synthesis updates will naturally reflect that dynamism. The status provided here reflects site input gathered in April 2024.

The LTAR Common Experiment is deployed in some form at all 18 LTAR sites, along with three satellite sites linked to a core LTAR site (Figure 1). Currently, cropland is the most common agroecosystem type included in the experiment (14 sites), followed by grazing land (seven sites) and integrated systems (four sites) for a total of 25 field experiments. Four sites conduct two experiments under different agroecosystem categories (Figure 1). Summaries of the Common Experiment

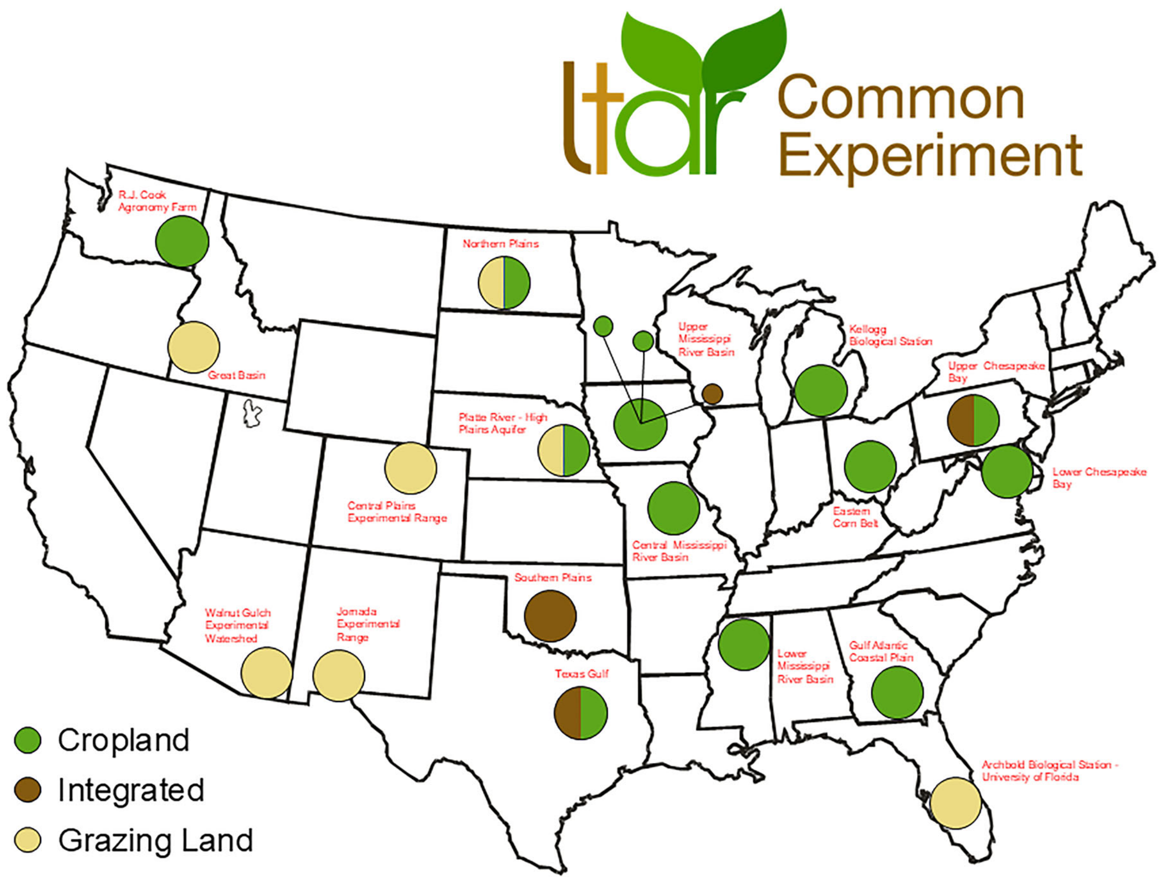

FIGURE 1 Agroecosystem types included in the Long-Term Agroecosystem Research (LTAR) network Common Experiment. Split circles imply two separate experiments at a site under different categories. Small circles reflect satellite sites joined to a core LTAR site. Map version, April 2024.

within agroecosystem type are shared below, with additional details provided by individual site description papers (this issue). Deployed agroecosystem types have expanded and evolved within the network since 2018, as nine cropland sites and six sites each for grazing land and integrated systems were included in Spiegal et al. (2018) (satellite sites were not included in 2018). (*Note*: After preparation and acceptance of site description papers in this issue, a 19th LTAR site was designated: Northern Headwaters. This new LTAR site comprises two previous satellite sites at St. Paul and Morris, MN. For purposes of this overview, we have retained the April 2024 structure of LTAR Common Experiment sites.)

While the experiment shares a common treatment contrast, there are notable differences in deployment across network sites (Tables S1–S3). Starting times, measurement scales, and design features and terminology are tailored to match site realities with regard to available resources and stakeholder preferences. For example, the inclusion of additional alternative treatments to test multiple agricultural innovations is common. Moreover, terminology for the alternative treatment is variable across sites, as innovative (characterized by a new idea, method, or device), aspirational (characterized by a futuristic vision), or adaptive (providing, contributing to, or marked by adjustment to environmental conditions) are used based on site preferences. Increased interest in sustainable agriculture has generated numerous terms for alternative practices with associated environmental narratives (Newton et al., 2020; Schall et al., 2018), underscoring the importance of using words and phrases for the experiment that are acceptable to local clientele. However, investigators will need to reconcile the diversity of terms used for the Common Experiment when communicating outcomes from network-wide syntheses. For purposes of this report, prevailing and alternative will be used as treatment descriptors.

4.1 | Cropland sites

Cropland sites include Central Mississippi River Basin (CMRB), Eastern Corn Belt (ECB), Gulf Atlantic Coastal Plain (GACP), KBS, Lower Chesapeake Bay (LCB), Lower Mississippi River Basin (LMRB), Northern Plains (NP), Platte River–High Plains Aquifer (PR-HPA), R.J. Cook Agronomy Farm (CAF), Texas Gulf (TG), Upper Chesapeake

TABLE 2 Management approaches included in treatment contrasts for Long-Term Agroecosystem Research (LTAR) network cropland Common Experiment sites.

LTAR site	Rotation	Cover crops	Tillage management	Nutrient management	Pest management	Water management	Other[a]
Central Mississippi River Basin (CMRB)	X	X	X	X	X		
Eastern Corn Belt (ECB)	X	X	X	X		X	
Gulf Atlantic Coastal Plain (GACP)	X	X					
Kellogg Biological Station (KBS)	X	X	X	X	X		X
Lower Chesapeake Bay (LCB)	X	X		X	X		
Lower Mississippi River Basin (LMRB)		X	X		X	X	
Northern Plains (NP)		X					X
Platte River–High Plains Aquifer (PR–HPA)	X	X		X	X	X	
R.J. Cook Agronomy Farm (CAF)			X	X			
Texas Gulf (TG)			X				
Upper Chesapeake Bay (UCB)	X	X		X	X		
Upper Mississippi River Basin – Ames (UMRB-Ames)		X	X	X			
Upper Mississippi River Basin – Morris (UMRB-Morris)		X	X				
Upper Mississippi River Basin – St. Paul (UMRB-St. Paul)		X	X	X			X

[a]Other management approaches include addition of prairie strips (KBS), residue removal (NP), and strategic glyphosate application and tillage of Kura clover (*Trifolium ambiguum* Bieb.) (UMRB-St. Paul).

Bay (UCB), and Upper Mississippi River Basin (UMRB) at Ames, IA, Morris, MN, and St. Paul, MN (Figure 1). Production regions associated with ECB, KBS, LMRB, PR–HPA, and UMRB are dominated by cropland, while regions associated with CAF, NP, and TG are characterized by a mix of cropland, rangeland, and hay production (Bean et al., 2021). A mix of grazed pasture, hay production, and cropland comprise regions associated with CMRB, GACP, LCB, and UCB. Corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), and small grains are common agricultural commodities across most cropland sites, accounting for >40% of US cereal crop production annually (Kleinman et al., 2018). Production of oilseeds and pulse crops is shared at CAF and NP, while cotton (*Gossypium hirsutum* L.) is grown in regions represented by GACP, LMRB, and TG. Beef or dairy cattle are common in nearly all cropland site regions, with select sites associated with production of poultry (ECB, GACB, LCB, LMRB, TG, UCB, and UMRB), swine (CMRB, ECB, LCB, PR–HPA, and UMRB), sheep (NP), and catfish (LMRB). Erosion, water quality, increased pest pressure, and resilience to weather extremes are major agricultural challenges associated with cropland sites (Spiegal et al., 2018).

Six management approaches are currently considered in treatment contrasts at cropland sites: rotation, cover crops, tillage, nutrients, pests, and water (Table 2). Cover crops, nutrients, and tillage are most frequently considered in treatment designs, with their inclusion at 12, 9, and 9 sites, respectively. Generally, alternative treatments include cover crops, conservation tillage (including no-till), and adaptive/precision approaches to crop nutrients (Table S1). Alternative treatments also include longer and/or more diverse crop rotations at seven cropland sites (CMRB, ECB, GACP, KBS, LCB, PR–HPA, and UCB). Integrated pest management is incorporated in the alternative treatment at CMRB, KBS, LCB, LMRB, PR–HPA, and UCB, whereas uniform pest management is used in the prevailing treatment. Water management is addressed at three sites, with alternative treatments incorporating drainage control structures (ECB) or adaptive irrigation methods (LMRB and PR–HPA) (Table S1). Management approaches considered in the Common Experiment but applied at individual sites include prairie strips (KBS), residue removal (NP), and perennial cover crops (UMRB-St. Paul).

Incorporation of management approaches into treatment designs varies considerably across sites, with six approaches considered at KBS, five at CMRB, ECB, and PR–HPA, four at LCB and UCB, three at LMRB, UMRB-Ames, and UMRB-St. Paul, two at GACP, NP, UMRB-Morris, and CAF, and one at TG. Most cropland sites adjust treatments every 2 to 6 years (Table S1), typically aligning with the completion of a crop rotation cycle. Four cropland sites adjust their treatments on a variable frequency (CAF, LMRB, UMRB-Morris, and UMRB-St. Paul). The cropland Common Experiment is evaluated at the plot scale at 12 sites, field scale at 9 sites, and both scales at 7 sites (Table S1). In some cases, field-scale treatments are replicates of plot-scale treatments, while in other cases they are on-farm adaptations of plot-scale treatments.

TABLE 3 Management approaches included in treatment contrasts for Long-Term Agroecosystem Research (LTAR) network integrated Common Experiment sites.

LTAR site	Forage source	Grazing management	Cover crops	Tillage management	Nutrient management
Southern Plains (SP)		X		X	
Texas Gulf (TG)	X	X	X		X
Upper Chesapeake Bay (UCB)		X			
Upper Mississippi River Basin – Platteville (UMRB-Platteville)			X	X	X

4.2 | Integrated sites

Sites with experiments that include grazing livestock with crops and/or pasture in the treatment design are designated integrated sites, and include Southern Plains (SP), TG, UCB, and UMRB-Platteville (Figure 1). Production regions associated with SP and TG are characterized by cropland, grazing land, and hay, whereas cropland, hay, and other land uses define production regions for UCB and UMRB-Platteville (Bean et al., 2021). Shared agricultural commodities at SP and TG include beef cattle, forages, small grains, and cotton, while UCB and UMRB-Platteville share production of dairy cattle, beef cattle, poultry, forages, small grains, corn, and soybean (Kleinman et al., 2018). Broadly, agricultural production concerns associated with integrated sites include increased pest pressure, suboptimal forage production, erosion, and water quality (Spiegal et al., 2018).

Integrated sites differ in their expression of five management approaches included in the Common Experiment: forage source, grazing, cover crops, tillage, and nutrients (Table 3). Forage source differs between treatments at TG, with the prevailing treatment using seeded forage oats and perennial pasture and the alternative treatment using seeded cover crops. Inclusion of cover crops in the alternative treatment also occurs at UMRB-Platteville. Cover crops, in the form of interseeded cereal rye (*Secale cereale* L.), are also used at UCB, though the practice is applied to both treatments. Grazing management differs between prevailing and alternative treatments at SP, TG, and UCB. Tillage management differs between treatments at SP and UMRB-Platteville, with prevailing and alternative treatments associated with conventional and conservation tillage, respectively. Nutrient management differs at UMRB-Platteville and TG. At UMRB-Platteville, fall-injected dairy manure is used in the prevailing treatment and side-dressed N and manure-based fertilizer products are used in the alternative treatment. At TG, nutrients are applied to the prevailing treatment using common application rates, while nutrient management for the alternative treatment is based on soil test results. Among integrated sites, four management approaches differ between prevailing and alternative treatments at TG, while three management approaches differ between treatments at UMRB-Platteville. Two management approaches differ between treatments at SP, and a single management factor (grazing management—ungrazed vs. grazed) encompasses the treatment contrast at UCB. Treatments are adjusted annually (SP), every 5 years (UMRB-Platteville), or on a variable frequency (TG and UCB) (Table S2). All integrated sites conduct their common experiment at the field scale (Table S2).

4.3 | Grazing land sites

Sites where vegetation is or was predominantly native grasses, grass-like plants, forbs, or shrubs and are actively managed for grazing, browsing, or occasional hay production are grazing land sites, and include Archbold Biological Station-University of Florida (ABS-UF), Central Plains Experimental Range (CPER), Great Basin (GB), Jornada Experimental Range (JER), NP, PR–HPA, and Walnut Gulch Experimental Watershed (WGEW) (Figure 1). Six grazing land sites are strongly associated with regions characterized by rangeland or hay production (Bean et al., 2021), while the remaining site (PR–HPA) is more strongly associated with cropland. All grazing land sites share beef cattle as a major agricultural commodity (Kleinman et al., 2018). Invasive plants, soil degradation, and suboptimal forage production and utilization reflect persistent challenges across grazing land sites (Spiegal et al., 2018).

Six management approaches differ among grazing land sites: grazing system, livestock type, supplementation, prescribed fire, nutrients, and vegetation management (Table 4). Differences in grazing management between prevailing and alternative treatments are most common among approaches, occurring at ABS-UF, CPER, GB, JER, PR–HPA, and NP. Livestock breed varies at JER, where Angus and Angus-Hereford cattle are used in the prevailing treatment and Rarámuri Criollo cattle (a heritage breed) in the alternative treatment. Supplement feed management differs between treatments at JER (reflecting differences in feeding protocols inherent to grain vs. grass supply chains), while at PR–HPA cattle are provided distillers grain in the alternative treatment.

TABLE 4 Management approaches included in treatment contrasts for Long-Term Agroecosystem Research (LTAR) network grazing land Common Experiment sites.

LTAR site	Grazing management	Livestock type	Supplement management	Fire management	Nutrient management	Other[a]
Archbold Biological Station-University of Florida (ABS-UF)	X			X		X
Central Plains Experimental Range (CPER)	X					
Great Basin (GB)	X					X
Jornada Experimental Range (JER)	X	X	X			
Northern Plains (NP)	X			X		X
Platte River–High Plains Aquifer (PR–HPA)	X		X		X	
Walnut Gulch Experimental Watershed (WGEW)						X

[a]Other management approaches include mechanical removal of shrubs and overseeding diverse plant traits into pastures (ABS-UF), practices to suppress invasive annual grasses (GB), rangeland seeding to enhance vegetation diversity (NP), and aerially applied herbicides to control velvet mesquite (*Prosopis velutina* Woot.) (WGEW).

Prescribed fire is managed differently in both prevailing and alternative treatments at ABS-UF, while at NP prescribed fire is used for vegetation management in the alternative treatment only. Nutrient management varies only at PR–HPA, with smooth brome (*Bromus inermis* L.) pastures in the prevailing treatment receiving synthetic N while the alternative treatment is unfertilized. Practices across grazing land sites aimed at suppressing growth of specific plants are applied at GB (invasive annual grasses), WGEW (*Prosopis velutina* Woot.), and ABS-UF (woody species). Rangeland seeding is deployed at NP to enhance vegetation diversity. Three management approaches are applied concurrently at ABF-UF, JER, PR–HPA, and NP, while two approaches are applied at GB. Single management approaches are evaluated at CPER and WGEW. Adjustments to grazing land treatments occur annually (CPER and GP), every 4 years (WGEW), every 5 years (PR–HPA), or variably (ABS-UF, JER, and NP) (Table S3). Grazing land treatments in the Common Experiment are expressed across a range of spatial scales (plot to supply chain). Five of seven grazing land sites evaluate treatments at multiple spatial scales (Table S3).

TABLE 5 Information source categories used for defining and refining treatments in the Long-Term Agroecosystem Research (LTAR) network Common Experiment.

Source category	Number of site experiments using source
Research teams	16
Extension personnel	11
Cooperating producers	9
Survey results	5
Research data and results	5
Commodity/agribusiness representatives	5
Non-governmental partners	5
Governmental partners	4
Private partners	2
Stakeholder groups	7
Other stakeholders	3
University collaborators	5

4.4 | Sources to define and refine treatments

Sources used to guide the definition and refinement of treatments across agroecosystem types fall within 12 categories (Table 5). Sources used most frequently include research teams (16 sites), extension personnel (11 sites), and cooperating producers (nine sites), while others also use university collaborators (five sites) and private partners (two sites). Stakeholder groups formed specifically for the purpose of the Common Experiment are used at seven sites (ABS-UF, CMRB, GB, KBS, NP-cropland, NP-grazing land, and UCB-cropland), although individuals within those groups likely align with other categories. Within research teams, participating scientists are involved most frequently (14 of 16 sites), with remaining sources including farm managers (CAF), project staff (NP-cropland), and personnel at other LTAR sites (PR–HPA-cropland). Survey data are used to define prevailing practices at some sites (GACP, KBS, PR–HPA-cropland, PR–HPA-grazing land, and UMRB-Ames) (Tables S1–S3).

5 | MEASUREMENTS, METHODS, AND DATA MANAGEMENT

While agroecosystems in the Common Experiment share common goals (e.g., the sustainable production of agricultural commodities), developing applicable measurements across all sites can be challenging. LTAR attempts to solve this problem by using a core set of performance indicators to evaluate the tradeoffs and co-benefits of the management treatments

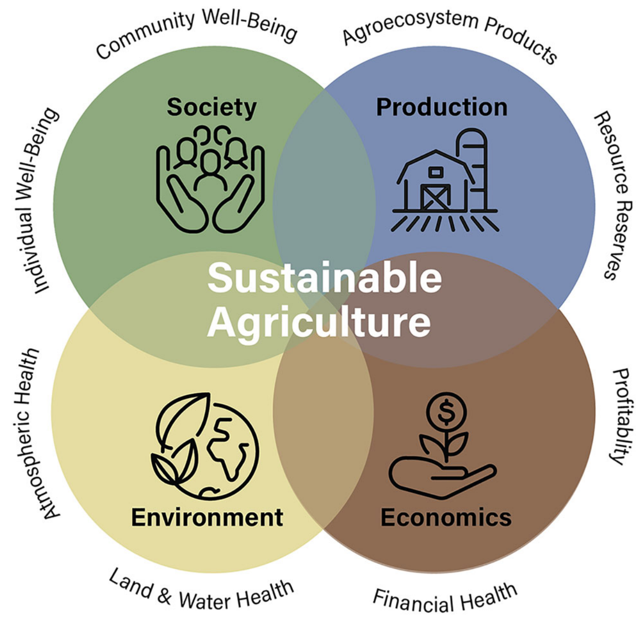

FIGURE 2 Agricultural sustainability framework for the Long-Term Agroecosystem Research (LTAR) network (generalized version, 2024). Eight attributes characterize the status of an agroecosystem across four domains: production, economic, environmental, and society. Performance indicators and their metrics are used to measure the status of the attributes.

(Spiegal et al., 2022). Metrics with their associated measurement protocols track the status of different indicators within four domains: production, economics, environment, and society (Figure 2). Metrics must have lasting scientific value by providing insights into production efficiencies, environmental impacts, and socioeconomic aspects related to treatments evaluated in the experiment. Ideal metrics are readily quantified, sensitive to change, accurate and precise, broadly applicable across agroecosystems, inexpensive, and interpretable and valued by multiple stakeholders (Karl et al., 2017). Additionally, metrics must be useful for modeling in order to provide a foundation for developing predictions of the delivery of ecosystem services under different land use and climate change scenarios. Pragmatic considerations often drive which metrics can be measured at a site based on available infrastructure, equipment, expertise, and labor. Given this reality, metric selection for the Common Experiment has been guided by prioritizing scientific rigor, linkages to Common Experiment goals, the feasibility of measurements across sites, and regional priorities defined by stakeholders.

LTAR network working groups have identified standardized and measurable biophysical metrics to calculate indicators that assess the status of agroecosystem attributes. For cropland sites, metrics have been prioritized within a primary, secondary, and tertiary framework, with primary metrics intended for all sites unless significant barriers exist or the metric is not applicable. Secondary metrics have high value and are encouraged but not considered essential for all sites. Tertiary metrics are included where resources permit or where metrics are of particular importance to a site. Within the production indicator, there are currently 75 metrics with 24 designated as primary, 11 as secondary, and 40 as tertiary. The full list of primary biophysical metrics as proposed for cropland sites is included in (Table S4). Oftentimes, primary metrics require associated metrics to allow for efficiency calculations. For example, water use efficiency calculations measure a set of complementary metrics that encompass soil water content, yield, water vapor flux, water potential, precipitation, and irrigation (Hoover et al., 2022).

Standardization of protocols is crucial for research that is multi-site, multidisciplinary, and multi-scientist (Eagle et al., 2017; Kladivko et al., 2014; Robertson et al., 1999). Workgroups have prioritized protocols first for primary metrics, leaving secondary and tertiary protocols to be developed in the future. A template was established to standardize content and format across protocols and includes categories for field methodology, sampling size, laboratory procedures, best practices for quality control, metadata, covariate metrics, and sample archiving (see Protocol Template in SI). Protocols have been developed to unify methods across sites and are published as a compilation on *protocols.io* (Abendroth et al., 2024). Individual sites may collect data more frequently than outlined by the Common Experiment protocols due to site-specific research questions. Doing so will serve to expand and deepen insights arising from the Common Experiment.

The infrastructure supporting LTAR network data has evolved significantly since the network's inception. Currently, a turnkey cloud-based data management system is under development and will be reviewed in a subsequent network data publication. The standardized metrics and protocols serve as foundational structure for data entry processes used in the LTAR Common Experiment. These standards align with the network's goal to enhance data consistency, data sharing, and research outcomes across sites.

Assessing the performance of agricultural innovations across multiple sites with different management practices requires novel approaches to normalize data representing key indicators of sustainability (MacLaren et al., 2022). Drawing from expertise in rangeland monitoring, LTAR scientists developed an innovative benchmarking approach to allow for cross-site analysis of experimental outcomes (Spiegal et al., 2022; Webb et al., 2024). Briefly, the approach involves establishing site-specific benchmarks that represent the desired outcome of management in terms of each indicator. Treatments are then assessed for their departure from selected benchmarks, thereby allowing for a normalized quantitative comparison of data, which can then be aggregated for cross-site analyses. This approach is inherently flexible, allowing sites to select indicators and associated benchmarks that are most relevant to stakeholders. Additional background on the

LTAR indicator framework, along with an example of its application at the enterprise scale, may be found in Spiegal et al. (2024). Complementary to this approach, efforts are underway within the LTAR network to ascertain areas of representativeness using geospatial analytical methods that can extrapolate and regionalize results from experimental treatments (e.g., Bean et al., 2021; Kumar et al., 2023). The combination of an integrated framework allowing for cross-site analysis combined with a geospatial framework to model and extrapolate results will enhance the impact of the LTAR Common Experiment.

6 | OUTLOOK

The promise of the LTAR Common Experiment is significant. Implementation of a harmonized experimental framework at sites representing much of the contiguous United States while applying aligned measurement protocols at multiple spatial scales over an extended period exemplifies an ambitious research endeavor envisioned to significantly enhance the sustainability of US agriculture. The experiment is designed to evolve through the dynamic expression of prevailing and alternative agroecosystems guided by experimental findings and stakeholder input. Leveraged research infrastructure and expertise under a common cause provide the necessary scaffolding of place, people, and purpose for achieving the full potential of network-based agricultural research (Tsegaye et al., 2024). Initial cross-site research efforts in LTAR reflect this potential (Baffaut et al., 2020; Browning et al., 2021; Menefee et al., 2022; Spiegal et al., 2020; Welikhe et al., 2023).

While the promise of the LTAR Common Experiment is apparent, a cautionary note is warranted. Differences in the application of the experimental framework along with varying degrees of stakeholder engagement reflect not a uniform cross-site experiment but a mosaic of aligned research efforts across LTAR sites. Site differences in these critical attributes are grounded in pragmatic realities related to land access, site expertise, and resource availability (discussed below). Collectively, these differences may serve as thresholds for what can be reasonably achieved under the guise of network research.

6.1 | Research infrastructure

An inherent strength of LTAR sites is their capacity to support long-term research through established infrastructure that is consistently available due to a stable funding source. Land access to conduct field research is a core infrastructure requirement that allows for the assessment of agricultural innovations over decadal timescales, as envisioned for the Common Experiment. Such access, however, is unequal in extent and control across LTAR sites. Sites co-located on university campuses, for instance, are frequently limited to land allotments that make accommodating larger scale field experiments difficult. Sites located near major population centers face pressures from residential development that also constrain the footprint of field research while increasing the possibility of urban/rural conflict (Fienitz & Siebert, 2021). Moreover, sites that lease their land for research are subject to the whims of landowners who may change practices unexpectedly, sell the land for development, or lease it solely for production purposes.

Transitioning field research to working farms and ranches is one approach to address limited and unstable land access. Evaluations at larger spatial scales are more naturally aligned with operational scales for typical farms and ranches, while potentially offering greater heterogeneity of biophysical conditions under which to conduct assessments. Additionally, research on farms and ranches can serve to remove the "safety net" existing at research facilities that can skew socioeconomic and environmental outcomes (Lockeretz & Anderson, 1993). While there are notable challenges to on-farm/ranch research (Doole et al., 2023), partnering with producers for evaluations at larger spatial scales has practical implications under a co-production research framework where knowledge generation is rooted in producer-scientist relationships (Lacoste et al., 2022). Such arrangements could be ideal for prevailing practices in the Common Experiment, recognizing the need to ensure input from all site stakeholders is considered through clear communication protocols. Pairing management practices between scales—where larger scales are evaluated on-farm/ranch while plot/paddock scales are evaluated at a research facility—requires compromise among team members but can be a powerful mechanism to accelerate innovation development and adoption (Riar & Bhullar, 2020). Finally, institutional support to ensure continuous on-farm/ranch engagement over the long term is necessary (Doole et al., 2023).

6.2 | Human capital

Current engagement in the LTAR Common Experiment consists of a diverse portfolio of investigators with expertise largely in agronomic, ecological, and environmental sciences. As such, research teams at LTAR sites are well-positioned to understand tradeoffs among biophysical attributes within the LTAR sustainability framework (Figure 2). Addressing non-biophysical attributes, such as financial health and individual and community well-being, however, is currently limited in the Common Experiment due to a lack of LTAR scientists with expertise in the socioeconomic sciences. Though there is broad acceptance that agricultural problems cannot be evaluated in isolation from social and economic factors (Prokopy, 2011; Robertson et al., 2004), the capacity to integrate transdisciplinary outcomes is exceedingly complex (Wilmer et al., 2022; Wulfhorst et al., 2022). Investments by USDA-ARS to better understand human dimension aspects of agricultural management are reflected by the continued recruitment of social scientists to the LTAR network (e.g., University of Idaho, 2024).

Opportunities to explore solutions with stakeholders to solve agricultural problems is a distinguishing feature inherent to the design of the Common Experiment. Effective stakeholder engagement is critical to successful co-production research efforts where participatory partnerships apply data-driven approaches to agroecosystem management (Szetey et al., 2023; Wilmer et al., 2018). This feature underscores the need for dedicated engagement and communication capacity at the site level. Currently, this role is present at only select LTAR sites, resulting in the stakeholder engagement role often being led by scientists. Expanding this capacity across the network with full-time science engagement and communication professionals would bring consistency to engagement efforts while addressing the urgent need to share relatable stories articulating why agricultural science matters to the general public (USDA-ARS, 2024b; Grace & Kaufman, 2013). Moreover, dedicated personnel in this role could serve to expand the stakeholder pool to better represent underserved and minority populations across LTAR sites.

Harmonized, interoperable, and well-documented data from the Common Experiment serve as the foundation for cross-site analyses, decision support applications for stakeholders, and modeling activities (Tsegaye et al., 2024). Ensuring site-specific data are uploaded from each Common Experiment into the "data pipeline" requires site parity in data management capabilities so that protocols for collecting, formatting, and sharing data are deployed consistently. At the network level, the centralized data system currently in development would benefit from an affiliated data scientist for the Common Experiment.

6.3 | Network science

The complexity of agricultural problems requires collaborative research. It is not possible for a single laboratory, university, or private research institution to marshal the necessary resources and expertise to develop agroecosystems that can meet escalating production demands amid the broad range of stressors and expectations affecting agriculture. The LTAR Common Experiment is positioned to contribute to the development of agroecosystems that can meet these challenges, but—as noted above—increased investments in network capacity are needed to achieve its full potential. Doing so will not only address critical support for the Common Experiment at individual sites but also provide the coordination needed at the network level for an efficient and effective long-term, cross-location research effort.

In addition to increased investments in network capacity, the extent to which the Common Experiment thrives will be influenced through participation by and leadership from individual scientists at LTAR sites. The Common Experiment is a "top-down" research effort that relies on "bottom-up" engagement. While network outcomes have a strong potential for high science impact, scientist time in coordinating multi-site research projects is significant and may come at the cost of addressing site-specific research tied to stakeholder requests. The opportunity cost to network engagement can be greatest for young scientists who might otherwise invest their energies on short-term research endeavors to jump-start their careers. While targeted funding for temporary staff (e.g., postdoctoral researchers) is a means to efficiently compile, analyze, and report data from the Common Experiment, the capacity to do so is conditional upon available funding. Moreover, the institutional knowledge gained by temporary staff during their appointments is lost to the network when staff transition to permanent positions outside of the LTAR orbit. This concern may be short-term, however, for as the Common Experiment matures and accumulates harmonized datasets, opportunities for young scientists to explore site-specific and network-wide research questions will expand. In the meantime, incentives for LTAR scientists to participate and/or lead network-level research projects may serve to lower barriers to active participation. Additionally, having local stakeholders who equally value site-specific outcomes and network-level syntheses would reconcile apprehensions associated with participation and leadership in the Common Experiment.

All told, the potential for transformative change arising from coordinated long-term research conducted across geographically dispersed sites, such as that embodied by the LTAR Common Experiment, is enormous. The need for such research has never been greater.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Table S1. Mean values of root and pore fractions (mm^3/mm^3) at the two smallest root and pore size groups. The groups were referred to as 75 µm and 150 µm, which were further summed and defined as very fine roots and medium pores. The ranges of root and pore diameters representing 75 µm size group are 75-113 and 36-108 µm, respectively. The ranges of root and pore diameters representing 150 µm size group are 113-187 and 108-180 µm, respectively.

Size group	Range of diameters (µm)	Root fraction (mm^3/mm^3)							
		Cultivars						Ecotypes	
		Alamo	Kanlow	Southlow	CaveinRock	Blackwell	Trailblazer	Lowland	Upland
75	75-113	0.00014^{BC}	0.00017^{A}	0.00013^{BC}	0.00014^{B}	0.00012^{BC}	0.00011^{C}	0.00016^{A}	0.00013^{B}
150	113-187	0.00057^{B}	0.00073^{A}	0.00066^{AB}	0.00074^{A}	0.00055^{BC}	0.00042^{C}	0.00065^{A}	0.00059^{A}
Very fine root (75+150)	75-187	0.00071^{AB}	0.00090^{A}	0.00079^{AB}	0.00088^{A}	0.00067^{B}	0.00053^{C}	0.00081^{A}	0.00072^{B}
		Pore fraction (mm^3/mm^3)							
		Alamo	Kanlow	Southlow	CaveinRock	Blackwell	Trailblazer	Lowland	Upland
75	36-108	0.0123^{B}	0.0138^{AB}	0.0062^{C}	0.0159^{A}	0.0106^{B}	0.0067^{C}	0.0131^{A}	0.0098^{B}
150	108-180	0.0194^{AB}	0.0190^{AB}	0.0150^{C}	0.0205^{A}	0.0159^{BC}	0.0141^{C}	0.0192^{A}	0.0164^{B}
Medium pore (75+150)	36-180	0.0317^{A}	0.0328^{A}	0.0212^{B}	0.0364^{A}	0.0265^{B}	0.0208^{B}	0.0323^{A}	0.0262^{B}

Note: different letters within each size group mark significant differences (p <0.05) among six cultivars (Root fraction: n = 12 and pore fraction: n = 8) or between two ecotypes.

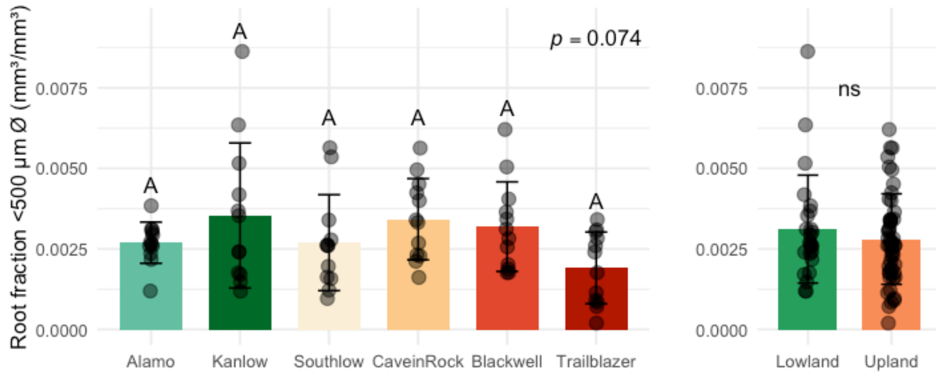

Figure S1. Fraction of root <500 µm diameter (Ø) in six switchgrass cultivars individually and grouped by two ecotypes. Error bars represent standard deviation, and dots represent individual data points. Since difference in the root fraction was not significant with $p > 0.05$, letters on the bars were same across the cultivars. Letter 'ns' between two ecotypes indicates no significant difference between two ecotypes with $p > 0.05$.

Table S2. Correlation coefficients among very-fine roots, medium pores, distance (Dist.) to pore and POM, microbial biomass C (MBC), and soil C contents across six switchgrass, two lowland, and four upland cultivars.

		Very fine root	Medium pore	Dist. to pore	Dist. to POM	MBC	Soil C
All cultivars (n=24)	Very fine root						
	Medium pore	**0.41***					
	Dist. to pore	**-0.49***	**-0.60****				
	Dist. to POM	**-0.52****	**-0.59****	**0.55****			
	MBC	**0.43***	**0.37***	**-0.36***	-0.20		
	Soil C	**0.65*****	0.19	-0.33	**-0.43***	**0.43***	
Lowland cultivars (n=8)	Very fine root						
	Medium pore	0.01					
	Dist. to pore	-0.02	-0.07				
	Dist. to POM	0.20	**-0.88****	-0.02			
	MBC	0.01	-0.14	**-0.83****	0.04		
	Soil C	**0.86****	0.19	0.36	-0.08	0.37	
Upland cultivars (n=16)	Very fine root						
	Medium pore	**0.45***					
	Dist. to pore	**-0.53***	**-0.61****				
	Dist. to POM	**-0.65****	**-0.49***	**0.57***			
	MBC	**0.48***	0.26	-0.12	-0.01		
	Soil C	**0.60****	0.17	**-0.45***	**-0.49***	**0.59****	

Note: Bolded values indicate statistical significances at $p < 0.05$, and the marked *, **, and ** denote coefficient levels at the p <0.05, <0.01, and <0.001 level, respectively.

Table S3. Probability (power) of detecting statistically significant results at $\alpha = 0.05$ in the comparison of soil C contents among six switchgrass cultivars and the required number of replicated blocks under randomized complete block design.

Number of replicated blocks	*P* value	Power (%)
5	0.115	56.4
6	0.065	66.8
7	**0.035**	75.2
8	**0.018**	82.3
9	**0.009**	88.6
10	**0.003**	**94.4**

Note: The estimate of the variance was 0.046. Bolded values indicate statistical significances at $p < 0.05$ and the detecting probability >90% for statistical differences.

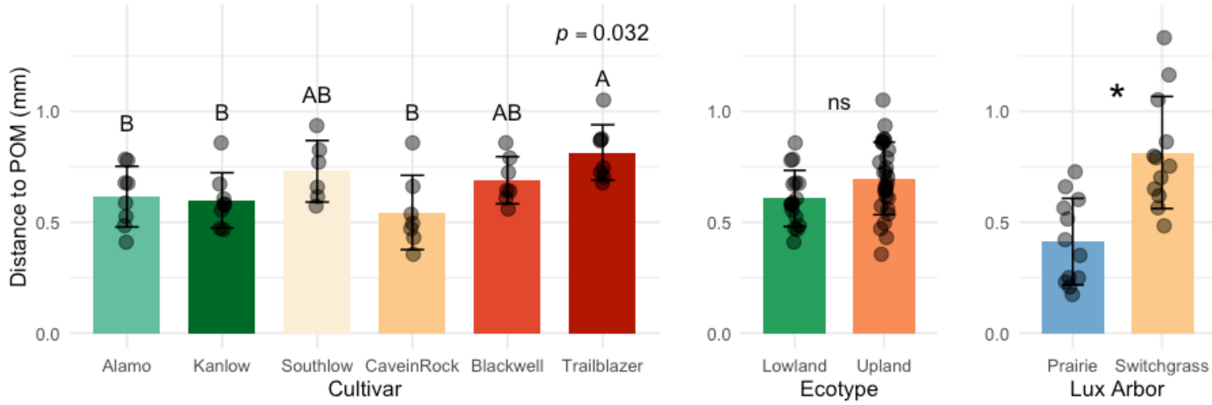

Figure S2. Distance to POM of six switchgrass cultivars individually, grouped by ecotypes, and taken by two vegetation of a former observation in the adjacent region (Lux Arbor, Michigan, USA) with soils classified as the same soil taxonomy and texture (Lee et al., 2023). The switchgrass cultivar in the former observation was Cave-in-Rock, and prairie vegetation included switchgrass as one of 18-species mixture. Error bars represent standard deviation, and dots represent individual data points. Different letters indicate significant differences at $p<0.05$ among six cultivars (n = 8), letter 'ns' indicates no significant difference between two ecotypes, and marks * indicate significant differences with $p<0.05$ between two vegetation in Lux Arbor site (n = 12).

Table S2. Select attributes for integrated sites included in the Long-Term Agroecosystem Research (LTAR) Network Common Experiment, April 2024.

LTAR Network Site	Experiment location	Experiment establishment year	Treatment	Treatment descriptors	Sources to define/refine treatments	Frequency of treatment adjustment	Spatial scales currently evaluated
Southern Plains (SP)	El Reno, OK 35.56 N, 98.03 W	2024	Prevailing	Winter wheat Grazed, hayed, and harvested for grain or grazed and harvested for grain Conventional tillage Nutrient management by soil tests Uniform pest management	Participating scientists	Annual adjustments to grazing practices	Field
			Alternative	Annual cool and warm season mixed forage cover crops Grazed Conservation tillage Nutrient management by soil tests Uniform pest management			
Texas Gulf (TG)	Riesel, TX 31.48 N, 96.88 W	2011	Prevailing	Seeded and grazed forage oats Perennial pasture Set cow/calf stocking rates Continuous grazing Nutrient applied using common application rates	Participating scientists Stakeholder groups University partners	Variable	Field
			Alternative	Seeded and grazed cover crops Perennial pasture Adaptive cow/calf stocking rates Rotational grazing Nutrient management by soil tests			
Upper Chesapeake Bay (UCB)	Rock Springs, PA 40.72 N, 77.94 W	2018	Prevailing	Short-season corn (harvested as grain) interseeded w/ cereal rye No grazing No-tillage Nutrient management by university recommendations Pest management by university recommendations	Participating scientists Commodity representative University extension	Variable	Field
			Alternative	Short-season corn (harvested as grain) interseeded w/ cereal rye Grazed by beef cows late fall & early spring No-tillage Nutrient management by university recommendations Pest management by university recommendations			

Table S2. Cont'd.

LTAR Network Site	Experiment location	Experiment establishment year	Treatment	Treatment descriptors	Sources to define/refine treatments	Frequency of treatment adjustment	Spatial scales currently evaluated
Upper Mississippi River Basin (UMRB) Platteville, WI	Platteville, WI 42.71 N, 90.39 W	2023	Prevailing	4-yr corn silage; 3-yr alfalfa Conventional tillage No cover crops No grazing Fall injected dairy manure	Participating scientists Farmer-led watershed groups Dairy Management Inc.	5 years	Field
			Alternative	4-yr corn silage; 3-yr alfalfa No tillage Cover crop (winter rye) No grazing Manure-based fertilizer products Sidedress nitrogen applications			

Table S3. Select attributes for grazing land sites included in the Long-Term Agroecosystem Research (LTAR) Network Common Experiment, April 2024.

LTAR Network Site	Experiment location	Experiment establishment year	Treatment	Treatment descriptors	Sources to define/refine treatments	Frequency of treatment adjustment	Spatial scales currently evaluated
Archbold Biological Station-University of Florida (ABS-UF)	Venus, FL 27.15 N, 81.19 W Ona, FL 27.39 N, 81.94 W	2017	Prevailing	Native and cultivated pastures Cow-calf Conventional grazing Conventional prescribed fire	Stakeholders Research data	Variable	Pasture
			Alternative	Native and cultivated pastures Cow-calf Rotational grazing Patch-burn, fire frequency, forage species manipulation			
Central Plains Experimental Range (CPER)	Nunn, CO 40.83 N, 104.72 W	2014	Prevailing	Native vegetation Beef cattle (stocker) Traditional, season-long (mid-May to September) continuous (single paddock) grazing management Flexible stocking rate (same as Alternative within years)	Participating scientists Stakeholders	Annual	Plot Pasture Ranch
			Alternative	Native vegetation Beef cattle (stocker) Collaborative adaptive multi-paddock rotational grazing management Flexible stocking rate (same as Prevailing within years)			
Great Basin (GB)	Mountain Home, ID 43.02 N, 115.77 W	2014	Prevailing	Invasive annual grassland Beef cattle Fixed grazing management Moderate stocking rate with fixed duration Management according to BLM allotment permit	Rancher stakeholders Research publications	Annual	Landscape Ranch
			Alternative	Invasive annual grassland Beef cattle Adaptive grazing management High stocking rate with flexible duration Management intended to suppress cheatgrass competition with desirable perennial species			

Table S3. Cont'd.

LTAR Network Site	Experiment location	Experiment establishment year	Treatment	Treatment descriptors	Sources to define/refine treatments	Frequency of treatment adjustment	Spatial scales currently evaluated
Jornada Experimental Range (JER)	Las Cruces, NM 32.56 N, 106.87 W	2020	Prevailing	Native vegetation; Feedlots Beef cattle (Angus and Angus-Hereford) Permanent fencing; "Best pasture" grazing Conventional supply chains connected to arid rangelands	Aridlands ranchers Extension personnel and customers Participating scientists	Variable	Pasture Ranch Supply chain
			Alternative	Native vegetation; Feedlots; Grass-finishing operations Heritage cattle genetics Precision ranching systems with virtual fencing Adaptive value chains connected to arid rangelands			
Northern Plains (NP)	Mandan, ND 46.77 W, 100.92 N	2019	Prevailing	Native vegetation Beef cattle (Angus and Angus-Hereford) Traditional/continuous grazing management Moderate stocking rate Grazing used for vegetation management	Stakeholder group	Variable	Plot Pasture
			Alternative	Native vegetation Beef cattle (Angus and Angus-Hereford) Adaptive grazing management Multi-species grazing (Angus and crossbred goats) High-density stocking rate Grazing and fire used for vegetation management Rangeland seeding for vegetation diversity			
Platte River - High Plains Aquifer (PR-HPA)	Mead, NE 41.18 W, 96.55 N	2016 (Prevailing) 2005 (Alternative)	Prevailing	Smooth brome pasture Yearling steers Season-long grazing N fertilized pastures	University extension USDA-NASS data USDA-ERS data UNL Beef Innovation Hub LTAR stakeholders	5 years	Plot Pasture
			Alternative	Smooth brome pasture Yearling steers Rotational summer grazing No N fertilizer Cattle supplemented with distillers grain			

Table S3. Cont'd.

LTAR Network Site	Experiment location	Experiment establishment year	Treatment	Treatment descriptors	Sources to define/refine treatments	Frequency of treatment adjustment	Spatial scales currently evaluated
Walnut Gulch Experimental Watershed (WGEW)	Santa Rita Experimental Range Sahuarita, AZ 31.81 N, 110.85 W	2016	Prevailing	Velvet mesquite allowed to increase to its natural limits	University faculty Action agency partners	4 years	Pasture
			Alternative	Velvet mesquite treated with aerially-applied herbicides			

Table S4. Primary metrics for biophysical indicators associated with LTAR cropland sites. Protocols are included in the third column and outline data collection guidelines for network-level harmonization. Additional protocols are being developed and can be found using keywords "LTAR" and "Common Experiment" at https://www.protocols.io.

Biophysical Indicators	Primary Metric Name	Protocol
Productivity	Aboveground biomass staying in the field	dx.doi.org/10.17504/protocols.io.bp2l62zmkgqe/v1
Productivity	Aboveground biomass (staying): C concentration	dx.doi.org/10.17504/protocols.io.bp2l62km5gqe/v1
Productivity	Aboveground biomass (staying): N concentration	dx.doi.org/10.17504/protocols.io.bp2l62km5gqe/v1
Productivity	Aboveground biomass (staying): P concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1
Productivity	Aboveground biomass (staying): K concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1
Productivity	Aboveground biomass (staying): S concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1
Productivity	Aboveground biomass leaving the field (Yield/Biomass)	
Productivity	Collection of grain yield data using a yield monitor	dx.doi.org/10.17504/protocols.io.rm7vzjm1rlx1/v1
Productivity	Post-processing of spatial grain yield data	dx.doi.org/10.17504/protocols.io.4r3l2qmy3l1y/v1
Productivity	Aboveground biomass (leaving): Fresh moisture	
Productivity	Aboveground biomass (leaving): Test weight	
Productivity	Aboveground biomass (leaving): C concentration	dx.doi.org/10.17504/protocols.io.bp2l62km5gqe/v1
Productivity	Aboveground biomass (leaving): N concentration	dx.doi.org/10.17504/protocols.io.bp2l62km5gqe/v1
Productivity	Aboveground biomass (leaving): P concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1
Productivity	Aboveground biomass (leaving): K concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1
Productivity	Aboveground biomass (leaving): S concentration	dx.doi.org/10.17504/protocols.io.14egn6bnql5d/v1

Table S4. Cont'd.

Biophysical Indicators	Primary Metric Name	Protocol
Productivity	Aboveground biomass (leaving): Crude protein	dx.doi.org/10.17504/protocols.io.n2bvjn6wpgk5/v1
Productivity	Aboveground biomass (leaving): Neutral detergent fiber concentration	dx.doi.org/10.17504/protocols.io.n2bvjn6wpgk5/v1
Productivity	Aboveground biomass (leaving): Acid detergent fiber	dx.doi.org/10.17504/protocols.io.n2bvjn6wpgk5/v1
Productivity	Aboveground biomass (leaving): lignin concentration	dx.doi.org/10.17504/protocols.io.n2bvjn6wpgk5/v1
Productivity	Aboveground biomass (leaving): Ash	dx.doi.org/10.17504/protocols.io.n2bvjn6wpgk5/v1
Productivity	Crop inputs and farm operations	
Productivity	Plant stand (population) at harvest	
Productivity	PhenoCam – Green Chromatic Coordinate	dx.doi.org/10.17504/protocols.io.ewov19j77lr2/v1

Table S4. Cont'd.

Biophysical Indicators	Primary Metric Name	Protocol
Biodiversity and Pest	Crop plant diversity	
Biodiversity and Pest	Non-crop plant diversity	dx.doi.org/10.17504/protocols.io.kxygxyzbzl8j/v1
Biodiversity and Pest	Crop pests	dx.doi.org/10.17504/protocols.io.bp2l62mzdgqe/v1
Biodiversity and Pest	Crop diseases	dx.doi.org/10.17504/protocols.io.bp2l62mzdgqe/v1
Biodiversity and Pest	Cereal crop mycotoxin concentration	dx.doi.org/10.17504/protocols.io.j8nlk8b6xl5r/v1
Biodiversity and Pest	Natural pest suppression	dx.doi.org/10.17504/protocols.io.rm7vzjm14lx1/v1
Biodiversity and Pest	Butterfly diversity and abundance	dx.doi.org/10.17504/protocols.io.14egn6bnpl5d/v1
Water Quality	Dissolved nitrate (NO_3) concentration	
Water Quality	Dissolved ammonia (NH_3) concentration	dx.doi.org/10.17504/protocols.io.j8nlk8b61l5r/v1
Water Quality	Total dissolved nitrogen (TDN) concentration	dx.doi.org/10.17504/protocols.io.5jyl82rkrl2w/v1
Water Quality	Total nitrogen (TN) concentration	dx.doi.org/10.17504/protocols.io.5jyl82rkrl2w/v1
Water Quality	Total dissolved phosphorus (TDP) concentration	dx.doi.org/10.17504/protocols.io.8epv5r7m6g1b/v1
Water Quality	Total phosphorus (TP) concentration	dx.doi.org/10.17504/protocols.io.8epv5r7m6g1b/v1
Water Quality	Total suspended solids	dx.doi.org/10.17504/protocols.io.261ge5pjog47/v2
Water Quality	Best practices for collection, handling, and analyses of water quality samples	dx.doi.org/10.17504/protocols.io.q26g71z68gwz/v1
Water Quantity	Rainfall	dx.doi.org/10.17504/protocols.io.e6nvw1kyzlmk/v1
Water Quantity	Snowfall	
Water Quantity	Irrigation water applied	dx.doi.org/10.17504/protocols.io.j8nlk86ydl5r/v1
Water Quantity	Discharge from artificial subsurface drains	dx.doi.org/10.17504/protocols.io.x54v92ewzl3e/v1
Water Quantity	Channelized surface flow discharge	dx.doi.org/10.17504/protocols.io.rm7vzj195lx1/v1
Water Quantity	Overland flow	dx.doi.org/10.17504/protocols.io.kxygxyk2zl8j/v1

Table S4. Cont'd.

Biophysical Indicators	Primary Metric Name	Protocol
Water Quantity	Infiltration	dx.doi.org/10.17504/protocols.io.81wgbzd9ygpk/v1
Water Quantity	Percolation	dx.doi.org/10.17504/protocols.io.81wgbzd9ygpk/v1
Water Quantity	Saturated hydraulic conductivity	dx.doi.org/10.17504/protocols.io.eq2lywz1qvx9/v1
Water Quantity	Soil bulk density	
Water Quantity	Soil water content	dx.doi.org/10.17504/protocols.io.261ge542yg47/v1
Water Quantity	Soil water potential and matric potential	dx.doi.org/10.17504/protocols.io.8epv5rzb4g1b/v1
Water Quantity	Depth to water table	dx.doi.org/10.17504/protocols.io.kqdg32eb7v25/v1
Water Quantity	Best practices for collection, handling, and analyses of water quantity measurements	
Soil	Soil organic carbon stocks and change	dx.doi.org/10.17504/protocols.io.q26g7yo1kgwz/v1
Soil	Soil health	
GHG* & Air Quality	Nitrous oxide and methane flux from soil	dx.doi.org/10.17504/protocols.io.yxmvmemw5g3p/v1
GHG & Air Quality	Sediment flux	dx.doi.org/10.17504/protocols.io.6qpvr8x23lmk/v1
GHG & Air Quality	Surface flux of carbon dioxide and water (Eddy covariance)	

* GHG = Greenhouse gas

LTAR Common Experiment

Metric Protocols

Context

The Long-term Agroecosystem Research (LTAR) Network includes a Common Experiment (CE) in its portfolio of coordinated research activities. Objectives of the CE include: 1) develop and evaluate production systems that promote the sustainable management of cropland, 2) identify, quantify, and understand mechanisms underlying tradeoffs and synergies among ecosystem services, and 3) use common indicators across multiple systems in different regions to understand and model ecosystem service outcomes. The assessment of common indicators across productivity, environmental, and human dimension domains is fundamental for developing science-based agricultural production systems.

This document serves as a protocol template for metrics included in the CE across eight indicator categories (i.e., productivity, biodiversity, water quality, water quantity, soil health, greenhouse gas mitigation & air quality, economic, and human dimensions).

Recommended Documentation

Generating protocols for metrics is inherently difficult when considering the variation in resources and expertise across LTAR sites. As such, protocols should be framed not as inflexible directives, but as recommendations that consider these differences without compromising data comparability across sites. To this end, it is advantageous to offer ‘preferred’ and ‘minimum’ protocol recommendations that vary in measurement intensity, frequency, and/or scale.

For each protocol, please adapt information gathered from your metrics spreadsheet generated in 2021 for ***primary metrics only***. Much information in that spreadsheet will either directly transfer or serve as a useful starting point for more detailed documentation. Please also provide a ‘Plain Language Summary’ including 1) a description of the metric, 2) why data from the metric is important, and 3) a synopsis of the method. The summary will serve as an effective tool for communicating about the LTAR CE to a wider audience.

Indicator Domain:

Metric Tier: Primary

Metric Name:

Plain Language Summary

One-paragraph description of the metric, why data from the metric is important, and a synopsis of the recommended method.

Protocol

Sections to include for each metric*:

- Sample collection, processing, and analysis
- Covariate metrics to be sampled concurrently
- Calculations
- QA/QC
- Archiving

*Information/guidance regarding labor and time requirements, equipment/supplies, QA/QC considerations (e.g., missing data, expected numeric bounds, precision, cross-lab standards, etc.), and potential pitfalls associated with assessments will be helpful for sites unfamiliar with the metric. Teams should tailor these sections to reflect their collective knowledge/expertise.

References (focus on those that are most helpful)

Illustrative Media (diagrams, photographs, instructional videos, etc.)

Table 1. Summary of recommendations for measurement of… .

Metric name:			
Attribute*	**Preferred**	**Minimum**	**Comments**
Spatial scale			
Frequency			
Covariate metrics			
Other			

Spatial scale = plot or field or both (tailor scale terms to site CE); Frequency interval = once, weekly, monthly, annually (preferred season?), 5-year, etc.; Covariate metrics = other metrics to sample concurrently.