Received: 29 March 2024 | Accepted: 9 September 2024 | Published online: 17 October 2024

DOI: 10.1002/agj2.21697

Agronomy Journal

ORIGINAL ARTICLE

Agronomy, Soils, and Environmental Quality

Deriving general principles of agroecosystem multifunctionality with the Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) network

K. Ann Bybee-Finley[1,2] | **Katherine Muller**[1] | **Kathryn E. White**[1] | **Timothy M. Bowles**[3] | **Michel A. Cavigelli**[1] | **Eunjin Han**[4] | **Harry H. Schomberg**[1] | **Sieglinde Snapp**[5] | **Frederi Viens**[6]

[1]USDA-ARS, Sustainable Agricultural Systems Laboratory, Beltsville, Maryland, USA

[2]Department of Crop and Soil Sciences, North Carolina State University, Raleigh, North Carolina, USA

[3]Department of Environmental Science, Policy and Management, University of California Berkeley, Berkeley, California, USA

[4]USDA-ARS, Adaptive Cropping Systems Lab, Beltsville, Maryland, USA

[5]International Maize and Wheat Improvement Center (CIMMYT), El Batán, Mexico

[6]Department of Statistics, Rice University, Houston, Texas, USA

Correspondence
K. Ann Bybee-Finley, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, North Carolina, USA.
Email: ann.bybee-finley@ncsu.edu

Assigned to Associate Editor Telmo JC Amado.

Funding information
National Institute of Food and Agriculture, Grant/Award Number: 2019-67019-29468

Abstract

Long-term agricultural field experiments (LTFEs) have been conducted for nearly 150 years. Yet lack of coordination means that synthesis across such experiments remains rare, constituting a missed opportunity for deriving general principles of agroecosystem structure and function. Here, we introduce the Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) project, which uses legacy data from North American LTFEs to address research questions about the multifunctionality of agriculture. The DRIVES Project is a network of researchers who have compiled a database of primary (i.e., observations) and secondary (i.e., transformed observations or modeling results) data from participating sites. It comprises 21 LTFEs that evaluate how crop rotational diversity impacts cropping system performance. The Network consists of United States Department of Agriculture, university, and International Maize and Wheat Improvement Center scientists (20 people) who manage and collect primary data from LTFEs and a core team (nine people) who organize the network, curate network data, and synthesize cross-network findings. As of 2024, the DRIVES Project database contains 495 site-years of crop yields, daily weather, soil analysis, and management information. The DRIVES database is findable, accessible, interoperable, and reusable, which allows integration with other public datasets. Initial research has focused on how rotational diversity impacts resilience in the face of adverse weather, nutritional quality, and economic feasibility. Our collaborative approach in handling LTFE data has established a model for data organization that facilitates broader synthesis studies. We openly invite other sites to join the DRIVES network and share their data.

Abbreviations: CIMMYT, International Maize and Wheat Improvement Center; DRIVES, Diverse Rotations Improve Valuable Ecosystem Services; LTFE, long-term agricultural field experiments; NIFA, National Institute for Food and Agriculture; SOM, soil organic matter.

1 | INTRODUCTION

To meet the 21st-century grand challenge of ensuring adequate food production while increasing the delivery of additional ecosystem services, agroecosystems need to be increasingly multifunctional (Foley et al., 2005). Diversifying agroecosystems is one consistent way to improve multifunctionality (Tamburini et al., 2020). For example, diverse crop rotations can improve crop yield and water regulation, enhance nutrient cycling, boost pest control, and improve important soil health indicators (Hegewald et al., 2018; Krupek et al., 2022; Tamburini et al., 2020; Vendig et al., 2023). In practice, short-term crop yield losses often occur when adopting new multifunctional practices because any change to a production system comes with a learning curve (Plastina et al., 2020). However, multifunctional practices are associated with long-term benefits, such as improved soil properties and reduced yield loss due to adverse weather (Sanford et al., 2021). Producers are often disincentivized from adopting practices that serve multiple functions beyond production because they face strong historical legacies from regulatory and market forces that incentivize simplified cropping systems (de Gorter et al., 2015; Hendrickson et al., 2013; A. Smith & Stirling, 2010).

Long-term field experiments (LTFEs) are invaluable resources providing critical underpinning evidence for the development of practical strategies to realize diversified cropping systems and multifunctional agroecosystems. Ecological theory and a plethora of studies show that critical variables (e.g., many soil properties) that underpin ecosystem multifunctionality and resilience are slow to change (Qiu et al., 2020). Management practices like reduced tillage, applying manures and other soil amendments, and crop residue incorporation must be in place for many years before researchers can detect "statistically significant" treatment effects (Bai et al., 2018). Several studies, for example, suggest that a minimum of 5 years is required to detect management-induced changes in soil organic C under the most rigorous assessment methods (Necpálová et al., 2014; Schrumpf et al., 2011; P. Smith et al., 2020). For crop rotation studies, multiple years are required to fully establish all rotations, followed by some minimum number of complete cycles before their effects can be assessed (Castellazzi et al., 2008; Teasdale & Cavigelli, 2017). Long-term experiments are also needed to understand the effects of management practice in the face of erratic events, such as droughts or pest outbreaks (Bowles et al., 2020). Furthermore, variables like crop yield stability require extended periods of time to capture the effects of practices across a spectrum of weather conditions (Reckling et al., 2021; Urruty et al., 2016).

While a single LTFE provides valuable longitudinal data about practices for a specific place or cropping system, synthesizing findings from multiple LTFEs vastly expands the inference space and provides unique insights about management practices that improve agroecosystem multifunctionality at a much broader scale. This is especially important given that the effects of management practices likely differ across environmental contexts, such as climate or edaphic characteristics. In experimentation, these environmental properties can condition treatment responses, such that some practices appear more effective in certain areas than others. Thus, syntheses could identify the conditions under which a given management practice impacts system performance and the extent of the impact. Further, the management context can markedly condition response to diversification in agroecosystems (Maclaren et al., 2022; Snapp et al., 2010). For example, crop rotations containing legumes often enhance crop performance when little or no synthetic N is applied, but this effect is smaller when synthetic N is supplied in abundance (Bybee-Finley et al., 2024; Maclaren et al., 2022).

Core Ideas

- Long-term agricultural field experiments are critical for understanding the multifunctionality of agroecosystems.
- The DRIVES (Diverse Rotations Improve Valuable Ecosystem Services) network synthesizes data across long-term experiments to understand the role of crop rotation diversity.
- The DRIVES Network has constructed a publicly available database containing daily weather and crop yield observations.

Agricultural science can draw inspiration from other scientific fields that have created data infrastructure and networks of expertise for cross-site synthesis and collaboration across long-term experiments. Ecologists in the United States developed the Long-Term Ecological Research Network (LTER) in 1980 (Iwaniec et al., 2021; Knapp et al., 2012) and the National Ecological Observatory Network (NEON) in the early 2000s (Dantzer et al., 2023). Some agricultural scientists have emphasized the importance of coordinated multi-site, long-term observations in agriculture (Robertson et al., 2008). In response, the United States Department of Agriculture Agricultural Research Service (USDA-ARS) funded the Long-Term Agroecosystem Research Network (LTAR) in the early 2010s, with a particular focus on developing the needed cross-site syntheses of long-term datasets (Kleinman et al., 2018; Walbridge & Shafer, 2011). Like-minded efforts are also being made internationally. The China National Soil Fertility and Fertilizer Efficiency Long-Term Monitor Network, established in the late 1980s, has eight long-term experiments (Zhao et al., 2010). The BonaRes Repository, created in 2015 as part of the German research strategy, which has merged with the European Joint Programming on Soil (EJP SOIL) for soil and agricultural research, had metadata on 616 long-term experiments as of 2022 (Donmez et al., 2022; Grosse & Wilfried, 2019). The Latin American Agronomic Research Network (RedAgAl), formalized in 2023, has 45 medium- and long-term trial sites in Latin America with uniform protocols and centralized data management (Fonteyne et al., 2023). The Global Long-term Experiments Network (GLTEN) was launched in 2019 as a worldwide metadata platform for long-term agricultural experiments (Lisboa et al., 2020). In addition to allowing cross-site syntheses, these efforts often provide a repository for long-term data and metadata, which preserves the contributions of individual experiments.

The Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) Project is one example of how the legacy of LTFE data can be extended to address research questions about multifunctionality of agriculture. The DRIVES Project connects multiple LTFEs that include crop rotations as treatments to better understand one of the oldest and well-known methods of diversifying cropping systems. The DRIVES Project consists of a network of USDA, university, and International Maize and Wheat Improvement Center (CIMMYT) scientists (20 people) who have managed and collected primary data from long-term experiments and a core team (nine people) that has convened the network, organized the data, and synthesized cross-network findings. The DRIVES Project has worked to quantify the effects of rotational diversity on productivity of individual crops and complete rotations, with the goal of identifying how much and what kind of crop diversity results in more multifunctional agroecosystems (Bybee-Finley et al., 2024). The DRIVES Project also provides the database infrastructure and network expertise to quantify the role of rotational complexity on additional ecosystem services such as soil health, economic performance, and provision of human nutrition. In doing so, the DRIVES Project has codified methods for handling long-term data in peer-reviewed publications and in publicly accessible protocols and scripts. These will be useful for researchers managing long-term agricultural experimental data and to further efforts for cross-site syntheses.

Results of DRIVES analyses will provide robust insights on the value of crop rotational diversity to meet the 21st-century grand challenge of designing multifunctional agroecosystems. For example, how might rotational diversity enable ecological intensification and reduce synthetic fertilizer inputs without compromising soil quality (Maclaren et al., 2022)? Or, how might the risk of crop loss be reduced under a changing climate (Bybee-Finley et al., 2024)? Or, to what extent can C input quantity and quality predict the accrual and quality of soil C stocks, as moderated by environmental context, rotational diversity, and soil properties? Results can be used to improve the accuracy of process-based crop/soil models to better represent changes in soil properties over time.

As with ecological studies on biodiversity-ecosystem function relationships, cross-site syntheses allow researchers to estimate the level of diversity at which crop yield or other ecosystem benefits saturate, generally, and then as conditioned by various environments. Results from cross-location syntheses can be used to set expectations and guide local management recommendations for farmers. The more general effect sizes of diversity could be used to advocate for policies that require a minimum level of diversity that ensures a level of multifunctionality and reduced risk of crop yield loss. Altogether, the evidence the DRIVES Project generates is valuable to agricultural stakeholders, including policymakers who set agendas for managing food security, government officials and agencies that allocate support for particular farming practices, and financial lenders that rely on accurate agricultural risk assessments to manage and successfully allocate credit to producers. The purpose of this paper is to convey the motivation for the DRIVES Project; describe the Project components, including the database; detail the research agenda; and reflect on experiences of organizing legacy data. Our aim is to cultivate interest in cross-site synthesis to derive general principles of multifunctional agroecosystems and their associated risk-reducing properties.

2 | BACKGROUND ON CROP ROTATIONAL DIVERSITY

Diversifying crops over space and time is one proposed strategy to create more multifunctional agroecosystems. Crop rotations are the most common form of crop diversification in industrialized agroecosystems (Beillouin et al., 2019). Rotations can also be diversified by incorporating cover crops, which increase spatial and temporal diversity without changing the cash crop rotation (Bybee-Finley & Ryan, 2018). Diversifying crop rotations can enhance the resilience of agroecosystems under an increasingly uncertain climate while reducing use of external inputs and maintaining crop yields (Bowles et al., 2020; Lin, 2011; Sanford et al., 2021).

Diverse crop rotations are an effective adaptation strategy in the face of adverse weather and climate change. Across time, crop yields of more diverse rotations are buffered against exposure to stress because different crops have different growing seasons such that all crops in a rotation may not be exposed to a given stressor (Gaudin et al., 2015). This buffering results in a “portfolio effect” where the net yield variation of all crops in a rotation is reduced compared with the average variation of the individual crops (Paut et al., 2020). Functional differences among species (e.g., plant architecture) that allow for greater resource recovery (Picasso et al., 2011) and allow for varying responses to stress (Elsalahy et al., 2020) further enhance the portfolio effect. Greater diversity of crops can affect plant-soil feedbacks and can lead to increases in soil health, which then buffer crops from adverse weather (Mooshammer et al., 2022).

Diverse rotations have been shown to support multiple ecosystem services, including soil organic C conservation (McDaniel et al., 2014; West & Post, 2002), pest suppression (Rusch et al., 2013), and protection of water quality (Tomer & Burkart, 2003; Tomer & Liebman, 2014). Rotation-induced changes in soil physical, chemical, and biological properties affect rooting depth, belowground oxygen concentration, water availability, microbial activity, microbially generated phytohormone concentrations, and nutrient cycling (Baldwin-Kordick et al., 2022; Ball et al., 2005; Bennett et al., 2012; McDaniel et al., 2014; McDaniel & Grandy, 2016).

Diverse crop rotations can increase crop yields (Beillouin et al., 2019; Zhou et al., 2020) and reduce fertilizer and pesticide inputs. Crop rotations can be designed and managed to accrue soil organic matter (SOM) by adding legumes, perennials, and cover crops to annual grain rotations (King & Blesh, 2018; McDaniel et al., 2014). Cover crops and perennial crops serve as a source of C and nutrients to support greater soil microbial biomass, diversity, and function (Garland et al., 2021; Pittelkow, Liang, et al., 2015; Potter et al., 2022; Tiemann et al., 2015; Venter et al., 2016). Thus, by increasing SOM and creating more diverse C and N pools (Breza et al., 2022), rotational diversity can help sustain crop yields in the long term by increasing soil N availability, especially with reduced synthetic N applications (Maclaren et al., 2022; M. E. Smith et al., 2023). Crop sequences can reduce pesticide use by increasing the proportion of low pesticide-use crops in rotation and enhancing the ecological regulation of pests (Guinet et al., 2023).

3 | DRIVES PROJECT DESCRIPTION

The DRIVES Project was conceptualized by participants who attended the *Corn in Context* conference in July 2018, which was coordinated by Drs. Matt Liebman and Marshall McDaniel at Iowa State University and funded by the USDA Agriculture and Food Research Initiative. The purpose of the conference was to review key findings related to the productivity, profitability, and environmental impacts of corn-based cropping systems, identify knowledge gaps about mechanisms contributing to multiple facets of cropping system performance, and explore opportunities to better use legacy data of US and Canadian long-term experiments. After the conference, while sharing a ride to the airport, a group of eager scientists, including a number of co-authors of this manuscript, decided to submit a competitive grant proposal to the Networks for Synthesis, Data Sharing, and Management program of the National Institute for Food and Agriculture (NIFA). The proposal, *Synthesizing Data From A Network Of Long-Term Diversified Cropping Systems Experiments To Reduce Producer Risk In An Uncertain Climate*, was funded ($500,000), and the project began in 2021.

FIGURE 1 The Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) logo designed by Julie Sterba.

The DRIVES Project (Figure 1) has three components: a network of scientists who manage and conduct research on long-term cropping systems experiments, a database of primary (i.e., observations) and secondary (i.e., transformed observations or modeling results) data from participating DRIVES sites, and an active research agenda, described below. The DRIVES Project is primarily led by two research scientists, supported by the NIFA grant, who manage DRIVES activities, and is supported by seven advising USDA-ARS, university, and CIMMYT scientists. The DRIVES Project has three research objectives:

1. Combine legacy data from long-term cropping systems experiments in North America with a crop rotation component and produce a database accessible for future meta-analysis and cross-site synthesis.
2. Assess the role of rotational diversity in buffering crop loss in the face of adverse weather and determine sustainable options for reducing producer risks under future weather scenarios.
3. Evaluate how crop production risks are influenced by crop rotations and identify significant gaps in our understanding of the mechanisms contributing to multiple facets of cropping system performance.

The DRIVES Project has resulted in a community of scientists who share experiences and generate research questions during bimonthly meetings using various formats of brainstorming, breakout sessions, and mapping exercises. Many DRIVES collaborators knew each other or had worked together previously (Figure 2, Figures S1 and S2). One-on-one virtual meetings with collaborators established trust and a willingness to share data with the network. This trust was formalized with a data-sharing agreement (Supporting Information S1), which is a contract detailing (1) expectations of how the DRIVES Project would use site data, (2) authorship

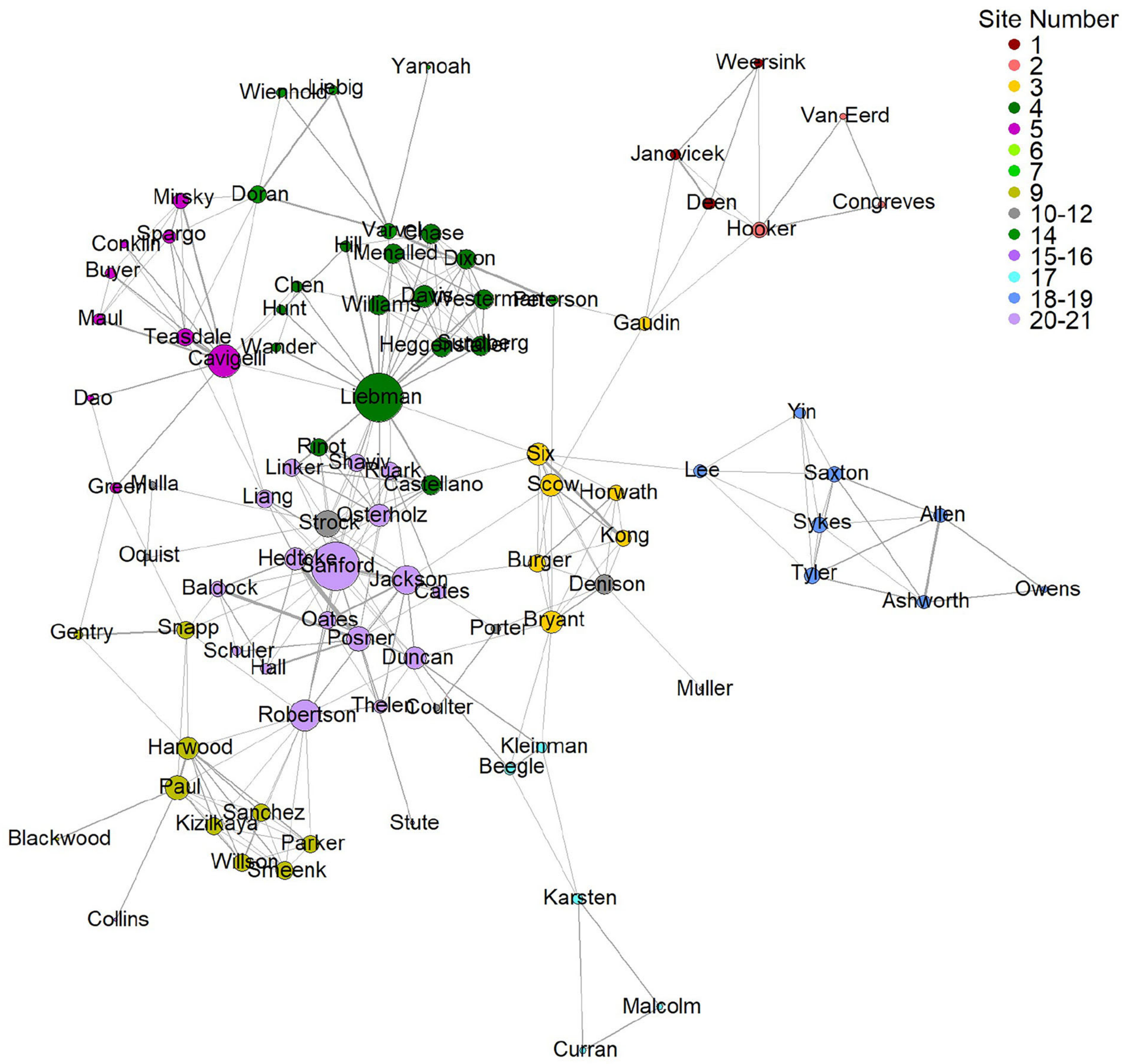

FIGURE 2 Author network figure created in R with the igraph package (Csardi et al., 2024). Circles represent authors from peer-reviewed journal articles attributed to Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) sites and lines represent co-authorship on these publications. Larger circles indicate that the author has published more articles attributed to DRIVES sites, and thicker lines indicate greater collaboration between authors. Circles are colored by DRIVES site numbers that correspond to Table 1. Only authors who have published at least two articles about DRIVES sites are featured. This network represents the largest number of connected authorships (92 of 119 authors) from the complete network (Figures S1 and S2).

guidelines, (3) what data would be shared by sites, and (4) the level of data access granted (e.g., available to the public or only to DRIVES researchers). Meetings are supplemented by bimonthly email updates. This community serves as a valuable forum where experiential knowledge about managing LTFEs (e.g., obtaining funding and managing experimental treatments) can be shared.

4 | DESCRIPTION OF DATA

Criteria for a site to be included in DRIVES are as follows: (1) treatments with contrasting crop rotations, (2) at least three cycles through the longest rotation, (3) every crop phase planted every year, and (4) ideally at least 10 years of data. In the beginning of 2024, the DRIVES database contained 495 site-years of data from 21 experiments and 87,300 crop yield observations (Table 1). The DRIVES data fit into four main categories that are interrelated and somewhat hierarchical: spatial and temporal information about (1) experimental design, (2) agronomic management, (3) observations, and (4) metadata about each of the first three categories (Figure 3, Supporting Information S2.1). Observations include both environmental context, such as weather, and responses such as crop yield and soil properties.

TABLE 1 Description of sites in the DRIVES (Diverse Rotations Improve Valuable Ecosystem Services) database.

Site No.	Experiment	Institution	Dominant soil order	MAT	MAP	Replicates	Start year	End year	No. of rotations	Additional management treatments	Rotations and management treatments
1	Elora Long-Term Rotation and Tillage trial[a]	University of Guelph, ON, Canada	Alfisol	6.1	902	4	1980		6	Chisel, moldboard tillage	Crossed
2	Ridgetown Long-term Rotation and Tillage trial[b]	University of Guelph, ON, Canada	Mollisol	9	871	4	1995		7	No till and moldboard tillage crossed with zero N, low N, medium N, and high N	Crossed
3	The Century Experiment[c]	University of CA Davis, USA	Entisol	16.6	485	3	1993	2021	6	Rainfed and irrigated; mineral fertilizer and reduced mineral fertilizer	Partially crossed
4	Marsden Long-term Rotation Study[d]	IA State University, USA	Mollisol	10	871	4	2002		3	Low and high herbicide treatments; mineral fertilizer and reduced mineral fertilizer + manure	Partially crossed
5	Farming Systems Project[e]	Beltsville Agricultural Research Center, USDA-ARS, MD, USA	Ultisol	13.2	1064	4	1996		5	Non-organic with no-till and chisel tillage and organic	Partially crossed
6	D5 Trial[f]	CIMMYT, Mexico	Mollisol	15.5	615	2	1991		3	No till and chisel tillage; partial removal, removal, or retention of residues	Partially crossed
7	Metepec Trial[f]	CIMMYT, Mexico	Mollisol	13.7	884	3	2014		3	No-till and chisel tillage; removal or retention of residues	Crossed
8	Tlaltizapan Trial	CIMMYT, Morelos, Mexico	Vertisol	24.4	881	2	2011		2	No-till and chisel tillage; removal or retention of residues	Crossed
9	Living Field Lab[g]	Kellog Biological Station, MI State University, USA	Alfisol	9.3	886	4	1993	2013	6	High synthetic N, low synthetic N, low synthetic N with supplementary compost, compost only; non-organic and organic	Partially crossed

(Continues)

TABLE 1 (Continued)

Site No.	Experiment	Institution	Dominant soil order	MAT	MAP	Replicates	Start year	End year	No. of rotations	Additional management treatments	Rotations and management treatments
10	Minnesota Long-Term Agricultural Research Network, Grand Rapids[h]	University of MN, USA	Mollisol/Alfisol	5.2	689	3	2011		3		
11	Minnesota Long-Term Agricultural Research Network, Lamberton[h]	University of MN, USA	Mollisol/Alfisol	7.3	721	4	2011		3		
12	Minnesota Long-Term Agricultural Research Network, Waseca[h]	University of MN, USA	Mollisol/Alfisol	7.3	920	4	2011		3		
13	Long-term Tillage and Cropping Systems Experiment[i]	Agroecosystem Management Research Unit, USDA-ARS, NE, USA	Mollisol	11	739	6	1981	2018	3	No-till, chisel tillage, tandem disk, ridge tillage, and subsoil tillage	Crossed
14	Long-term Crop Rotation Study[j]	Agroecosystem Management Research Unit, USDA-ARS, NE, USA	Alfisol/Mollisol	10	707	5	1983		7	Zero N, low synthetic N, and high synthetic N	Crossed
15	Triplett-Van Doren Long-term Tillage and Crop Rotation Sstudy, Hoytville[k]	OH State University, USA	Alfisol	10	856	3	1963		3	No-till, chisel tillage, and moldboard tillage	Crossed
16	Triplett-Van Doren Long-Term Tillage and Crop Rotation Study, Wooster[l]	OH State University, USA	Alfisol	10	977	3	1962		3	No-till, chisel tillage, and moldboard tillage	Crossed
17	Sustainable Dairy Cropping System Experiment[m]	PA State University, USA	Ultisol	9.8	990	4	2010		13	Pest management, tillage	Partially crossed
18	Long-term Systems Study, Milan[n]	University of TN, USA	Ultisol	15.2	1396	4	2002		16	Mineral fertilizer, poultry litter, and reduced mineral fertilizer	Crossed

(Continues)

TABLE 1 (Continued)

Site No.	Experiment	Institution	Dominant soil order	MAT	MAP	Replicates	Start year	End year	No. of rotations	Additional management treatments	Rotations and management treatments
19	Long-term Systems Study, Spring Hill[o]	University of TN, USA	Ultisol	15	1344	4	2002		16	Mineral fertilizer, poultry litter, and reduced mineral fertilizer	Crossed
20	Wisconsin Cropping Systems Trial, Arlington Research Station[p]	University of WI, USA	Mollisol	7.3	796	4	1990		5	Non-organic and organic	Partially crossed
21	Wisconsin Cropping Systems Trial, Lakeland Agricultural Center[p]	University of WI, USA	Mollisol	9	851	4	1990	2002	5	Non-organic and organic	Partially crossed

Note: In the "Rotations and management treatments" column, "crossed" refers to treatments that are present in all rotations and "partially crossed" refers to treatments that apply to a subset of rotations. All experiments are randomized complete block designs apart from Site 3, which was fully randomized. Mean annual temperature (MAT,˚C) and mean annual cumulative precipitation (MAP, mm) were calculated for the duration of each experiment site. A description of crop rotations at sites is given in Table S1.

[a]Gaudin et al. (2015).
[b]Chahal et al. (2021).
[c]Wolf et al. (2018).
[d]Davis et al. (2012).
[e]Cavigelli et al. (2008).
[f]Fonteyne et al. (2021).
[g]Snapp (2016).
[h](https://ltarn.cfans.umn.edu/).
[i]Wilhelm & Wortmann (2004).
[j]Sindelar et al. (2016).
[k]Dick & Doren (1985).
[l]Lal et al. (1994).
[m]Snyder et al. (2016).
[n]Ashworth et al. (2016).
[o]Ashworth et al. (2020).
[p]Posner et al. (2008).

Experimental design	Management	Observations	Meta information
• Experimental units meta	• Rotations	• *Yield*	• Site
• *Experimental treatments*	• *Planting and harvest dates*	• *Weather*	• Contacts
• Site-specific treatment types	• *Tillage*	• *Soil measurements*	• Weather station
• Site-specific treatment levels	• *Fertilizer*	• *More…*	• Crop
			• Crop variety
			• Soil testing methods

FIGURE 3 Tables in the Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) database. Italicized text indicates tables with a time component. The relational structure of the database can be found in Figure S3.

Building on the initial work of Bowles et al. (2020) and the Corn-in-Context meeting, sites in the DRIVES Network are primarily concentrated in maize (*Zea mays* L.) production regions (Figure 4). The experiments evaluate rotational diversity relative to a single continuous monoculture, often maize; multiple continuous monocultures; or two-crop rotations. The median number of crop rotations per experiment is three. Treatments are diversified by adding annual crops, cover crops, perennial crops, or some combination (a list of crop rotations for each site can be found in Table S1). Experiments are generally managed according to best local recommendations for field crop production. Seven sites have tillage treatments and three sites have fertility treatments crossed with rotation (Table 1). Four sites employ a cropping system study approach in which crop rotation, fertilizer, tillage, and/or weed management vary in intensity among experimental treatments (sites 4, 17, 20, and 21). Four other sites had additional treatments of continuous pastures (site 20) or prairies (sites 10–12), although these data are not currently included in the DRIVES database. Sites span the range of semiarid steppe to humid subtropics. Most are humid continental with hot summers ($n = 7$), humid subtropical with hot summers ($n = 5$), and humid continental with warm summers ($n = 4$) (Figure 4).

5 | DATABASE ORGANIZATION

The DRIVES Project has developed a findable, accessible, interoperable, and reusable (Wilkinson et al., 2016) database that increases the likelihood that its use will be widespread. The DRIVES database was initially organized across several platforms. Google Drive was used for early stages of database development, mainly for file sharing. Application Programming Interfaces (APIs) within Google Drive and Google Sheets provided data validation tools to create a preliminary relational structure, along with R packages to facilitate a scripting workflow (Bryan, 2023). This preliminary relational structure facilitated a transition to a PostgreSQL database managed through Directus (v11). Internal project files are shared through Microsoft OneDrive and scripts are managed through a Github repository. For more details about file management and workflow, see Supporting Information S2.2 and S2.3, respectively. The database will be made accessible to the public in late 2024.

The DRIVES database design is motivated by three guiding principles: flexibility, interoperability, and tractability for statistical models. *Flexibility* refers to the ability to add and revise information in the database and investigate a variety of research questions. The data structure must accommodate different experimental designs across sites, as well as changes to treatments within sites. Flexibility is also essential to workflow. Because it takes a long time to curate data, flexibility is important to segment data curation into manageable portions (e.g., How to prioritize data organization?; What level of detail in the data is necessary?; and How to add additional information?). To give readers a sense of the effort involved in data curation, it took two postdoctoral scientists 6 months to construct and test a viable database structure for experimental designs and crop yields.

DRIVES data are organized in a relational database with different types of information placed in separate tables (Supporting Information S2.1). This structure enhances flexibility by allowing new information to be added as new tables, or as new rows on existing tables. Tables are related through foreign keys, such as a site or crop identifier, which allow tables to be cross-referenced and merged. Many tables use a compound primary key consisting of multiple columns (e.g., the rotation identifier is the site identifier combined with a descriptive rotation code). Additionally, we have created a citation database using Zotero (Corporation for Digital Scholarship, 2023) for peer-reviewed publications produced by DRIVES sites. Each citation is tagged for location, years included in the analysis, and research topic.

We attempt to preserve information from sites in the most granular form to maximize options for downstream analysis. Data can then be reorganized into coarser categories suitable for addressing a research question. For example, triticale (x *Triticosecale* Wittmack) and oats (*Avena sativa* L.) are coded separately in the table describing crop rotations; if triticale

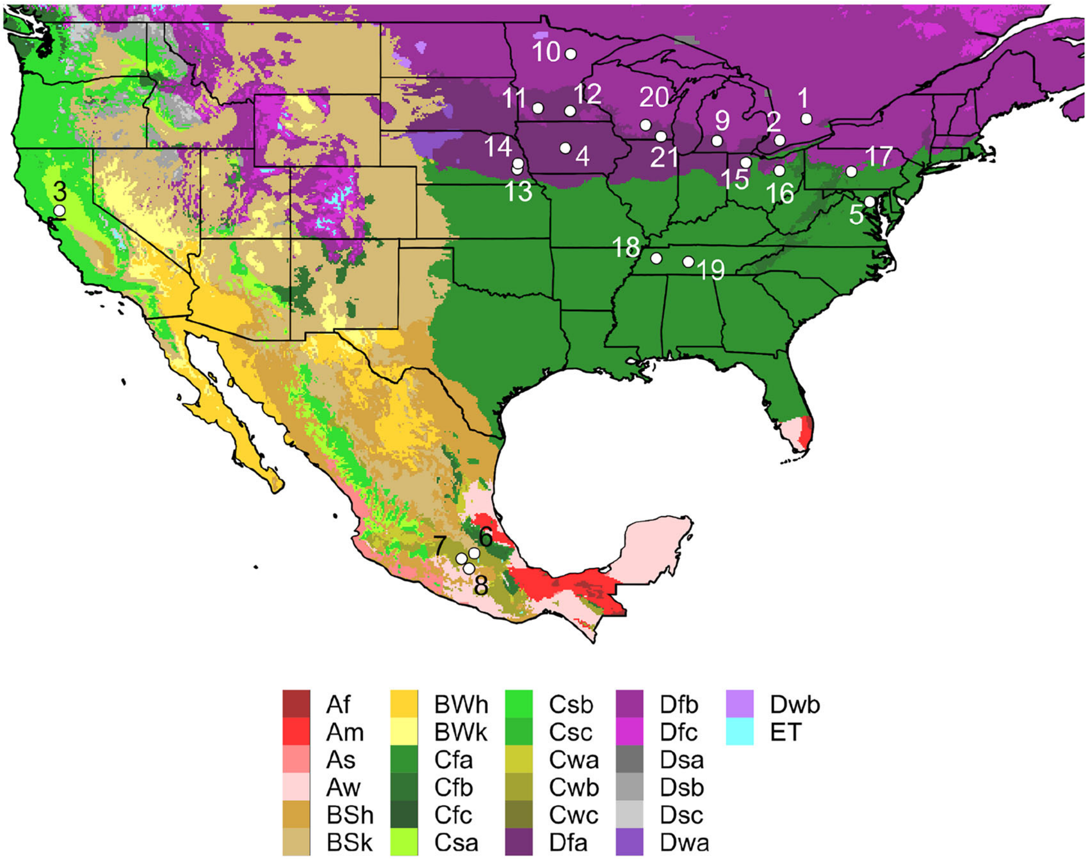

FIGURE 4 Map showing locations of the Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) sites (white points) in 2024 overlaid on a map of Köppen–Geiger climate classification (Rubel et al., 2017). Numbers correspond with site descriptions in Table 1. Climate classes in italics and bold below are those represented in the DRIVES Project: Tropical rainforest (Af), tropical monsoon (Am), tropical savanna dry winter (Aw), tropical savanna dry summer (As), hot arid desert (BWh), cold arid desert (BWk), semi-arid steppe (BS), humid subtropical climate with hot summer (Cfa), temperate oceanic climate with warm summer (Cfb), subpolar oceanic climate with cold summer (Cfc), temperate climate with dry, hot summer (Csa), temperate climate with dry, warm summer (Csb), temperature climate with dry, cold summer (Csc), temperate climate with dry winter and hot summer (Cwa), temperate climate with dry winter and warm summer (Cwb), temperate climate with dry winter and cold summer (Cwc), humid continental climate with hot summer (Dfa), humid continental climate with warm summer (Dfb), humid continental climate with cold summer (Dfc), continental climate with dry, hot summer (Dsa), continental climate with dry, warm summer (Dsb), continental climate with dry, cold summer (Dsc), continental climate with dry winter and hot summer (Dwa), continental climate with dry winter and warm summer (Dwb), polar tundra (ET).

replaces oats in a rotation, these crops can later be combined into a single rotation code of small grains. However, the effort of preserving information must be contextualized by research priorities and whether similar information is available from other sites. For example, perennial forage biomass data for individual harvests in DRIVES were summed across multiple harvests within a year as almost half of sites did not readily have perennial forage crop yields by harvest date.

Data tables need to be designed to accommodate differing experimental designs across sites (see Supporting Information S2.4 for more detailed examples). While it is easier to enter data in a wide format in which a separate column represents a separate variable (Table S2), when combining data from multiple experiments, a long format (e.g., a vertical design) is valuable as the table structure remains unaltered as additional variables are added as new rows; this approach also saves space for variables that occur in a subset of sites (Table S3). For example, the vertical design of our crop yield data (Table S3) has a different row for each crop fraction, meaning that sites that measure both wheat (*Triticum aestivum*) grain and straw will have two rows of data for the yield of that plot.

For the DRIVES database to be a useful resource for scientists outside of the DRIVES Network, it must be easy to comprehend the structure and terminology. *Interoperability* refers to the ability to transfer information within and beyond our network. Our primary strategy for interoperability was to maintain internal consistency and collect documentation in a data dictionary. Our data dictionary consists of three components: a dictionary of database tables, a dictionary of database columns, and a dictionary of variables used within columns.

The dictionary of tables provides an overview of each table in the database, along with a description of what a row represents within each table. For example, the crop information table has one row per crop. The crop yield table has one row for each crop fraction measured within each experimental unit for each year (e.g., site-specific plot in a year). The dictionary of columns provides descriptions for each column within each table. This dictionary includes information on whether columns represent foreign keys from other tables, and whether the column contains a variable described in the variables dictionary. The dictionary of variables describes categories used within tables that are not foreign keys from other tables. For example, we have a category describing types of crop fractions represented in the crop yield table (e.g., grain, stover, straw, etc.).

Consistent and clearly defined vocabulary helps facilitate translation to vocabularies used by other groups. However, there is a trend toward more formal ontologies in big data efforts (Arnaud et al., 2020). Formal ontologies are a structured way to define relationships among information types and hierarchically categorize information. Moving forward, we plan to incorporate ontologies into the DRIVES database by ensuring our internal ontologies can be easily matched to existing external ontologies.

Building the database requires consideration not only to immediate research questions, but also to anticipate future research questions. *Tractability* for statistical models requires organization of information in such a way that data can be extracted, combined, and aggregated to suit each analysis. Two strategies were pursued to facilitate preparing data for statistical models. The first strategy was to include columns that make it easy to filter out unwanted rows (see Table S4 for a detailed example). For example, in our crop yield dataset, we include a logical column indicating whether a crop fraction is removed from the field. This makes it easy to separate harvested products, such as grain, from residues that are incorporated into the soil. The second strategy was to create templates for tables involving time series observations such as crop yield or weather variables. The template data table contains a row for every potential observation including empty rows for missing observations that can be removed or imputed, depending on the downstream application. The data template strategy was also useful for quality control. Mismatches between the template and raw data provided by sites sometimes revealed an error in the raw data, such as a mislabeled plot identifier, or a mistake in the database tables used to generate the template. After correcting the mistakes, scripts were easily rerun to generate and refill the affected templates.

6 | DRIVES RESEARCH AGENDA

The motivation to build the DRIVES database was to facilitate analysis about the effects of crop rotations on system performance across multiple locations. The flexibility of the database enables easy integration with other datasets, including publicly available economic and nutrition data. This allows us and others to assess the impacts of rotational diversity using various response variables, such as units of energy, nutritional value, efficiency of resource use, or gross or net returns. Cropping systems will likely show trade-offs across metrics (Snapp et al., 2010), and each metric provides a partial assessment of any system.

A key strength of the DRIVES database is that it allows evaluation of outcomes for both complete rotations and individual crops. Past multisite studies of the impacts of rotational diversity on crop performance have focused on the response of an individual crop (Bowles et al., 2020; Maclaren et al., 2022; Marini et al., 2020; M. E. Smith et al., 2023). However, the effects of crop rotations are more than the sum of the effects on individual crops and thus should be examined at the system level. Systems-level analyses can reveal potential trade-offs of increasing rotational diversity (Sanford et al., 2021). Moreover, the portfolio effect can only be quantified when evaluating rotational diversity at the complete rotation level. Better understanding the portfolio effect and the impacts of functional (i.e., ability of crops to access resources) and response diversity (i.e., differing response of crops to stress) allow us to assess the value of rotational diversity on cropping system performance. The DRIVES database also allows consideration of additional management practices (e.g., tillage and fertility) or environmental conditions, which can interact with the effects of rotational diversity (Pittelkow, Linquist, et al., 2015; Snapp et al., 2010). The DRIVES Network is addressing and planning to address various critical research questions, which are summarized below.

6.1 | Crop yield responses to adverse weather

Rotational diversity has been proposed as a climate adaptation strategy to reduce vulnerability of cropping systems to adverse weather conditions (Petersen-Rockney et al., 2021). Vulnerability encompasses exposure to hazardous events, sensitivity to these events, potential impacts as a result of the events, and the capacity of producers to prepare and adapt to these events (U.S. Federal Government, 2021). Exposure to adverse weather events during critical growth periods has been linked to crop yield losses (Teasdale & Cavigelli, 2017). Crops likely differ in their sensitivity to weather variables because of their differing functional traits and responses to stress (Elsalahy et al., 2020), and different phenologies and critical growth periods (Teasdale & Cavigelli, 2017). With the DRIVES Project database, we can examine components of vulnerability separately and together and integrate responses for multiple crops in a rotation across weather scenarios in contrasting environments, thus quantifying how crop rotations serve as an adaptation strategy. We plan to use the legacy data to develop a theoretical framework for quantifying inherent vulnerability of crop rotations to adverse weather via a vulnerability index. The vulnerability index for a rotation will be derived from statistical analyses of the occurrence of adverse weather (e.g., drought, extreme heat, and excessive precipitation) during critical growth periods of component crops and the sensitivity of crop yields to adverse weather.

6.2 | Soil health

Diverse cropping systems are a key strategy for preventing or reversing soil degradation that threatens long-term agricultural stability. A meta-analysis conducted by McDaniel et al. (2014) concluded that diverse rotations enhanced soil organic C and N stocks, especially when diverse rotations included a cover crop or took place in regions with higher mean annual precipitation. Stabilization or accrual of soil C promotes soil aggregation and aggregate stability, water storage and availability, and microbially mediated nutrient cycling. All of these soil attributes can enhance crop yields, though positive evidence is limited (Miner et al., 2020; Oldfield et al., 2019). Even without a short-term yield benefit, management practices that promote healthy soils are essential for sustaining long-term agricultural production and reducing "leakiness" of systems that are in a constant flux between nutrient saturation and deficit (Drinkwater & Snapp, 2007). Because soil C accrual and stabilization occur over long time scales (years or decades), long-term experiments are essential for evaluating benefits related to soil health.

The DRIVES Project aims to better understand the interactions between crop rotations, dynamic soil physical/chemical/biological properties, and crop yields. Most DRIVES sites have measured soil organic carbon, and about half have concurrently measured bulk density, although sampling protocols vary considerably. Process-based crop/soil simulation models could help disentangle interacting mechanisms among crops, soil, environment, and management and identify adaptation measures for long-term sustainability. However, current process-based models are incomplete representations of soil C pool transformations and require further improvements (Berardi et al., 2024). Soils data from LTFEs are vital in improving and validating process-based soil models by capturing changes in dynamic soil properties over time (Paustian et al., 1995). DRIVES Project data will be used to improve the abilities of process-based crop and soil models to quantify short- and long-term effects of rotational management on crop yield and soil health in diverse environments.

6.3 | Nutritive value of grains and forages

Global agencies like the United Nations have highlighted that current food systems dominated by few and highly uniform crops are undermining human nutrition (iPES Food, 2016; Kennedy et al., 2017). Increasing diversity of agrifood systems by increasing crop rotation diversity has been proposed to reduce hunger and improve food security and sustainable agricultural production (Altieri, 1999; Bommarco et al., 2013; Frison et al., 2006). However, relatively few studies have connected agricultural production practices to nutritional outcomes in industrialized agricultural systems as compared with subsistence agricultural systems. The DRIVES database provides a platform for evaluating the hypothesis that more diverse crop rotations provide a broader range of consumable macronutrients (protein, fat, and carbohydrate) and micronutrients (vitamins and minerals) at the cost of reduced caloric output compared to less diverse crop rotations. Nutrient content and caloric output can be estimated for each crop using the USDA National Nutrient Database for Standard Reference (Haytowitz et al., 2019) and then combined by rotations to evaluate potential tradeoffs associated with increased rotational diversity.

6.4 | Economic performance

More diverse rotations may have economic benefits due to lower production costs. For example, while lower value crops in more diverse rotations can reduce revenues (Davis et al., 2012; Janovicek et al., 2021; Liebman et al., 2008), increased rotational diversity can also reduce weed pressure and the amount of pesticides required (Fonteyne et al., 2020; Liebman et al., 2008), thereby reducing input costs and environmental impacts. More diverse rotations that include legumes can reduce the amount of synthetic N fertilizer required to maintain cash crop yields (Davis et al., 2012; Liebman et al., 2008). Using the DRIVES database, we plan to quantify impacts of crop rotational diversity on producer economic performance, including production costs. Moreover, more diverse rotations have been shown to reduce the risk of reduced crop yields under poor conditions (Bybee-Finley et al., 2024). Applying this finding to economic impacts of risk management (e.g., participation in futures markets and crop insurance payments) is another area that the DRIVES Project will explore.

7 | FUTURE ASPIRATIONS AND LESSONS LEARNED

7.1 | Expanding the database

Expanding the number of sites and the richness of data will enhance the value of the DRIVES database. Because the DRIVES Project is based in North America, contains LTFEs with industrialized field crop production, and has a research agenda focused on the role of rotational diversity, DRIVES prioritizes sites with these attributes that have at least 10 years of data or data for three rotation cycles. One obvious avenue for expansion would be including more wheat-based long-term experiments located in the Great Plains of the United States, Canada, and northern Mexico that would provide a more robust understanding of the role of rotational diversity in these regions and cropping systems. Any LTFE that meets the inclusion criteria is welcome to participate in the DRIVES Project.

We intend to periodically update the database with additional data from participating sites. Data additions have been manual thus far, which requires a firm understanding of each experiment's layout and careful reformatting of data for synthesis. We plan to develop a data entry template to facilitate data sharing and quality control. A dedicated data manager for a synthesis project like DRIVES is necessary to oversee the iterative process of entering data from multiple sites more efficiently (e.g., communicate desirable data formats and address common problems).

7.2 | Challenges and opportunities of aggregating legacy data

Organizing legacy datasets at this scale is not for the faint-hearted as data from individual sites were not initially designed to be compatible. The task requires strong organizational skills, tenacity, some subject matter expertise, and frequent communication with the primary data collectors. One major challenge of aggregating legacy data is that data collection protocols varied across sites. Some differences have had minimal impact on the data quality, particularly for crop yields. For example, destructive harvests for crop yield data have resulted in comparable values to county averages, regardless of spatial area harvested (e.g., whether samples were collected using a quadrat or a selection of rows in the field). However, synthesis of soil data is more difficult because different protocols lead to incomparable results. For example, soil sampling protocols used by DRIVES researchers involved differing spatial representation, time intervals, and depths. Kladivko et al. (2014) reported that detailed, standardized protocols are essential for comparing data across sites and drawing inferences about soil and cropping system responses to climate across a region. Moving forward, we envision the DRIVES Project co-producing sampling protocols with DRIVES collaborators that meet the needs of individual sites and the network.

Although the DRIVES database provides ample data for synthesis, it has made us aware of the limitations for cross-site analysis. While individual sites have published on topics such as weed management (e.g., Teasdale et al., 2004), disease incidence (e.g., Govaerts et al., 2007), and soil microbial communities (e.g., Castle et al., 2019), the relevant observational data are not widely available across the network. Further exploration of the citation database will likely reveal limited representation from certain disciplines (e.g., pathology, entomology, weed science, and sociology). Investigators from those disciplines who use available DRIVES data may help fill some of these gaps. Identifying such gaps may stimulate new research designed to use similar protocols in multiple DRIVES Network sites.

In conclusion, the DRIVES Project, through its collaborative efforts, has enhanced—and will continue to enhance—our understanding of the multifunctional potential of crop rotational diversity. By combining data from various agricultural LTFE sites, the project helps bridge the gap between ecological theory and agronomic practices. Our work aims to highlight the importance of collecting and analyzing long-term field experiment data. Synthesis of long-term research across sites is essential for understanding the broader effects of multifunctional agricultural practices since effects are often not apparent in shorter time scales or at the spatial scale of a single site. DRIVES' comprehensive database is a clear example of how collaborative research can address key agricultural challenges. Looking forward, the expansion of the DRIVES database will increase its impact, making it an even more valuable tool for future agricultural research.

AUTHOR CONTRIBUTIONS

K. Ann Bybee-Finley: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; visualization; writing—original draft; writing—review and editing. **Katherine E. Muller**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing—original draft; writing—review and editing. **Kathryn E. White**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Timothy M. Bowles**: Conceptualization; funding acquisition; project administration; supervision; writing—original draft; writing—review and editing. **Michel A. Cavigelli**: Conceptualization; data curation; funding acquisition; project administration; resources; supervision; writing—original draft; writing—review and editing. **Eunjin Han**: Conceptualization; writing—original draft; writing—review and editing. **Harry H. Schomberg**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing. **Sieglinde Snapp**: Conceptualization; funding acquisition; resources; supervision. **Frederi Viens**: Conceptualization; funding acquisition; supervision; writing—review and editing.

ACKNOWLEDGMENTS

This work would not have been possible without the efforts of the primary data collectors and managers of long-term field experiments and their staff: Oscar Bañuelos Tavarez, Adrian A. Correndo, Leonardo Deiss, Simon Fonteyne, Axel Garcia y

Garcia, Amélie CM Gaudin, David C. Hooke, Ken Janovicek, Virginia Jin, Gregg Johnson, Heather Karsten, Matt Liebman, Marshall D. McDaniel, Gregg Sanford, Marty R. Schmer, Jeffrey Strock, Virginia R. Sykes, Nele Verhulst, Brook Wilke, and their predecessors.

This research was supported in part by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, grant 2019-67019-29468 Synthesizing Data From A Network Of Long-Term Diversified Cropping System Experiments To Reduce Producer Risk In An Uncertain Climate. Additional funding came from an Agricultural Research Service (ARS) Administrator Funded Post Doctoral Award and ARS base funds.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

K. Ann Bybee-Finley https://orcid.org/0000-0001-5770-3696
Katherine Muller https://orcid.org/0000-0001-9144-3867
Kathryn E. White https://orcid.org/0000-0001-7690-8611
Timothy M. Bowles https://orcid.org/0000-0002-4840-3787
Eunjin Han https://orcid.org/0000-0001-6208-7410
Harry H. Schomberg https://orcid.org/0000-0001-7628-5805
Frederi Viens https://orcid.org/0000-0001-9162-8212

REFERENCES

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. In M. G. Paoletti (Ed.), *Invertebrate biodiversity as bioindicators of sustainable landscapes* (pp. 19–31). Elsevier.

Arnaud, E., Laporte, M.-A., Kim, S., Aubert, C., Leonelli, S., Miro, B., Cooper, L., Jaiswal, P., Kruseman, G., Shrestha, R., Buttigieg, P. L., Mungall, C. J., Pietragalla, J., Agbona, A., Muliro, J., Detras, J., Hualla, V., Rathore, A., Das, R. R., … King, B. (2020). The ontologies community of practice: A CGIAR initiative for big data in agrifood systems. *Patterns*, *1*(7), 100105. https://doi.org/10.1016/j.patter.2020.100105

Ashworth, A. J., Allen, F. L., Saxton, A. M., & Tyler, D. D. (2016). Long-term corn yield impacted by cropping rotations and bio-covers under no-tillage. *Agronomy Journal*, *108*(4), 1495–1502. https://doi.org/10.2134/agronj2015.0453

Ashworth, A. J., Owens, P. R., & Allen, F. L. (2020). Long-term cropping systems management influences soil strength and nutrient cycling. *Geoderma*, *361*, 114062. https://doi.org/10.1016/j.geoderma.2019.114062

Bai, Z., Caspari, T., Gonzalez, M. R., Batjes, N. H., Mäder, P., Bünemann, E. K., de Goede, R., Brussaard, L., Xu, M., Ferreira, C. S. S., Fan, H., Mihelič, R., Glavan, M., & Tóth, Z. (2018). Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. Agriculture. *Ecosystems & Environment*, *265*, 1–7. https://doi.org/10.1016/j.agee.2018.05.028

Baldwin-Kordick, R., De, M., Lopez, M. D., Liebman, M., Lauter, N., Marino, J., & Mcdaniel, M. D. (2022). Comprehensive impacts of diversified cropping on soil health and sustainability. *Agroecology and Sustainable Food Systems*, *46*(3), 331–363. https://doi.org/10.1080/21683565.2021.2019167

Ball, B. C., Bingham, I., Rees, R. M., Watson, C. A., & Litterick, A. (2005). The role of crop rotations in determining soil structure and crop growth conditions. *Canadian Journal of Soil Science*, *85*(5), 557–577. https://doi.org/10.4141/S04-078

Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters*, *14*(12), 123001. https://doi.org/10.1088/1748-9326/ab4449

Bennett, A. J., Bending, G. D., Chandler, D., Hilton, S., & Mills, P. (2012). Meeting the demand for crop production: The challenge of yield decline in crops grown in short rotations. *Biological Reviews*, *87*(1), 52–71. https://doi.org/10.1111/j.1469-185X.2011.00184.x

Berardi, D. M., Hartman, M. D., Brzostek, E. R., Bernacchi, C. J., Delucia, E. H., Von Haden, A. C., Kantola, I., Moore, C. E., Yang, W. H., Hudiburg, T. W., & Parton, W. J. (2024). Microbial-explicit processes and refined perennial plant traits improve modeled ecosystem carbon dynamics. *Geoderma*, *443*, 116851. https://doi.org/10.1016/j.geoderma.2024.116851

Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution*, *28*(4), 230–238. https://doi.org/10.1016/j.tree.2012.10.012

Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., Deen, W., Drury, C. F., Garcia Y Garcia, A., Gaudin, A. C. M., Harkcom, W. S., Lehman, R. M., Osborne, S. L., Robertson, G. P., Salerno, J., Schmer, M. R., Strock, J., & Grandy, A. S (2020). Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth*, *2*(3), 284–293. https://doi.org/10.1016/j.oneear.2020.02.007

Breza, L. C., Mooshammer, M., Bowles, T. M., Jin, V. L., Schmer, M. R., Thompson, B., & Grandy, A. S (2022). Complex crop rotations improve organic nitrogen cycling. *Soil Biology and Biochemistry*, *177*, 108911. https://doi.org/10.1016/j.soilbio.2022.108911

Bryan, J. (2023). *googlesheets4: Access Google Sheets using the Sheets API V4* (Version 1.1.1) [Computer software]. CRAN. https://CRAN.R-project.org/package=googlesheets4

Bybee-Finley, K., & Ryan, M. (2018). Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture*, *8*(6), 80. https://doi.org/10.3390/agriculture8060080

Bybee-Finley, K. A., Muller, K., White, K. E., Cavigelli, M. A., Han, E., Schomberg, H. H., Snapp, S., Viens, F., Correndo, A. A., Deiss, L., Fonteyne, S., Garcia y Garcia, A., Gaudin, A. C. M., Hooker, D. C., Janovicek, K., Jin, V., Johnson, G., Karsten, H., Liebman, M., … Bowles, T. M. (2024). Rotational complexity increases cropping system output under poorer growing conditions. *One Earth*, *7*(9), 1638–1654. https://doi.org/10.1016/j.oneear.2024.07.008

Castellazzi, M. S., Wood, G. A., Burgess, P. J., Morris, J., Conrad, K. F., & Perry, J. N. (2008). A systematic representation of crop rotations. *Agricultural Systems*, *97*(1), 26–33. https://doi.org/10.1016/j.agsy.2007.10.006

Castle, S. C., Samac, D. A., Sadowsky, M. J., Rosen, C. J., Gutknecht, J. L. M., & Kinkel, L. L. (2019). Impacts of sampling design on estimates of microbial community diversity and composition in agricultural soils. *Microbial Ecology*, *78*(3), 753–763. https://doi.org/10.1007/s00248-019-01318-6

Cavigelli, M. A., Teasdale, J. R., & Conklin, A. E. (2008). Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agronomy Journal*, *100*(3), 785–794. https://doi.org/10.2134/agronj2006.0373

Chahal, I., Hooker, D. C., Deen, B., Janovicek, K., & Van Eerd, L. L. (2021). Long-term effects of crop rotation, tillage, and fertilizer nitrogen on soil health indicators and crop productivity in a temperate climate. *Soil and Tillage Research*, *213*, 105121. https://doi.org/10.1016/j.still.2021.105121

Corporation for Digital Scholarship. (2023). *Zotero* [Computer software]. https://www.zotero.org

Csardi, G., Nepusz, T., Traag, V., Szabolcs, H., Zanini, F., Noom, D., Muller, K., Salmon, M., Antonov, M., & Chan Zuckerberg Initiative. (2024). *igraph: Network analysis and visualization in R* (Version 2.0.3) [Computer software]. CRAN. https://CRAN.R-project.org/package=igraph

Dantzer, B., Mabry, K. E., Bernhardt, J. R., Cox, R. M., Francis, C. D., Ghalambor, C. K., Hoke, K. L., Jha, S., Ketterson, E., Levis, N. A., Mccain, K. M., Patricelli, G. L., Paull, S. H., Pinter-Wollman, N., Safran, R. J., Schwartz, T. S., Throop, H. L., Zaman, L., & Martin, L. B. (2023). Understanding organisms using ecological observatory networks. *Integrative Organismal Biology*, *5*(1), obad036. https://doi.org/10.1093/iob/obad036

Davis, A., Hill, J., Chase, C., Johanns, A., & Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS One*, *7*(10), e47149. https://doi.org/10.1371/journal.pone.0047149

de Gorter, H., Drabik, D., & Just, D. R. (2015). Measures of biofuel policy impact on food commodity prices. In *The economics of biofuel policies: Impacts on price volatility in grain and oilseed markets* (pp. 47–66). Palgrave Macmillan.

Dick, W. A., & Van Doren, D. M. (1985). Continuous tillage and rotation combinations effects on corn, soybean, and oat yields. *Agronomy Journal*, *77*(3), 459–465. https://doi.org/10.2134/agronj1985.00021962007700030023x

Donmez, C., Blanchy, G., Svoboda, N., D'hose, T., Hoffmann, C., Hierold, W., & Klumpp, K. (2022). Provision of metadata of European agricultural long-term experiments through BonaRes and EJP SOIL collaboration. *Data in Brief*, *42*, 108226. https://doi.org/10.1016/j.dib.2022.108226

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in agroecosystems: Rethinking the management paradigm. *Advances in Agronomy*, *92*, 163–186.

Elsalahy, H. H., Bellingrath-Kimura, S. D., Roß, C.-L., Kautz, T., & Döring, T. F. (2020). Crop resilience to drought with and without response diversity. *Frontiers in Plant Science*, *11*, Article 721. https://doi.org/10.3389/fpls.2020.00721

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Fonteyne, S., Burgueño, J., Albarrán Contreras, B. A., Andrio Enríquez, E., Castillo Villaseñor, L., Enyanche Velázquez, F., Escobedo Cruz, H., Espidio Balbuena, J., Espinosa Solorio, A., Garcia Meza, P., González Galindo, F., González Regalado, J., Govaerts, B., López Durante, J. D., López Ramírez, A., Martínez Gamiño, M. A., Martínez Hernández, F., Mora Gutiérrez, M., Nieves Navarro, A. I., … Verhulst, N. (2021). Effects of conservation agriculture on physicochemical soil health in 20 maize-based trials in different agro-ecological regions across Mexico. *Land Degradation and Development*, *32*(6), 2242–2256. https://doi.org/10.1002/ldr.3894

Fonteyne, S., Odjo, S., & Verhulst, N. (2023). *Research platforms within CIMMYT's innovation hubs and the Latin American Agronomic Research Network (RedAgAL)*. Zenodo. https://zenodo.org/records/10360260

Fonteyne, S., Singh, R. G., Govaerts, B., & Verhulst, N. (2020). Rotation, mulch and zero tillage reduce weeds in a long-term conservation agriculture trial. *Agronomy*, *10*(7), 962. https://doi.org/10.3390/agronomy10070962

Frison, E. A., Smith, I. F., Johns, T., Cherfas, J., & Eyzaguirre, P. B. (2006). Agricultural biodiversity, nutrition, and health: Making a difference to hunger and nutrition in the developing world. *Food and Nutrition Bulletin*, *27*(2), 167–179. https://doi.org/10.1177/156482650602700208

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D. S., Herzog, C., Romdhane, S., Saghai, A., Spor, A., Wagg, C., Hallin, S., Maestre, F. T., Philippot, L., Rillig, M. C., & Van Der Heijden, M. G. A. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nature Food*, *2*(1), 28–37. https://doi.org/10.1038/s43016-020-00210-8

Gaudin, A. C. M., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One*, *10*(2), e0113261. https://doi.org/10.1371/journal.pone.0113261

Govaerts, B., Fuentes, M., Mezzalama, M., Nicol, J. M., Deckers, J., Etchevers, J. D., Figueroa-Sandoval, B., & Sayre, K. D. (2007). Infiltration, soil moisture, root rot and nematode populations after 12 years of different tillage, residue and crop rotation managements. *Soil and Tillage Research*, *94*(1), 209–219. https://doi.org/10.1016/j.still.2006.07.013

Grosse, M., & Wilfried, H. (2019). *Long-term field experiments in Germany* [Dataset]. BonaRes Repository. https://doi.org/10.20387/BonaRes-3TR6-MG8R

Guinet, M., Adeux, G., Cordeau, S., Courson, E., Nandillon, R., Zhang, Y., & Munier-Jolain, N. (2023). Fostering temporal crop diversification to reduce pesticide use. *Nature Communications*, *14*(1), 7416. https://doi.org/10.1038/s41467-023-43234-x

Haytowitz, D. B., Ahuja, J. K. C., Wu, X., Somanchi, M., Nickle, M., Nguyen, Q. A., Roseland, J. M., Williams, J. R., Patterson, K. Y., Li, Y., & Pehrsson, P. R. (2019). *USDA National Nutrient Database for Standard Reference, Legacy Release* [Dataset]. USDA. https://doi.org/10.15482/USDA.ADC/1529216

Hegewald, H., Wensch-Dorendorf, M., Sieling, K., & Christen, O. (2018). Impacts of break crops and crop rotations on oilseed rape productivity: A review. *European Journal of Agronomy*, *101*, 63–77. https://doi.org/10.1016/j.eja.2018.08.003

Hendrickson, M., James, H., & Heffernan, W. D. (2013). Vertical integration and concentration in US agriculture. In P. B. Thompson & D. M. Kaplan (Eds.), *Encyclopedia of food and agricultural ethics* (pp. 1–10). Springer.

iPES Food. (2016). *From uniformity to diversity: A paradigm shift from industrial agriculture to diversified agroecological systems.*

International Panel of Experts on Sustainable Food Systems. https://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf

Iwaniec, D. M., Gooseff, M., Suding, K. N., Samuel Johnson, D., Reed, D. C., Peters, D. P. C., Adams, B., Barrett, J. E., Bestelmeyer, B. T., Castorani, M. C. N., Cook, E. M., Davidson, M. J., Groffman, P. M., Hanan, N. P., Huenneke, L. F., Johnson, P. T. J., Mcknight, D. M., Miller, R. J., Okin, G. S., … Vivoni, E. R. (2021). Connectivity: Insights from the U.S. Long Term Ecological Research Network. *Ecosphere*, *12*(5), e03432. https://doi.org/10.1002/ecs2.3432

Janovicek, K., Hooker, D., Weersink, A., Vyn, R., & Deen, B. (2021). Corn and soybean yields and returns are greater in rotations with wheat. *Agronomy Journal*, *113*(2), 1691–1711. https://doi.org/10.1002/agj2.20605

Kennedy, G., Hunter, D., Garrett, J., & Padulosi, S. (2017). *Leveraging agrobiodiversity to create sustainable food systems for healthier diets*. UNSCN News. https://cgspace.cgiar.org/handle/10568/89400

King, A. E., & Blesh, J. (2018). Crop rotations for increased soil carbon: Perenniality as a guiding principle. *Ecological Applications*, *28*, 249–261. https://doi.org/10.1002/eap.1648

Kladivko, E. J., Helmers, M. J., Abendroth, L. J., Herzmann, D., Lal, R., Castellano, M. J., Mueller, D. S., Sawyer, J. E., Anex, R. P., Arritt, R. W., Basso, B., Bonta, J. V., Bowling, L. C., Cruse, R. M., Fausey, N. R., Frankenberger, J. R., Gassman, P. W., Gassmann, A. J., Kling, C. L., … Villamil, M. B. (2014). Standardized research protocols enable transdisciplinary research of climate variation impacts in corn production systems. *Journal of Soil and Water Conservation*, *69*(6), 532–542. https://doi.org/10.2489/jswc.69.6.532

Kleinman, P. J. A., Spiegal, S., Rigby, J. R., Goslee, S. C., Baker, J. M., Bestelmeyer, B. T., Boughton, R. K., Bryant, R. B., Cavigelli, M. A., Derner, J. D., Duncan, E. W., Goodrich, D. C., Huggins, D. R., King, K. W., Liebig, M. A., Locke, M. A., Mirsky, S. B., Moglen, G. E., Moorman, T. B., … Walthall, C. L. (2018). Advancing the sustainability of US agriculture through long-term research. *Journal of Environmental Quality*, *47*(6), 1412–1425. https://doi.org/10.2134/jeq2018.05.0171

Knapp, A. K., Smith, M. D., Hobbie, S. E., Collins, S. L., Fahey, T. J., Hansen, G. J. A., Landis, D. A., La Pierre, K. J., Melillo, J. M., Seastedt, T. R., Shaver, G. R., & Webster, J. R. (2012). Past, present, and future roles of long-term experiments in the LTER Network. *Bioscience*, *62*(4), 377–389. https://doi.org/10.1525/bio.2012.62.4.9

Krupek, F. S., Redfearn, D., Eskridge, K. M., & Basche, A. (2022). Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. *Geoderma*, *409*, 115594. https://doi.org/10.1016/j.geoderma.2021.115594

Lal, R., Mahboubi, A. A., & Fausey, N. R. (1994). Long-term tillage and rotation effects on properties of a central Ohio soil. *Soil Science Society of America Journal*, *58*(2), 517–522. https://doi.org/10.2136/sssaj1994.03615995005800020038x

Liebman, M., Gibson, L. R., Sundberg, D. N., Heggenstaller, A. H., Westerman, P. R., Chase, C. A., Hartzler, R. G., Menalled, F. D., Davis, A. S., & Dixon, P. M. (2008). Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the central Corn Belt. *Agronomy Journal*, *100*(3), 600–610. https://doi.org/10.2134/agronj2007.0222

Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. *Bioscience*, *61*(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4

Lisboa, C. C., Storkey, J., Cerri, C. E. P., Thierfelder, C., Quincke, J. A., Chivenge, P., & Snapp, S. (2020, May 4–8). *The global long-term agricultural experiment network* [Conference preentation]. EGU General Assembly 2020, Online. https://meetingorganizer.copernicus.org/EGU2020/EGU2020-7283.html

Maclaren, C., Mead, A., Van Balen, D., Claessens, L., Etana, A., De Haan, J., Haagsma, W., Jäck, O., Keller, T., Labuschagne, J., Myrbeck, Å., Necpalova, M., Nziguheba, G., Six, J., Strauss, J., Swanepoel, P. A., Thierfelder, C., Topp, C., Tshuma, F., … Storkey, J. (2022). Long-term evidence for ecological intensification as a pathway to sustainable agriculture. *Nature Sustainability*, *5*, 770–779. https://doi.org/10.1038/s41893-022-00911-x

Marini, L., St-Martin, A., Vico, G., Baldoni, G., Berti, A., Blecharczyk, A., Malecka-Jankowiak, I., Morari, F., Sawinska, Z., & Bommarco, R. (2020). Crop rotations sustain cereal yields under a changing climate. *Environmental Research Letters*, *15*(12), 124011. https://doi.org/10.1088/1748-9326/abc651

McDaniel, M. D., & Grandy, A. S. (2016). Soil microbial biomass and function are altered by 12 years of crop rotation. *Soilless*, *2*(4), 583–599. https://doi.org/10.5194/soil-2-583-2016

McDaniel, M. D., Tiemann, L. K., & Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, *24*(3), 560–570. https://doi.org/10.1890/13-0616.1

Miner, G. L., Delgado, J. A., Ippolito, J. A., & Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agricultural & Environmental Letters*, *5*(1), e20023. https://doi.org/10.1002/ael2.20023

Mooshammer, M., Grandy, A. S., Calderón, F., Culman, S., Deen, B., Drijber, R. A., Dunfield, K., Jin, V. L., Lehman, R. M., Osborne, S. L., Schmer, M., & Bowles, T. M. (2022). Microbial feedbacks on soil organic matter dynamics underlying the legacy effect of diversified cropping systems. *Soil Biology and Biochemistry*, *167*, 108584. https://doi.org/10.1016/j.soilbio.2022.108584

Necpálová, M., Anex, R. P., Kravchenko, A. N., Abendroth, L. J., Del Grosso, S. J., Dick, W. A., Helmers, M. J., Herzmann, D., Lauer, J. G., Nafziger, E. D., Sawyer, J. E., Scharf, P. C., Strock, J. S., & Villamil, M. B. (2014). What does it take to detect a change in soil carbon stock? A regional comparison of minimum detectable difference and experiment duration in the north central United States. *Journal of Soil and Water Conservation*, *69*(6), 517–531. https://doi.org/10.2489/jswc.69.6.517

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *Soilless*, *5*(1), 15–32. https://doi.org/10.5194/soil-5-15-2019

Paustian, K., Elliott, E. T., Collins, H. P., Cole, C. V., & Paul, E. A. (1995). Use of a network of long-term experiments for analysis of soil carbon dynamics and global change: The North American model. *Australian Journal of Experimental Research*, *35*(7), 929–939. https://doi.org/10.1071/ea9950929

Paut, R., Sabatier, R., & Tchamitchian, M. (2020). Modelling crop diversification and association effects in agricultural systems. *Agriculture, Ecosystems & Environment*, *288*, 106711. https://doi.org/10.1016/j.agee.2019.106711

Petersen-Rockney, M., Baur, P., Guzman, A., Bender, S. F., Calo, A., Castillo, F., De Master, K., Dumont, A., Esquivel, K., Kremen, C., Lachance, J., Mooshammer, M., Ory, J., Price, M. J., Socolar, Y., Stanley, P., Iles, A., & Bowles, T. (2021). Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Frontiers in Sustainble Food Systems*, *5*, Article 564900. https://doi.org/10.3389/fsufs.2021.564900

Picasso, V. D., Brummer, E. C., Liebman, M., Dixon, P. M., & Wilsey, B. J. (2011). Diverse perennial crop mixtures sustain higher productivity over time based on ecological complementarity. *Renewable Agriculture and Food Systems*, *26*(4), 317–327. https://doi.org/10.1017/S1742170511000135

Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., Van Gestel, N., Six, J., Venterea, R. T., & Van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*(7534), 365–368. https://doi.org/10.1038/nature13809

Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., Van Gestel, N., Six, J., Venterea, R. T., & Van Kessel, C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, *183*, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020

Plastina, A., Liu, F., Miguez, F., & Carlson, S. (2020). Cover crops use in Midwestern US agriculture: Perceived benefits and net returns. *Renewable Agriculture and Food Systems*, *35*(1), 38–48. https://doi.org/10.1017/S1742170518000194

Posner, J. L., Baldock, J. O., & Hedtcke, J. L. (2008). Organic and conventional production systems in the Wisconsin Integrated Cropping Systems Trials: I. Productivity 1990–2002. *Agronomy Journal*, *100*(2), 253–260. https://doi.org/10.2134/agronj2007.0058

Potter, T. S., Vereecke, L., Lankau, R. A., Sanford, G. R., Silva, E. M., & Ruark, M. D. (2022). Long-term management drives divergence in soil microbial biomass, richness, and composition among upper Midwest, USA cropping systems. *Agriculture, Ecosystems & Environment*, *325*, 107718. https://doi.org/10.1016/j.agee.2021.107718

Qiu, J., Carpenter, S. R., Booth, E. G., Motew, M., & Kucharik, C. J. (2020). Spatial and temporal variability of future ecosystem services in an agricultural landscape. *Landscape Ecology*, *35*(11), 2569–2586. https://doi.org/10.1007/s10980-020-01045-1

Reckling, M., Ahrends, H., Chen, T.-W., Eugster, W., Hadasch, S., Knapp, S., Laidig, F., Linstädter, A., Macholdt, J., Piepho, H.-P., Schiffers, K., & Döring, T. F. (2021). Methods of yield stability analysis in long-term field experiments. A review. Agronomy for. *Sustainable Development*, *41*(2), Article 27. https://doi.org/10.1007/s13593-021-00681-4

Robertson, G. P., Allen, V. G., Boody, G., Boose, E. R., Creamer, N. G., Drinkwater, L. E., Gosz, J. R., Lynch, L., Havlin, J. L., Jackson, L. E., Pickett, S. T. A., Pitelka, L., Randall, A., Reed, A. S., Seastedt, T. R., Waide, R. B., & Wall, D. H. (2008). Long-term agricultural research: A research, education, and extension imperative. *Bioscience*, *58*(7), 640–645. https://doi.org/10.1641/B580711

Rubel, F., Brugger, K., Haslinger, K., & Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorologische Zeitschrift*, *26*, 115–125. https://doi.org/10.1127/metz/2016/0816

Rusch, A., Bommarco, R., Jonsson, M., Smith, H. G., & Ekbom, B. (2013). Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. *Journal of Applied Ecology*, *50*(2), 345–354. https://doi.org/10.1111/1365-2664.12055

Sanford, G. R., Jackson, R. D., Booth, E. G., Hedtcke, J. L., & Picasso, V. (2021). Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. *Field Crops Research*, *263*, 108071. https://doi.org/10.1016/j.fcr.2021.108071

Schrumpf, M., Schulze, E. D., Kaiser, K., & Schumacher, J. (2011). How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences*, *8*(5), 1193–1212. https://doi.org/10.5194/bg-8-1193-2011

Sindelar, A. J., Schmer, M. R., Jin, V. L., Wienhold, B. J., & Varvel, G. E. (2016). Crop rotation affects corn, grain sorghum, and soybean yields and nitrogen recovery. *Agronomy Journal*, *108*(4), 1592–1602. https://doi.org/10.2134/agronj2016.01.0005

Smith, A., & Stirling, A. (2010). The politics of social-ecological resilience and sustainable socio-technical transitions. *Ecology and Society*, *15*(1), 11. https://www.jstor.org/stable/26268112

Smith, M. E., Vico, G., Costa, A., Bowles, T., Gaudin, A. C. M., Hallin, S., Watson, C. A., Alarcòn, R., Berti, A., Blecharczyk, A., Calderon, F. J., Culman, S., Deen, W., Drury, C. F., Garcia, A. G. Y., García-Díaz, A., Plaza, E. H., Jonczyk, K., Jäck, O., … Bommarco, R. (2023). Increasing crop rotational diversity can enhance cereal yields. *Communications Earth & Environment*, *4*(1), Article 89. https://doi.org/10.1038/s43247-023-00746-0

Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., Van Egmond, F., Mcneill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219–241. https://doi.org/10.1111/gcb.14815

Snapp, S. S. (2016). *Living Field Laboratory at the Kellogg Biological Station, Hickory Corners, MI (1992 to 2012) ver 24* [Dataset]. EDI Data Portal. https://doi.org/10.6073/pasta/76c22606a2a67cbca8f33149d3b5dfb6

Snapp, S. S., Gentry, L. E., & Harwood, R. (2010). Management intensity–not biodiversity–the driver of ecosystem services in a long-term row crop experiment. Agriculture. *Ecosystems & Environment*, *138*(3), 242–248. https://doi.org/10.1016/j.agee.2010.05.005

Snyder, E. M., Curran, W. S., Karsten, H. D., Malcolm, G. M., Duiker, S. W., & Hyde, J. A. (2016). Assessment of an integrated weed management system in no-till soybean and corn. *Weed Science*, *64*(4), 712–726. https://doi.org/10.1614/WS-D-16-00021.1

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van Der Heijden, M. G. A., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, *6*(45), eaba1715. https://doi.org/10.1126/sciadv.aba1715

Teasdale, J. R., & Cavigelli, M. A. (2017). Meteorological fluctuations define long-term crop yield patterns in conventional and organic production systems. *Scientific Reports*, *7*(1), Article 688. https://doi.org/10.1038/s41598-017-00775-8

Teasdale, J. R., Mangum, R. W., Radhakrishnan, J., & Cavigelli, M. A. (2004). Weed seedbank dynamics in three organic farming crop rotations. *Agronomy Journal*, *96*(5), 1429–1435. https://doi.org/10.2134/agronj2004.1429

Tiemann, L. K., Grandy, A. S., Atkinson, E. E., Marin-Spiotta, E., & Mcdaniel, M. D. (2015). Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecology Letters*, *18*(8), 761–771. https://doi.org/10.1111/ele.12453

Tomer, M. D., & Burkart, M. R. (2003). Long-term effects of nitrogen fertilizer use on ground water nitrate in two small watersheds. *Journal of Environmental Quality*, *32*(6), 2158–2171. https://doi.org/10.2134/jeq2003.2158

Tomer, M. D., & Liebman, M. (2014). Nutrients in soil water under three rotational cropping systems, Iowa, USA. *Agriculture, Ecosystems & Environment*, *186*, 105–114. https://doi.org/10.1016/j.agee.2014.01.025

U.S. Federal Government. (2021). *U.S. climate resilience toolkit*. http://toolkit.climate.gov/

Urruty, N., Tailliez-Lefebvre, D., & Huyghe, C. (2016). Stability, robustness, vulnerability and resilience of agricultural systems. A review. *Agronomy for Sustainable Development*, *36*(1), Article 15. https://doi.org/10.1007/s13593-015-0347-5

Vendig, I., Guzman, A., De La Cerda, G., Esquivel, K., Mayer, A. C., Ponisio, L., & Bowles, T. M. (2023). Quantifying direct yield benefits of soil carbon increases from cover cropping. *Nature Sustainability*, *6*, 1125–1134. https://doi.org/10.1038/s41893-023-01131-7

Venter, Z. S., Jacobs, K., & Hawkins, H.-J. (2016). The impact of crop rotation on soil microbial diversity: A meta-analysis. *Pedobiologia*, *59*(4), 215–223. https://doi.org/10.1016/j.pedobi.2016.04.001

Walbridge, M. R., & Shafer, S. R. (2011, September 26–30). *A Long-Term Agro-Ecosystem Research (LTAR) network for agriculture* [Conference presentation]. The Fourth Interagency Conference on Research in the Watersheds, Fairbanks, AK, United States.

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. *Soil Science Society of America Journal*, *66*(6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930

Wilhelm, W. W., & Wortmann, C. S. (2004). Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. *Agronomy Journal*, *96*(2), 425–432. https://doi.org/10.2134/agronj2004.4250

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 160018. https://doi.org/10.1038/sdata.2016.18

Wolf, K. M., Torbert, E. E., Bryant, D., Burger, M., Denison, R. F., Herrera, I., Hopmans, J., Horwath, W., Kaffka, S., Kong, A. Y. Y., Norris, R. F., Six, J., Tomich, T. P., & Scow, K. M. (2018). The century experiment: The first twenty years of UC Davis' Mediterranean agroecological experiment. *Ecology*, *99*(2), 503. https://doi.org/10.1002/ecy.2105

Zhao, B.-Q., Li, X.-Y., Li, X.-P., Shi, X.-J., Huang, S.-M., Wang, B.-R., Zhu, P., Yang, X.-Y., Liu, H., Chen, Y. I., Poulton, P., Powlson, D., Todd, A., & Payne, R. (2010). Long-term fertilizer experiment network in China: Crop yields and soil nutrient trends. *Agronomy Journal*, *102*(1), 216–230. https://doi.org/10.2134/agronj2009.0182

Zhou, W., Guan, K., Peng, B., Shi, J., Jiang, C., Wardlow, B., Pan, M., Kimball, J. S., Franz, T. E., Gentine, P., He, M., & Zhang, J. (2020). Connections between the hydrological cycle and crop yield in the rainfed U.S. Corn Belt. *Journal of Hydrology*, *590*(August), 125398. https://doi.org/10.1016/j.jhydrol.2020.125398

SUPPORTING INFORMATION

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

How to cite this article: Bybee-Finley, K. A., Muller, K., White, K. E., Bowles, T. M., Cavigelli, M. A., Han, E., Schomberg, H. H., Snapp, S., & Viens, F. (2024). Deriving general principles of agroecosystem multifunctionality with the Diverse Rotations Improve Valuable Ecosystem Services (DRIVES) network. *Agronomy Journal*, *116*, 2934–2951. https://doi.org/10.1002/agj2.21697