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Comparing cover crop research in farmer-led and researcher-led experiments in the Western Corn Belt

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Cover crops can mitigate soil degradation and nutrient loss and can be used to achieve continuous living cover in cropping systems, although their adoption in the Western Corn Belt of the United States remains low. It is increasingly recognized that cover crop integration into corn (*Zea mays* L.)-based crop rotations is complex, requiring site and operation specific management. In this review, we compared on-farm, farmer-led field scale trials to researcher-led trials carried out in small plots on University of Nebraska-Lincoln experiment stations. Although there is a range of cover crop research conducted in the state, there is no synthesis of the scope and key results of such efforts. Common cover crop challenges and goals in the state are similar to those reported nationwide; challenges include adequate planting timing, associated costs, and weather, while a top goal of cover crop use is to improve soil health. Farmer-led trials most frequently compared a cover crop to a no-cover crop control, likely reflecting a desire to test a basic design determining site-specific performance. Both researcher-led and farmer-led trials included designs testing cash crop planting timing, while some portion of farmer-led trials tested cover crop seeding rates, which are directly related to reported cover crop challenges. Farmer-led trials were carried out on a greater variety of soils, including sandy soils, whereas sandy soils were absent from researcher-led trials. More than half of farmer-led experiments were conducted on fields with slopes of 6–17% while most researcher-led experiments were conducted on fields with slopes of <1%. Mean cover crop biomass production was 600 kg/ha in farmer-led and 2,000 kg/ha in researcher-led trials. Crop yields were not significantly affected by cover crops in either farmer-led or researcher-led trials. Such comparisons demonstrate that in some instances, cover crop research is addressing challenges, and in some instances, it could be expanded. This synthesis expands our knowledge base in a way that can promote co-learning between different scales of experiments, and ultimately, reduce risks associated with cover crop management and further promote continuous living cover of agricultural landscapes.

KEYWORDS

field scale, experiment station, small plots, cover crops, cereal rye, mix cover crop

1. Introduction

Replacing fallow periods with a cover crop is one strategy toward continual living cover of the soil garnering significant recent attention, including investment from government and private-industry initiatives (Basche et al., 2020; Wallander et al., 2021) as well as expansive on-farm research initiatives (Bowman et al., 2022; Practical Farmers of Iowa, 2022). Cover crop research finds that replacing fallow periods improves a wide range of soil health and agronomic indicators, even after just a few years, including quantifiable increases to properties such as aggregation, infiltration, as well as reduced erosion, runoff, weed biomass, and enhanced nutrient cycling (Stewart et al., 2018; Nichols et al., 2020). However, cover crops are still only grown on approximately 3–4% of the cropland acres across leading commodity crop producing states such as Iowa, Illinois, and Nebraska (USDA-NASS, 2017). Researchers investigating the lack of adoption have focused on perceived biological, technical, or economic barriers to cover crops (Arbuckle and Roesch-McNally, 2015; Roesch-McNally et al., 2018). Successful adopters of cover crops often describe a more systems-based approach to soil health and crop management in general that accounts for other functions such as weed suppression, forage production and soil fertility (Church et al., 2020). However, success with cover crops also requires intentional shifts in multiple elements of cash crop management to optimize their benefits (Basche and Roesch-McNally, 2017). Overall, effective integration of cover crops is complex, requiring site and operation-specific adaptations.

The state of Nebraska, located in the Western Corn Belt and in the Northern Great Plains, is an especially useful region to understand cover crop use and adoption. The state contains climatic diversity from humid or semi-humid conditions in the southeast (approximately 850 mm annual rainfall) to semi-arid conditions in the west (approximately 400 mm annual rainfall), which is also represented in its commodities and cropping systems (Zomer et al., 2008; HPRCC, 2022). Nebraska is a top producing state for several major commodities in the United States including corn (*Zea mays* L.), soybean [Glycine max (L.) Merr.], cattle, and contains significant crop acreage for wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa L.*), and sorghum [*Sorghum bicolor* (L.) Moench] (USDA-NASS, 2021). The state also has more irrigated cropland acres than any other in the U.S. and irrigation is utilized on approximately one-third of harvested acreage (USDA-NASS, 2017). The propensity to livestock in Nebraska, the range of cropping systems and climatic regions, as well as its significant acreage utilizing irrigation suggests that many different agricultural regions of the U.S. might draw parallels from the cover crop research conducted in the state. Notably, a recent survey of producers, consultants, and agricultural researchers found that the three greatest challenges to cover crop adoption in the state of Nebraska are (1) the short window of time between cash crop harvest and cover crop planting; (2) input costs including the cost of cover crop seeding; and (3) weather issues (Das et al., 2022). Similar challenges have been reported by other Nebraska producers (Oliveira et al., 2019) and nationwide (Myers and Watts, 2015).

Decision-making processes in agriculture are not only based on biological and economic factors, but also social, cultural, relational, and value-driven influences (Prokopy et al., 2008, 2019; Carlisle, 2016). The transfer of knowledge and innovative practices is enhanced in learning environments that provide in-group communication, community support and trusting relationships (Wick et al., 2019; Charatsari et al., 2020). A unique form of such learning environments are on-farm trials, where organizations with research capacity and expertise, including non-profit organizations or Land Grant Universities (i.e., extension educators or university researchers) collaborate with farmers to address specific research questions on the farmer's land. Recently, global networks of on-farm research practitioners have recognized the transformative value of this model of research and outreach to merge experiences, drive innovation, advance technology adoption, while improving profitability and environmental stewardship (Lacoste et al., 2022).

In Nebraska, an on-farm research program organized by the University of Nebraska Extension began in 1990 with a group of farmers in Eastern Nebraska and expanded in the early 2010s to include state-wide trials (Thompson et al., 2019). Trials are co-developed by farmers, University extension educators or researchers and sometimes other stakeholders such as Natural Resource Districts; and are motivated by a shared goal to address a specific research question. They are farmer-led in the sense that farmers manage the trials using their own equipment in large plots in their fields. In contrast, agronomic trials led by researchers at the University of Nebraska-Lincoln's agricultural experiment stations typically have small plots and do not involve producers, however they may also be informed by stakeholder involvement.

Producers often view small plot studies as less reliable than large scale or on-farm studies because they perceive small plot studies to be less representative on actual farm operations (Laurent et al., 2022). In contrast, interviews with participants in Nebraska's on-farm research program found that most trusted the results from their own studies and more than 50% of producers had made changes in their operation due to the study results (Thompson et al., 2019). However, most on-farm study findings from Nebraska have not been published, except at the local level. Making this information available to regional and national audiences could support knowledge sharing with the potential to increase adoption of cover crops. Including findings from on-farm or farmer-led studies in the scientific literature could also lead to a more comprehensive, nuanced view of cover crops than relying on researcher-led studies alone. For example, insight into which cover crop practices have been tested on farms could provide information for researchers to either further test promising practices or test alternatives. Additionally, evaluating the breadth of research in Nebraska, both farmer-led and researcher-led, can help determine how adequate ongoing research efforts are to address cover crop related challenges in the state across a range of climate conditions and cropping systems.

The objectives for our study were to compare farmer-led and researcher-led cover crop experiments from Nebraska, to identify similarities and differences in treatments evaluated, environments assessed as well as cover crop outcomes. We selected two outcomes, cover crop biomass and cash crop yield, as these are widely used indicators for agronomic performance and reported in most studies. This information can support addressing farmers' needs, informing objectives for future studies, and promoting conservation practices that seek to increase continuous living cover in annual crop rotations. The unique, coordinated, and extensive database for on-farm research and reporting *via* the On-Farm Research Network lends itself well to a comparison with researcher-led trials. With this analysis we wanted to address the following research questions: (1) How do farmer-led and researcher-led cover crop experiments compare in terms of treatments evaluated and environments assessed? (2) How do farmer-led and researcher-led cover crop experiments compare in terms of management and outcomes such as cover crop biomass and yield impacts? In answering these questions, our work fills an important knowledge gap of strategically comparing researcher-led and farmer-led cover crop research to build a knowledge base that potentially reduces risks associated with cover crops and ultimately supports continuous living cover systems at a broader scale.

2. Methods and materials

2.1. Trial compilation

We built our database from two primary sources: The Nebraska On-Farm Research Network for farmer-led experiments and Web of Science for the researcher-led experiments in the state of Nebraska. The Nebraska On-Farm Research Network is the University of Nebraska Extension's on-farm research program (Nebraska On-Farm Research Network, 2022a,b). The program was initiated in 1990 with a group of farmers in Eastern Nebraska and has since expanded across the state. The on-farm trials are initiated either by farmers, researchers, and/or other stakeholders, or typically some combination thereof. Experiments are implemented on farmer's fields using their equipment and labor. University extension educators and researchers assist with trial design, data collection and data analysis (Thompson et al., 2019). Treatments in these trials reflect what farmers want to compare which does not always include a control or check plot, however, in some cases participating researchers may suggest or select treatments. The experimental design in these studies is randomized complete blocks with at least 3 replications or paired comparison designs with at least 5 replications. The plots are usually large, at least the width of the harvest equipment (often around 12 m) and are at least 100-m long to obtain an accurate estimate from the combine yield monitor. The large plot size sets them apart from the small plot studies found at experimental stations, which typically measure 6 × 10 m. Management information and experiment data are gathered from the farmers or university personnel collaborating with the farmers. Researchers or extension educators working with the On-Farm Research Network carry out the statistical analysis and write an annual report. The current On-Farm Research Network database (https://on-farm-research.unl.edu/farm-research-results) includes annual reports detailing experimental design, site and management information, measurements, statistical analysis, and results. Yield results are always included in on-farm reports, but often no other data are measured.

We carried out our search of the Nebraska On-Farm Research Network in March of 2022. To capture all types of cover crops, including green manures, we used the keywords of "cover crop", "green manure", and "catch crop". The latter two key words did not return any entries. The key words "cover crop" resulted in 96 entries, each representing 1 year of a study at one site (field), with study years ranging from 2004 to 2020. From these 96 entries, we selected only studies that had a report and where the cover crop was grown in the same or the year before data was reported. We excluded 19 studies because they did not contain a cover crop and a no-cover crop control (check) treatment as an important goal of this work was to compare yield outcomes which could not be done for experiments without check treatments. Since many trials had more than two treatment comparisons (i.e. cover crop A vs. no cover crop; cover crop B vs. no-cover crop) a total of 89 site-year by treatment comparisons were included in the analysis.

We searched Web of Science for researcher-led, peer-reviewed publications, using the topic "cover crop*" *and* 1990–2020 (year published) *and* University of Nebraska Lincoln (affiliation). This returned 114 results, including studies that investigated green manures. To access publications by researchers affiliated with USDA-ARS, a second search with the topic "cover crop*" *and* 1990–2020 (year published) *and* United States Department of Agriculture (USDA) (affiliation) *and* Nebraska (all fields) was carried out, with 44 results, some of which were also returned in the first search. From these two searches, we selected publications reporting field trials in Nebraska (modeling studies or literature reviews were excluded), had replicated and randomized designs, compared the cover crop treatment(s) to a control (no cover crop) treatment, and reported cash crop grain yield and cover crop biomass data. Based on these selection criteria, nine studies were included in the analysis and can be found in Table 1. Although one of these experiments was conducted on a commercial farm, we considered these experiments to be primarily led by researchers given their inclusion in the peer-reviewed literature, although it is possible their designs were informed through partnership with farmers. The researcher-led studies included at least two sites and 2 years per site and often compared several cover crop treatments to a no-cover crop treatment. Thus, the researcher-led studies represent 290 individual site-year by treatment comparisons.

2.2. Database development

We categorized experiments based on their treatments (i.e., comparisons of cover crop species or termination methods) and management (i.e., crop rotations, cover crop species). We categorized crop rotations into the following groups: corn-soybean (where the cover crop is planted following a corn crop and the soybean is planted following the cover crop), continuous corn, small grains such as wheat or rye (*Secale cereale* L.) in rotation (uniquely counted even if rotation included corn or soybean), or other cash crops. We grouped cover crops by plant family including grasses, legumes, brassicas, or mixtures (any cover crop with more than one species present). We further extracted site-specific information on environments such as soils, field topography (slope), location and irrigation (yes/no). Locations were categorized according to the nine NOAA Climate Divisions within the state (NOAA, 2022).

To determine experimental outcomes, we extracted the cash crop yield and cover crop biomass data for each site-year. In

TABLE 1 List of researcher-led, peer-reviewed publications included in the database.

References	Crop rotation including cover crop species
Blanco-Canqui et al. (2017)	Continuous corn, cereal rye winter cover crop*
Kessavalou and Walters (1999)	Corn-soybean, Continuous corn, cereal rye winter cover crop
Koehler-Cole et al. (2017)	Soybean-winter wheat-corn, spring planted red and white clover cover crops
Koehler-Cole et al. (2020)	Corn-soybean, cereal rye winter cover crop and mixture cover crop of cereal rye, forage radish, hairy vetch, and winter pea
Nielsen et al. (2016)	Proso millet, spring cover crop of flax, oat, pea, rapeseed or mixture, winter wheat
Power et al. (1991)	Continuous corn, hairy vetch winter cover crop
Ruis et al. (2017)	Continuous corn, cereal rye winter cover crop
Williams et al. (2000)	Corn silage-soybean; barley, cereal rye, winter wheat, winter triticale, hairy vetch winter cover crops
Wortman et al. (2012)	Sunflower-soybean-corn; two-, four-, six-, eight-way mixture of spring planted cover crops including hairy vetch, buckwheat, mustards, field pea, radish, crimson clover, rape and chickling vetch

*Experiment conducted at on-farm location.

researcher-led trials, corn yield data was determined using plot combines that harvested the central two or three rows of each plot. In on-farm studies, plot yield is determined using a yield monitor on a full-size combine or a weigh wagon (Thompson, 2022, personal communication). Yields were adjusted to 15.5% moisture for corn, 13% moisture for soybean, and 13.5% moisture for wheat or rye. All researcher-led studies included cover crop biomass measurements compared to approximately half of the farmer-led experiments. Cover crop biomass in researcher-led trials was measured by cutting above-ground biomass in a known area, often a 0.3 × 1.5 m frame, drying the biomass in a forced air oven, and weighing the dried biomass. In farmer-led trials biomass was collected in a similar way, although it may have been air-dried instead of oven-dried. Biomass data was converted to kg/ha. We do not report other data collected from these experiments (such as soil health measurements) because such data were very limited, and the focus of our analysis was on comparing treatments, site-specific conditions, management, as well as yield and biomass outcomes between researcher-led and farmer-led trials.

Variables could have one or multiple observations, for example in farmer-led trials, the variable "location" had only one observation per study, but each researcher-led study could have two or more locations. We counted observations and presented them as percent totals for both farmer-led and researcher-led experiments. Where multiple observations or no information was included (such as two soil types at one location, or no soil type or slope given), the percent total represents the total number of sites or observations reporting information. Not all experiments could be categorized for all information due to incomplete data reporting.

2.3. Statistical analysis of cash crop impacts

To evaluate the effect of cover crops on cash crop yields in both types of experiments, we calculated response ratios for each site-experiment year that included yield information. The response ratio represents the natural log of the yield of the cash crop following a cover crop divided by the yield of the cash crop in the control treatment, a common metric utilized to compare results from different studies (Hedges et al., 1999). To calculate cover crop yield effects across experiments, we considered the effect of location as a random variable to account for similarities in each environment (St. Pierre, 2001). Studies were weighted by the number of experimental replications in the statistical model (Adams et al., 1997). Yield changes were back-transformed from the natural log and converted to percent changes to aid in interpretation of results.

3. Results and discussion

3.1. Treatments evaluated

A range of treatments were included in both the farmer-led and researcher-led experiments, from which we can infer goals of the trials (Figure 1). The most common treatment included in the researcher-led experiments was cover crop species comparisons (31%), while the most common treatment for the farmer-led experiments was cover crop compared to a no cover crop control (29%). Farmer-led experiments also compared cover crop species, but to a lesser extent (16%). Both types of experiments included trials evaluating cash crop planting timing and planting rates. Farmer-led experiments involved a diverse range of treatments, which included grazing (6%), cover crop seeding rates (12%), and interseeding cover crops (12%) (Figure 1). Researcher-led experiments included a divergent range of treatments evaluated, including tillage (6%), N rates (6%), irrigation (13%), and residue removal (13%), none of which were explicitly a part of any on-farm experiments in our database. Treatments evaluating irrigation, residue removal or tillage, for example, may not be as practical to conduct at the scale of a commercial farm as they might be on a smaller experiment scale.

The survey and interview work in the state provides insight into producer challenges and goals related to cover crops which can inform how well cover crop research is designed to address such goals and challenges. Important cover crop challenges reported in Nebraska were the short window of time for cover crop growth, cover crop input costs, and weather issues (Oliveira et al., 2019; Das et al., 2022). Both researcher-led and farmer-led trials included designs testing cash crop planting timing, while some farmer-led

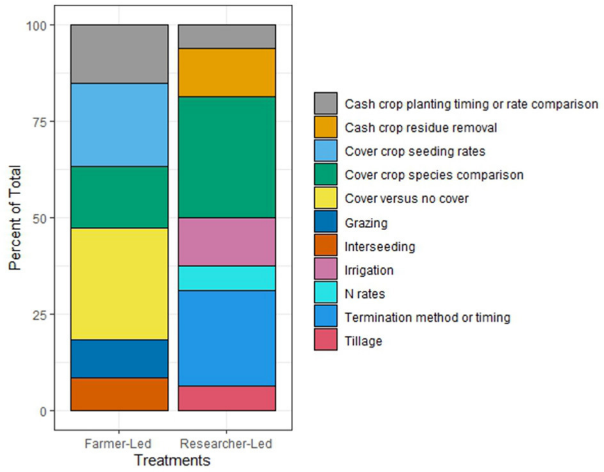

FIGURE 1
Experimental treatments used in farmer-led ($n = 89$) and researcher-led trials ($n = 290$). The bar graph shows the percentage of studies or observations that used a certain treatment out of the total number of studies.

trials tested cover crop seeding rates, which are directly related to these challenges.

Treatments focused on comparing cover crops vs. controls, as well as seeding rates, were included at higher percentages in on-farm experiments and could reflect the commonly cited goal of increasing efficiency and reducing costs for farmers participating in trials (Thompson et al., 2019). Managing input costs may have been the justification for seeding rate studies, while weather issues, in particular cold winters, are likely the rationale for interseeding, cover crop species comparisons as well as cash crop planting timing experiments. In general, however, we might assume that the large portion of farmer-led trials testing cover crop vs. no cover crop comparison are aimed at a central goal of determining cover crop performance on their specific farms.

3.2. Crop rotations including cover crops

The predominant cropping system for the farmer-led experiments was corn-soybean (77%), while researcher-led experiments were balanced between continuous corn and corn-soybean cropping systems (33% each) (Figure 2). Small grain crops such as wheat were included in both types of experiments (17% of researcher-led and 14% of farmer-led experiments), as were other cash crops including alfalfa, sunflower (*Helianthus annus L.*), and proso millet (*Panicum miliaceum*) (17% of researcher-led and 4% of farmer-led). The most utilized cover crops in both types of experiments were grasses, representing 43% of researcher experiments and 65% of on-farm experiments. On-farm experiments were more likely to include mixtures (33%) compared to researcher experiments (21%). None of the on-farm experiments reported individually evaluating brassicas and only a limited few worked with monoculture legumes, while monoculture legumes and brassicas were included in researcher-led experiments (Figure 2). Such cropping system patterns broadly align with the major field crops grown in the state, including corn (44% of harvested cropland), soybean (24% of harvested cropland), and wheat and alfalfa (4% each of harvested cropland) (USDA-NASS, 2022).

A survey of Nebraska producers conducted in 2014 found that the most frequently selected objectives of cover crop use were related to soil health—specifically, soil organic matter, soil erosion, and soil water holding capacity—while forage production was the fourth most common objective (Drewnoski et al., 2015). We might assume that including cover crops mixtures in farmer-led experiments are intended to meet soil health goals, few of these report data beyond cover crop biomass and yield. Although reporting on other outcomes (i.e., soil properties measured) was outside the scope of our study, there are initiatives within the state assessing and finding soil health improvements at cover crop on-farm experiments (Krupek et al., 2022a,b).

3.3. Experiment environments

The predominant region for both types of experiments was East Central Nebraska, representing 67% of researcher experiments and 75% of on-farm experiments. Remaining experiments were evenly distributed across the Southeast, Northeast, Central, South Central and Panhandle regions of the state (Figure 2). This is partly due to the distribution of farms across the state, with more, but smaller farms in the Eastern regions; and a greater proportion of pastureland in the western regions (USDA-NASS, 2021). In the more arid western regions of the state, perceived or reported negative cash crop effects of cover crops due to their water use (Nielsen et al., 2016) could limit research efforts.

Silty clay loam and silty loam are common soils in Eastern Nebraska and were represented in both kinds of trials. In contrast, sandy soils were not found in any researcher-led trials but comprised about 27% of the soils in farmer-led trials. Farmer-led experiments were more likely to be conducted on fields with greater slopes; approximately 54% of soil types reported in the on-farm experiments had 6 to 17% slopes. Most researcher-led experiment fields were relatively limited in topography, with 60% having $<1\%$ slopes and all with a maximum slope of 6% (Figure 2).

Research stations in Nebraska are mostly located on sites with fine-textured soils and little to no slope which has implications for soil health and plant productivity. More representative results on cover crop growth and effects on soil health and crop yields are obtained by including farmer-led trials in statistical analysis and subsequent management recommendations. In this context, farmer-led trials complement those led by researchers in painting a more realistic picture of opportunities and challenges associated with cover crops in this region, particularly for those grown under less optimal conditions (Laurent et al., 2022).

Irrigation was present on about half of the fields for the farmer-led and approximately 29% of the fields for the researcher-led experiments, closer to the state average of approximately 35% of farms with irrigation (USDA-NASS, 2017). Further, two of the nine peer-reviewed studies included experiments on both irrigated and non-irrigated sites (Figure 2).

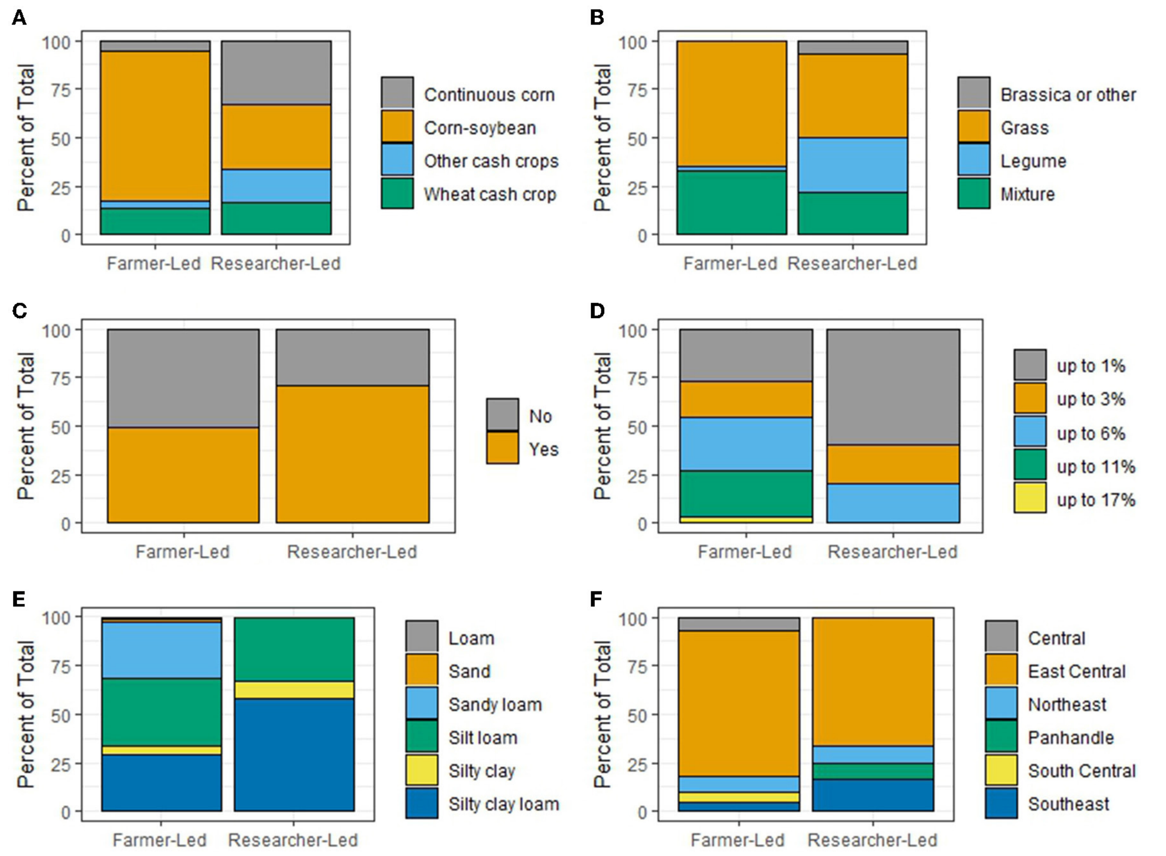

FIGURE 2
Management and environment information [**(A)** crop rotation, **(B)** cover crop species, **(C)** irrigation, **(D)** field slope, **(E)** soil type, and **(F)** Nebraska region] in farmer-led ($n = 89$) and researcher-led ($n = 290$) trials. The bar graph shows the percentage of studies or observations out of the total number of studies reporting information for each variable.

In general, we found a greater variety of environments (soils, climate regions) represented in the farmer-led compared to researcher-led experiments. This further emphasizes the value of on-farm experimentation in a state with a diverse environment such as Nebraska to test and validate management systems, and to demonstrate efficacy of practices under more variable (i.e., greater slopes, lesser soil quality) and potentially more challenging growing conditions. Although we might expect to find that researcher-led trials are more frequently conducted on homogeneous fields, such experiments can allow for studying management or collecting detailed data that would be difficult to do at a larger scale. Additionally, comparing the types of experiments and goals at these different scales can allow for reciprocal exchange of information—testing what has proven effective at a smaller scale on a larger scale, and vice versa, informing smaller scale research based on farmer interest.

3.4. Cash crop yields after cover crops

Yield differences due to cover crops appeared smaller in farmer-led than in researcher-led trials. In farmer-led experiments, we calculated an average yield decline of 3.4% occurred across all cash crops (standard error 11%) while in researcher-led trials, we calculated an average yield decline of 7.0% (standard error 5.6%) (Figure 3). However, neither of these differences were statistically different from zero. Laurent et al. (2022) similarly found few differences in crop yields when comparing small-plot trials to on-farm fungicide trials. In general, this trend of cash crop yield variability mirrors other studies which have found that grass cover crops can slightly decrease corn yields while legumes and mixes lead to neutral to positive impacts in corn (Miguez and Bollero, 2005; Marcillo and Miguez, 2017). Interestingly, Marcillo and Miguez (2017) found that yield declines in peer-reviewed experiments with corn following cover crops decreased in time, representing the learning curve expressed by farmers (Roesch-McNally et al., 2018). However, farmer self-reported data notes that cover crops consistently lead to cash crop yield improvements (CTIC, 2017), which aligns with the lower yield variability on-farm experiments compared to researcher-led experiments. This could also be a result of the fact that experiment stations often design trials in a factorial manner, vs. more of a "systems approach", where farmers alter several aspects of management concurrently (Basche and Roesch-McNally, 2017; Church et al., 2020). Our analysis is unique in its inclusion both of on-farm (farmer-led) and experiment-station (researcher-led) studies; publication bias is often a concern in meta-analyses and systematic reviews (Philibert et al., 2012). While our analysis is not purely reflective of either methodology, comparing farmer-led experiments published in reports vs. researcher-led experiments from peer-reviewed literature, provides insight into differences of scale, goals, management, and resulting outcomes. This can contribute to improving farmer trust and confidence in alternative management that is tailored more specifically to their operations, and importantly, that such management can be profitable (Nielsen, 2010; SARE, 2017; Kyveryga, 2019).

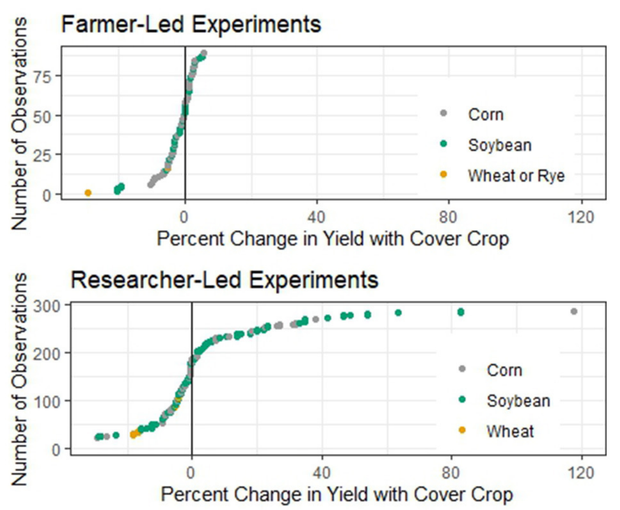

FIGURE 3
The change in percent in cash crop grain yield following a cover crop in farmer-led and researcher-led trials for all comparisons in the database. The three crops for which grain yield information was analyzed were corn (gray dots), soybean (green dots), and wheat (orange dots). The vertical black line indicates the average of all experiments.

3.5. Cover crop biomass

Cover crop biomass ranged from 31 to 3,054 kg/ha in farmer-led experiments with an average of 582 kg/ha (from 39 site-experiment years reporting cover crop biomass data) and from 9 kg/ha to 7,160 kg/ha at the researcher-led experiments with an average of 2,009 kg/ha (from all 290 site-experiment years included in the database) (Figure 4). These values are within the lower end of the range reported in a global assessment of cover crop biomass for semi-arid and cold climates most reflective of the state of Nebraska (annual precipitation <750 mm, USDA Plant Hardiness Zone <5), where mean cover crop biomass was estimated at 2,610 ± 2,420 Mg (Ruis et al., 2019). For the experiments in our database, there were several that found cover crop mixtures to have greater biomass than some of the grass only species experiments. Researcher-led experiments were more likely to include and report biomass for legume or other species (brassica, linaceae), which followed a similar distribution of biomass values compared to grass species (Figure 4).

Farmers manage their cover crops as part of profit-oriented system whereas researchers manage their cover crop to test a hypothesis. Farmers may terminate cover crops early to maximize the cash crop growing season, use cash crops with a long maturity group, and/or plant cover crops only after all cash crops on their operation are harvested. These practices shorten the available time

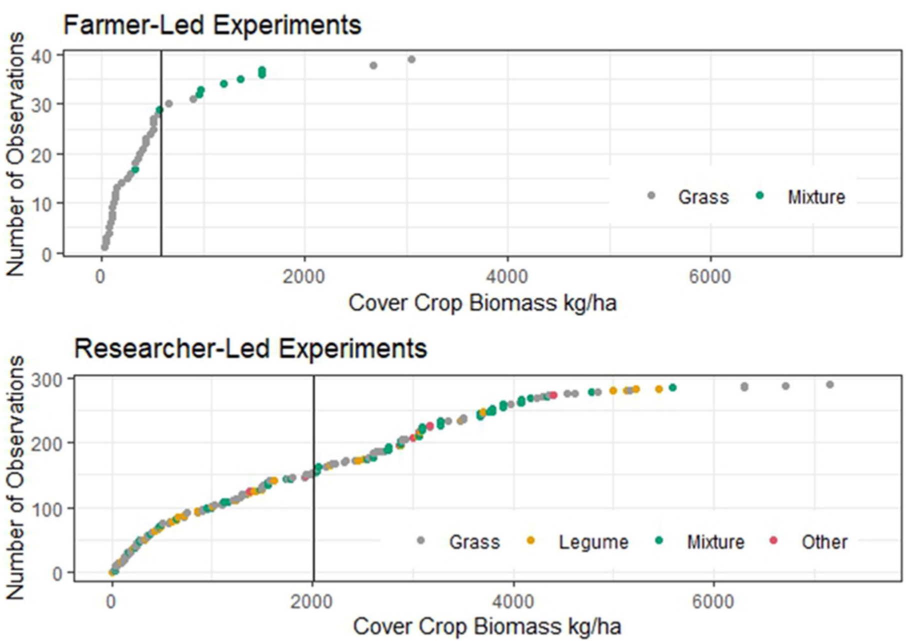

FIGURE 4
Cover crop biomass in kg/ha in farmer-led and researcher-led trials for all comparisons in the database. The cover crops for which biomass information was analyzed were grasses (gray dots), legumes (orange dots), mixtures (green dots) and other (red dots). The vertical black line indicates the average of all experiments.

for cover crop growth and could explain the lower productivity in on-farm trials. Previous researcher-led studies in the Western Corn Belt emphasized the need to establish cover crops earlier to increase productivity for example by interseeding the cover crop into cash crop stands (Peterson et al., 2019; Ruis et al., 2019). Interestingly, while several on-farm trials have tested interseeding (Figure 1), at this time there is a lack of researcher-led, peer-reviewed Nebraska studies on this topic. Additionally, it could be that the less optimal environments found in on-farm experiments account for some of the lower cover crop biomass performance. This illustrates the complementary role farmer-led studies have in testing and refining innovative or emerging technologies. When producers and researchers collaborate, results from farmer-led studies can be peer-reviewed and published, extending the findings to a larger audience, and creating the opportunity for wider trust and acceptance of results.

3.6. Study limitations

Our database was limited by the desire to comprehensively assess cover crop outcomes in different scales of experiments for one important and diverse U.S. state. Our database was also limited by differences in reporting across farmer-led and researcher-led trials. We selected experiments that measured and reported cash crop yields and/or cover crop biomass and compared it to a no-cover crop control treatment. Our inclusion criteria (namely that a no-cover crop control and cash crop yields were requirements) resulted in the exclusion of several researcher-led and farmer-led studies that are not counted in terms of their experimental designs and environments. We realize that the exclusion of cover crop studies investigating research questions that do not necessitate a no-cover control may not have captured the breadth of cover crop studies conducted in Nebraska. We also recognize that all studies cannot measure or focus on each potential crop, soil, or other impact of cover crops. However, because our goal was to concurrently compare treatments, environments, and outcomes of cover crop experiments at two different scales, not all potential experiments fulfilled our database criteria. Regardless, this analysis includes 89 site-year by treatment farmer-led and 290 site-year by treatment researcher-led comparisons, representing a robust database that captures trends from across the state of Nebraska.

A related limitation is that objectives were rarely stated in on-farm studies, so we do not know what specific purpose cover crops were to fulfill, beyond our classification of treatments included. Farmers may target a specific area of their field for cover crops, for example to prevent erosion on a slope. This may have influenced how they managed their cover crops, impacting biomass and crop yields. In addition, data collection also differed between the two sets of studies, especially for yields. The considerably larger plot size of farmer-led trials may have reduced overall yield variability, suggesting that treatment differences may be easier to detect in on-farm studies (Laurent et al., 2022).

Despite the diversity of cropping systems and climates in Nebraska, the majority of both types of experiments were concentrated in the relatively wetter East Central region of the state. Cover crop research in drier environments can further inform management to reduce water-related risks often reported by producers. For example, a more recent study that was not included in our review, suggested that non-winter hardy small grains may be a more productive, yet less water-intensive cover crop for Central and Western Nebraska than cereal rye (Rosa et al., 2021).

4. Conclusion

Although farmer-led and researcher-led cover crop trials differed with respect to treatments and management, we found many similarities between the two types of experiments. Cover crops did not significantly increase or decrease cash crop yields. We found that yield variability was lower at farmer-led compared to researcher-led experiments. Researcher-led experiments on average produced more cover crop biomass and included more brassica and legume cover crops, whereas farmer-led experiments included more mixtures. Farmer-led experiments were more likely to occur in a range of environmental conditions, across more variable landscapes and in some instances on soils of inherently lower productivity. Farmers may have multiple goals for cover crops, including forage for livestock, that may be more complex to conduct on a smaller scale. Conversely, researcher-led experiments assessed treatments such as irrigation, tillage and residue removal that are more complex or not possible to conduct at a larger scale. Identifying crop rotations, cover crop species and cultivars adapted to local soils and climates will be important to achieve continuous living cover in Nebraska's diverse cropping systems. Farmer-led trials due to their greater diversity in local soils and climates can play an important role in this endeavor. Future research should ensure greater representation of environmental conditions and agronomic systems, for example by including more farmer-led trials in research publications and greater collaboration between farmers and researchers.

Author contributions

KK-C and AB: conceptualization, research design, analysis, and writing manuscript. LT and JR: data collection and editing manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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