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LETTER

Evaluating strategies for sustainable intensification of US agriculture through the Long-Term Agroecosystem Research network

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Abstract
Sustainable intensification is an emerging model for agriculture designed to reconcile accelerating global demand for agricultural products with long-term environmental stewardship. Defined here as increasing agricultural production while maintaining or improving environmental quality, sustainable intensification hinges upon decision-making by agricultural producers, consumers, and policy-makers. The Long-Term Agroecosystem Research (LTAR) network was established to inform these decisions. Here we introduce the LTAR Common Experiment, through which scientists and partnering producers in US croplands, rangelands, and pasturelands are conducting 21 independent but coordinated experiments. Each local effort compares the outcomes of a predominant, conventional production system in the region ('business as usual') with a system hypothesized to advance sustainable intensification ('aspirational'). Following the logic of a conceptual model of interactions between agriculture, economics, society, and the environment, we identified commonalities among the 21 experiments in terms of (a) concerns about business-as-usual production, (b) 'aspirational outcomes' motivating research into alternatives, (c) strategies for achieving the outcomes, (d) practices that support the strategies, and (e) relationships between

practice outreach and adoption. Network-wide, concerns about business as usual include the costs of inputs, opportunities lost to uniform management approaches, and vulnerability to accelerating environmental changes. Motivated by environmental, economic, and societal outcomes, scientists and partnering producers are investigating 15 practices in aspirational treatments to sustainably intensify agriculture, from crop diversification to ecological restoration. Collectively, the aspirational treatments reveal four general strategies for sustainable intensification: (1) reducing reliance on inputs through ecological intensification, (2) diversifying management to match land and economic potential, (3) building adaptive capacity to accelerating environmental changes, and (4) managing agricultural landscapes for multiple ecosystem services. Key to understanding the potential of these practices and strategies are informational, economic, and social factors—and trade-offs among them—that limit their adoption. LTAR is evaluating several actions for overcoming these barriers, including finding financial mechanisms to make aspirational production systems more profitable, resolving uncertainties about trade-offs, and building collaborative capacity among agricultural producers, stakeholders, and scientists from a broad range of disciplines.

Introduction

The world's population is expected to increase by roughly two billion during the next thirty years, and humanity is now facing the monumental challenge of reducing hunger among the poor, meeting the dietary demands of a growing middle class, and sustaining environmental quality, all in the context of an increasingly variable climate (Godfray *et al* 2010, Foley *et al* 2011, Alexandratos and Bruinsma 2012). Sustainable intensification—increasing production while minimizing or reversing the adverse impacts of agriculture—has emerged as a primary framework to meet this challenge (Godfray and Garnett 2014, Petersen and Snapp 2015, Rockström *et al* 2016).

In the United States, achieving sustainable intensification is hampered by climate change, entrenched norms and market structures, and the need for new information, technologies, and infrastructure (Reganold *et al* 2011, Tilman *et al* 2011, Petersen and Snapp 2015). The US Long-Term Agroecosystem Research (LTAR) network was established in 2014 to address these obstacles (Robertson *et al* 2008, Walbridge and Shafer 2011, Kleinman *et al* in preparation). LTAR's 18 sites have researched various aspects of sustainable intensification for decades to over a century and represent a diversity of regional agroecosystems nationwide (figure 1). These sites are now embarking on a 'common experiment' encompassing 21 independent but coordinated experiments linked by common objectives and measurements (table 1). Each local effort compares the outcomes of a local, predominant conventional production system ('business as usual') with the outcomes of an alternative production system hypothesized to advance sustainable intensification in locally appropriate ways ('aspirational').

The LTAR Common Experiment offers an unprecedented opportunity to gain local, regional, and national insights into critical issues underlying the sustainable intensification of US agriculture, including the nature of problems to be solved as well as approaches and key barriers to solving them. As region-specific, networked experimentation has recently been identified as a priority for sustainable intensification at a global level (Rockström *et al* 2016, Reynolds *et al* 2017), experiences from the LTAR Common Experiment can provide valuable lessons for efforts worldwide. To introduce LTAR's approach, we identify common themes that span the Common Experiment, including concerns about business-as-usual production, the strategies for sustainable intensification under investigation, the practices that support the strategies, and the factors that limit producers' adoption of those practices. We also explore options for overcoming barriers to adoption, focusing on areas where the current research portfolio could be expanded.

Methods

The LTAR Common Experiment comprises 21 experiments in agricultural lands across the United States (figure 1, table 1). Currently measurements are tailored to compare the effects of business-as-usual and aspirational management at the plot, field (pasture), and farm (ranch) scales, alongside efforts to develop open-access databases (https://ltar.nal.usda.gov) and modeling to link measurements to inferences at the scales of watersheds, regions, industries, and the nation (Walbridge 2013).

We used two web-based digital survey questionnaires, visual and tabular summaries of questionnaire data, and group discussion about the summaries to synthesize the multiple dimensions of the Common Experiment into a common framework (figure 2).

Our synthesis was structured according to a conceptual model that identifies the interactions of an agricultural production system suitable for a region (e.g. the business-as-usual or aspirational production

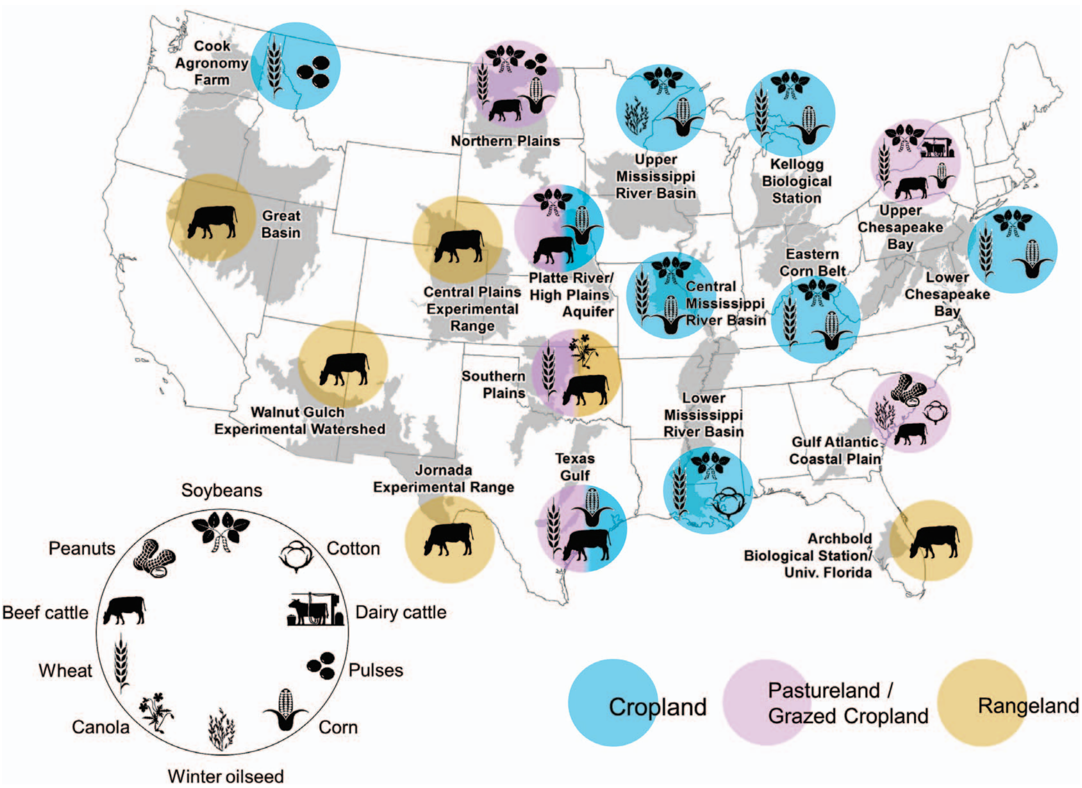

Figure 1. The Long-Term Agroecosystem Research network's Common Experiment is being conducted in croplands, rangelands, pasturelands, and grazed croplands across the United States. Gray polygons represent estimated regional inference spaces for the 18 LTAR sites based on Major Land Resource Areas (USDA-NRCS 2006), and black icons represent the products under investigation in the regions. Twenty-one experiments are being conducted by the 18 sites, as three sites are each conducting two experiments in two different agricultural land uses. Black icons by Shutterstock.com artists HuHu, iconizer, K N, NadzeyaShanchuk, Hein Nouwens, Oleg7799, VKA, and VoodooDot.

Figure 2. A synthesis framework containing five major elements of the Common Experiment (five boxes) with common themes shared among the 21 experiments within each element (lists in boxes).

Table 1. Summary of the 21 experiments in the LTAR Common Experiment. 'MAP zone' refers to general zone of mean annual precipitation in the United States, and 'Location' refers to US state and geographic coordinates of a primary research site.

Land use	Experiment	Location	MAP zone (mm)	Local concerns about business-as-usual production	Business-as-usual treatment	Aspirational treatment	Practices under investigation
Cropland	Central Mississippi River Basin	MO 39.27°N, 92.121°W	900-1500	Agrochemical inefficiencies, erosion, water quality, limited resilience to climate extremes	Corn/soybean rotation with annual aggressive tillage, uniform rates of seed and agrochemicals, no cover crops	Extended corn/soybean/wheat rotation with annual cover crops and no-till, site-specific management of seed, fertilizer, and pesticides. 4R nutrient stewardship.	Cover crops Precision technologies Tillage management
	Cook Agronomy Farm	WA 46.781°N, 117.082°W	< 600	Agrochemical inefficiencies, erosion, water quality, nutrient losses from soils, suboptimal C storage	3-year winter wheat/spring wheat/chickpea rotation with reduced tillage and uniform application of macronutrients	Same rotation with no-tillage and precision application of macronutrients	Precision technologies Tillage management
	Eastern Corn Belt	OH 40.031°N, 82.973°W	900-1500	Water quality, limited resilience to climate extremes. Land use affecting Lake Erie and the Ohio River Valley	Corn-soybean with rotational tillage (tillage prior to corn), nutrient and pesticide application at agronomic rates, and a tile drainage system that flows freely year-round	Introduction of wheat into corn/soybean rotation, cover crops, precision nutrient management, no-till, and drainage water management	Drainage management Precision technologies Tillage management
	Kellogg Biological Station	MI 42.405°N, 85.401°W	900-1500	Suboptimal crop production with seasonal drought. Erosion, water quality, N emissions, suboptimal C storage and biodiversity.	Corn/soybean rotation, conservation tillage with chisel plow, nutrient and pest management with commercial crop adviser rates, and GMO seeds and seed treatments	Corn/soybean/wheat rotation with winter cover crops. Permanent no-till or narrow-row shallow strip tillage. On-the-go-variable rate nutrient and pest management.	Cover crops Precision technologies Tillage management
	Lower Chesapeake Bay	MD 39.039°N, 76.918°W	900-1500	Suboptimal crop production with seasonal drought. Erosion, water quality, wetland conservation, urban interface. Land use affecting Chesapeake Bay.	Corn/soybean rotation used for crop fields with surface-applied manures, winter cover crop where subsidized. Rotational no-till. Conventional herbicide and N application. Nutrient management plan required.	Increase irrigated acreage and convert marginal land into conservation off-set programs. Innovative corn/soybean/wheat rotations with high biomass cover crops, no-till, and precision agriculture (pest, nutrients, and water).	Cover crops Precision technologies Tillage management
	Lower Mississippi River Basin	MS 34.366°N, 89.519°W	900-1500	Water competition; insect, weed, pathogen pressures; erosion; suboptimal C storage; water quality; fish health	Wheat/soybean/cotton rotation with no cover crops, conventional tillage, uniform nutrient application, proactive herbicide and insecticide, no edge of field buffer, and conventional irrigation	Soybean/cotton/wheat-soybean rotation with cover crops post-harvest or as intercrop, reduced tillage, precision nutrient application, IPM, edge of field buffers, and innovative irrigation	Cover crops Crop diversification Irrigation management
	Platte River/High Plains Aquifer (a)	NE 40.829°N, 96.667°W	600-899	Crop and forage production are limited by variable rainfall. Heterogeneous soils complicate nutrient and water availability to crops.	Maize/soybean rotation under rainfed or sprinkler irrigation. Fields managed uniformly.	Intensification through crop diversification and cover crops. Precision irrigation and fertilization to manage spatial variation.	Crop diversification Irrigation management Precision technologies

Table 1. *Continued.*

	Experiment	Location	MAP zone (mm)	Local concerns about business-as-usual production	Business-as-usual treatment	Aspirational treatment	Practices under investigation
	Texas Gulf (a)	TX 31.52°N, 96.9°W	600-899	Increasing production costs; limited resilience to climate extremes; water quality	Corn or hay/small grain rotation; no cover crops; conventional or conservation tillage; traditional rates of inorganic N, P	Corn or hay/small grain rotation with multispecies cover crop, reduced or no-till, poultry litter application, and inorganic N and P application based on Haney test	Cover crops Manure management Tillage management
	Upper Mississippi River Basin	IA 42.172°N, 93.275°W	600-899	Glyphosate-resistant weeds, soil compaction, erosion. Tile drainage affects runoff and Gulf of Mexico water quality	Corn/soybean rotation with tile drainage. No cover crops, chisel plow tillage, annual N application for corn, and glyphosate and insecticide as needed	Rotation of corn/winter camelina cover crop with soybeans overseeded. Minimized tillage and fertilizer application. Trifluralin and insecticide as needed. Camelina oil seed for biofuel.	Cover crops Crop diversification
Pastureland/Grazed Cropland	Gulf Atlantic Coastal Plain	GA 31.457°N, 83.703°W	900-1500	Water competition; insect weed, pathogen pressures; toxic dust emissions; water quality, suboptimal utilization of whole farm landscape	Cotton/cotton/peanut rotation with rye/rye/rye cover crop; conventional tillage, nutrient, pest, and weed management; linear move irrigation. On-farm cow-calf production on marginal land and/or crop residue with calves sold at weaning.	Cotton/grass/peanut rotation with rye+winter pea and rye cover crops rotated with a winter carinata cash crop. Cow-calf production integrated into all portions of the farm landscape during twelve months of the year. Biofuels.	Cover crops Crop diversification Graze annual crops
	Northern Plains	ND 46.825°N, 100.888°W	< 600	Insect, weed, pathogen pressures; limited resilience to climate extremes; suboptimal C storage; nutrient losses from soils	Spring wheat/corn/soybean rotation with no-till or minimum-till, no cover crop, uniform nutrient application, residue removal.	Dynamic and adaptive annual crop rotation with no-till, cover crops, and precision/variable nutrient and pesticide application. Post-harvest livestock grazing of crop residue and/or cover crops.	Adaptive management planning Cover crops Tillage management
	Platte River/ High Plains Aquifer (b)	NE 40.829°N, 96.667°W	600-899	Beef cattle production systems limited by amount of pasture when rainfall is low. Greenhouse gas emissions	Yearling steers with season-long grazing in dedicated pastures	Livestock grazing crop residue and cover crops. Calving date changes. Reduced time in feedlot.	Grass-fed beef production Graze annual crops Livestock-landscape matching
	Southern Plains (a)	OK 34.885°N, 98.023°W	600-899	Insect, weed, pathogen pressures; erosion; suboptimal soil C storage, low primary productivity	Beef cattle stockers on continuous “grazeout” wheat with conventional tillage for weed control	4-year rotation of grain-only wheat / dual-purpose wheat / grazeout wheat / canola, with stocker grazing on 2 of 4 years of rotation. No till. IPM.	Crop diversification Integrated pest management Tillage management
	Texas Gulf (b)	TX 31.52°N, 96.9°W	600-899	Suboptimal forage production, water quality, soil quality	Beef cattle on grazing oats pasture cultivated with tillage and inorganic fertilizers. Hay in winter. Separate herds with best pasture grazing.	Beef cattle on overseeded, multi-species pasture. Cattle intentionally rotated through pasture and cultivated paddocks.	Cover crops Graze annual crops Rotational grazing
	Upper Chesapeake Bay	PA 40.861°N, 77.763°W	900-1500	High input intensity (fertilizer, pesticides, energy), erosion, water quality, air pollution, enterprise solvency and profitability	Dairy cattle on pasture with alfalfa and silage corn. Imported fertilizers, pesticides, and fuels. Conventional pest management. Ineffective application of manure from on-farm CAFO. Minimal-management grazing.	Dairy cattle on diversified forage rotation with perennial grasses (biofuels). Precision nutrient management. Whole-farm integration. IPM. Energy independence. Conservation tillage.	Cover crops Graze annual crops Manure management

Table 1. *Continued.*

Land use	Experiment	Location	MAP zone (mm)	Local concerns about business-as-usual production	Business-as-usual treatment	Aspirational treatment	Practices under investigation
Rangeland	Archbold Biological Station / University of Florida	FL 27.183°N, 81.351°W	900-1500	Suboptimal forage production and utilization, biodiversity, and carbon storage. Land use affecting Everglades.	Cattle production with long rotation grazing and low-rate N fertilization on improved pastures during wet season. Long rotation grazing and Rx burns during dry season on semi-native and native range.	Cattle production with intensive rotation and fertilization on improved pastures during wet season. Low intensity rotation on semi-native and native range during dry season, with patch burning or Rx burning during wet—dry transition season.	Prescribed burning Rotational grazing
	Central Plains Experimental Range	CO 40.842°N, 104.716°W	< 600	Suboptimal forage production and utilization, biodiversity. Drought.	Stocker production on shortgrass steppe with May-Oct grazing (during the late spring and summer) at moderate stocking rates.	Stocker production on shortgrass steppe with collaborative adaptive rangeland management, including pulse grazing, flexible stocking rate, and patch burning options	Adaptive management planning Prescribed burning Rotational grazing
	Great Basin	ID 43.21°N, 116.75°W	< 600	Cheatgrass invasion of sagebrush/ bunchgrass rangeland; altered grass-fire cycle	Inflexible grazing use policies on public lands. Traditional cheatgrass treatments.	Management of public lands is adaptive to fire-cheatgrass cycle. Novel sagebrush-steppe restoration.	Adaptive management planning Rangeland restoration
	Jornada Experimental Range	NM 32.029°N, 106.59°W	< 600	Shrub dominance, perennial grass loss; drought, increasing aridity. Localized overgrazing can accelerate grass and soil losses. Options for local agriculture are diminishing.	Cow-calf production with British breeds (Angus crossbreds) and grain finishing in western OK and TX.	More options for agricultural production on rangelands, including cow-calf production with heritage Raramuri Criollo cattle with grass-finishing, cross-breeding, and roping cattle options. Brush management and range seeding.	Grass-fed beef production Livestock-landscape matching Rangeland restoration
	Southern Plains (b)	OK 34.885°N, 98.023°W	600-899	Suboptimal forage production and utilization on native tall grass prairie	Conventional cow-calf production. Treatment on native tall grass prairie with continuous grazing.	Cow-calf production with livestock size matched to environment and rotational grazing. Treatment on native tall grass prairie.	Adaptive management planning Livestock-landscape matching Rotational grazing
	Walnut Gulch Experimental Watershed	AZ 31.711°N, 110.064°W	< 600	Long term expansion of velvet mesquite and associated loss of NPP, perennial grasses, and biodiversity with accelerated erosion	Velvet mesquite allowed to increase to its natural limits	Velvet mesquite treated with aerially-applied herbicides	Rangeland restoration

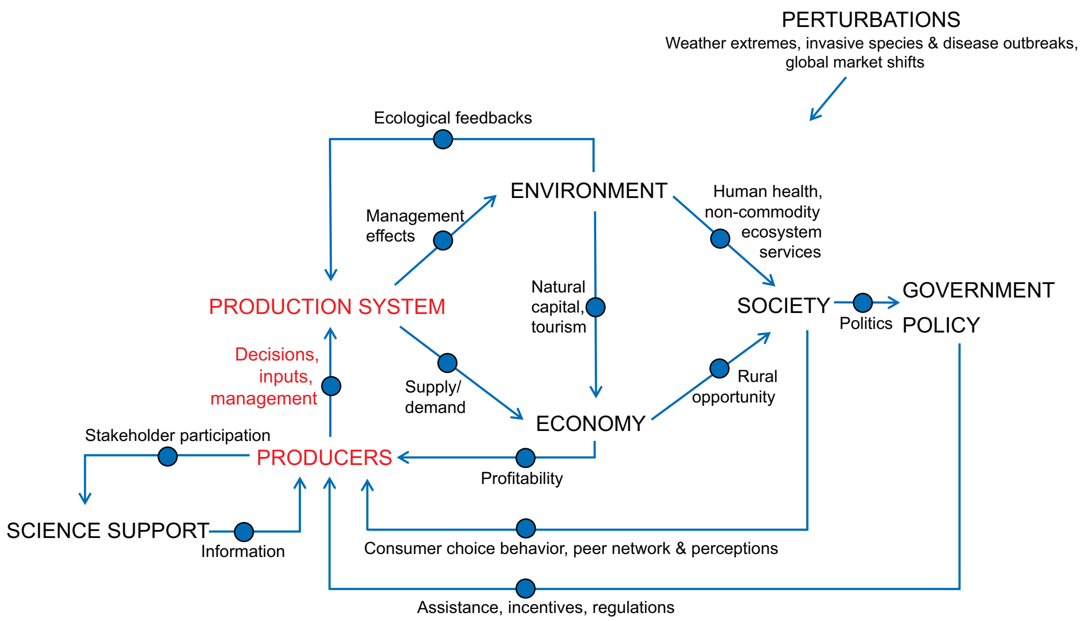

Figure 3. Conceptual model of interactions among agriculture, environment, economy, and society (cf. Fox *et al* 2009, Lescourret *et al* 2015, DeClerck *et al* 2016, Moraine *et al* 2017) used to frame our questionnaires and synthesize the multiple dimensions of the LTAR Common Experiment into a common framework (figure 2). The model centers on agricultural producers and their decision-making about selecting a production system (i.e. suite of management strategies and practices) suitable for a given agricultural region. Feedback loops mediated by profitability, environmental effects, societal factors, and policies can reinforce the status quo or prompt producers to adopt an alternative production system. External shocks (drivers and perturbations that are unaffected by feedbacks) can tip the entire system into alternative states (Walker and Meyers 2004). For decision-making, producers integrate knowledge of profit potential, government policies, and social interactions along with science-based information from universities, extension, and producer organizations (Rodriguez *et al* 2008, Lubell *et al* 2014). The nature, quality, and availability of scientific information are, in turn, influenced through participatory science with producers and other stakeholders (Neef and Neubert 2011). With their integrated insights, producers select the parts of the agricultural land mosaic under their management to be used for production or for other functions, such as wildlife habitat or watershed management. These site-level management decisions affect environmental conditions at the farm/ranch and landscape levels, which feed back to the production system (and ultimately profitability) via, for example, long-term changes in soil quality or pollinator biodiversity (Swain *et al* 2013, Brown and Havstad 2016, Rockström *et al* 2016). Environmental conditions produced by agricultural decisions also affect human health (e.g. dust emissions) and the production of non-commodity ecosystem services (e.g. waste treatment, scenic beauty). The environment influences the economy through opportunities for eco-and agro-tourism (Nickerson *et al* 2001) and natural capital, stocks of natural resources that yield ecosystem goods and services now and into the future (Costanza and Daly 1992). The production system affects the economy through the balance of supply and demand of agricultural commodities. In turn, the economy, including its transportation, agricultural infrastructures, and pricing for agricultural inputs, affects the chances that producers will turn a profit (Chandra and Thompson 2000). The health of the local economy also affects the local rural community, because lack of opportunities can lead to poverty, impermanence, and eventual outmigration (Ratcliffe *et al* 2016, Parry and Skaggs 2014, Cohen *et al* 2015). Perceptions of peers in the community and trends in consumer choice behavior can affect producers' management planning as well as their economic bottom lines. Societies influence government policies at all levels through the political process. Although the power of rural communities to shape policy varies (Lichter and Brown 2011), agricultural and environmental policies directly affect producers via price supports, regulations, and compensation for non-commodity ecosystem services (Reganold *et al* 2011).

system) with the environment, economy, society, government policy, and science support (figure 3). The model focuses on how these interactions affect producers' decisions to adopt (or maintain) business-as-usual or aspirational production systems.

Survey design and data collection

We designed a survey to develop a network-wide perspective on the Common Experiment using the conceptual model (figure 3) as an organizing framework. Given the relatively small size of the network, a comprehensive census approach (i.e. surveying all network sites) was possible (Salant and Dillman 1994). The survey included two questionnaires administered by the two lead authors on behalf of the network. Scientists from all 18 LTAR sites reviewed their published studies (https://data.nal.usda.gov/publications/ltar) and site-based knowledge to develop one response per experiment for each of the questionnaires. Primary respondents from each site are also authors of this article.

Through the 'Coordination Questionnaire' (supplement 1 available at stacks.iop.org/ERL/13/034031/mmedia), administered November 2015—October 2016, scientists described their study designs, their concerns about the business-as-usual production systems they are evaluating, and hypotheses about how their aspirational systems can address those concerns. Questions about concerns and hypotheses were open-ended but structured by ecosystem service categories (de Groot *et al* 2010) to elicit responses in terms of relationships between the focal production system and other components of the conceptual model (figure 3): provisioning services corresponded with the economy, regulating and supporting services with the environment, and cultural services with society.

Twenty-two concerns about business as usual were coded from the qualitative responses to the Coordination Questionnaire, and presence (1) or absence (0) of each concern for each experiment was tabulated (supplement 2). In October 2016, we generated an ordination of the experiments based on the tabulated data. Surprisingly, experiments dissimilar in land use and geography clustered in ordination space (supplement 3), revealing that concerns about business-as-usual production transcended land use and geography. We used the classification of business-as-usual concerns to design a second questionnaire focused on aspirational outcomes that directly address those concerns. With the second questionnaire, we sought to gain precision on the aspirational outcomes described qualitatively through the Coordination Questionnaire, and to identify potential barriers to those outcomes. Accordingly, the 'Aspirations Questionnaire' (supplement 3) used closed-ended responses to provide clear links between business-as-usual concerns, aspirations, and barriers. Because they proved uninformative, ecosystem service categories used in the Coordination Questionnaire were omitted from the second questionnaire and synthesis.

The Aspirations Questionnaire was administered January—February 2017. In a multiple-choice question, respondents selected from among 23 'aspirational outcomes' coded from qualitative responses to the Coordination Questionnaire (supplement 4). The outcomes were specific objectives of aspirational production approaches which, if met, would help achieve the primary goal of sustainable intensification. Then, through a multi-part question, scientists listed the three main practices in their aspirational treatments, and for each practice rated its level of existing outreach by Cooperative Extension and other groups (1 = none to minimal; 5 = extensive), rated its current level of adoption by producers (same scale), and provided a short response explaining discrepancies between the two ratings. Respondents were encouraged to frame discrepancies in terms of relationships between the production system and other components in the conceptual model (figure 3). This question elicited 61 unique practice entries, two to three per experiment (supplement 5). Adoption was rated less than, or equal to, outreach for 58 of the 61 practice entries. Short responses were given for 47 of the 58 entries: 31 cases in which adoption was rated lower than outreach, and 16 cases in which the two ratings were equal. Due to the instructions given in the questionnaire and the nature of the responses, we considered all 47 short responses to be explanations for why practice adoption lags behind outreach. Nineteen reasons for the lag were coded from the 47 explanations, and presence (1) or absence (0) of each reason was tabulated for the 47 practice entries (supplement 5). Next, fifteen practices were coded from the 61 practice entries. Each practice code was assigned one rating for outreach and one for adoption by averaging ratings across practice entries with the code (supplement 5 and 6). Presence (1) or absence (0) of the 19 reasons that adoption lags behind outreach were tabulated for each practice code.

Coding and tabulation of qualitative survey data were performed using basic descriptive and thematic coding methods per Saldaña (2016).

Synthesis process

In February—August 2017, co-authors analyzed iterative versions of tabular and graphical summaries of survey results via in-person and virtual meetings. Graphics were created using data available in supplementary materials, with the ggplot package in R version 3.2.5 (Wickham 2009, R Core Development Team 2015).

We identified common concerns about business-as-usual production by categorizing the 22 concerns used in the ordination into broader themes (supplement 2). The 23 aspirational outcomes were categorized into themes (supplement 4) corresponding with the conceptual model (figure 3) and primary goals for LTAR and sustainable agriculture (National Research Council 2010, Kleinman *et al* in review).

The 15 practice codes (hereafter, 'practices'), were categorized into practice types (supplement 5) per USDA-NRCS conservation practice standards (USDA-NRCS 2017) and LTAR site publications. Practices applied mainly to lands used for crops and/or forages were categorized as 'cropland management' practices. Practices applied mostly to lands grazed by livestock were categorized as 'grazingland management' practices. Practices applied less directly to land and more directly to management of the overall microeconomics of the farm or ranch operation were categorized as 'enterprise management' practices (*sensu* Lowrance *et al* 1986).

We identified general strategies for sustainable intensification that emerged from the 21 aspirational treatments by assimilating the intentions of the 15 practices, the aspirational outcomes motivating LTAR research, and general literature cited in this paper.

To identify common reasons that adoption lags behind outreach, we categorized the reasons present for six or more practices into broader themes. We also analyzed how ratings and reasons varied with practice type (supplement 5).

Results

Our synthesis revealed that scientists across the LTAR network share common concerns about business-as-usual production, which resolved into three broad themes (figure 2). In response to those concerns, scientists are motivated by aspirational outcomes in the environment, economy, and society (figure 2), with societal outcomes currently emphasized less overall (figure 4).

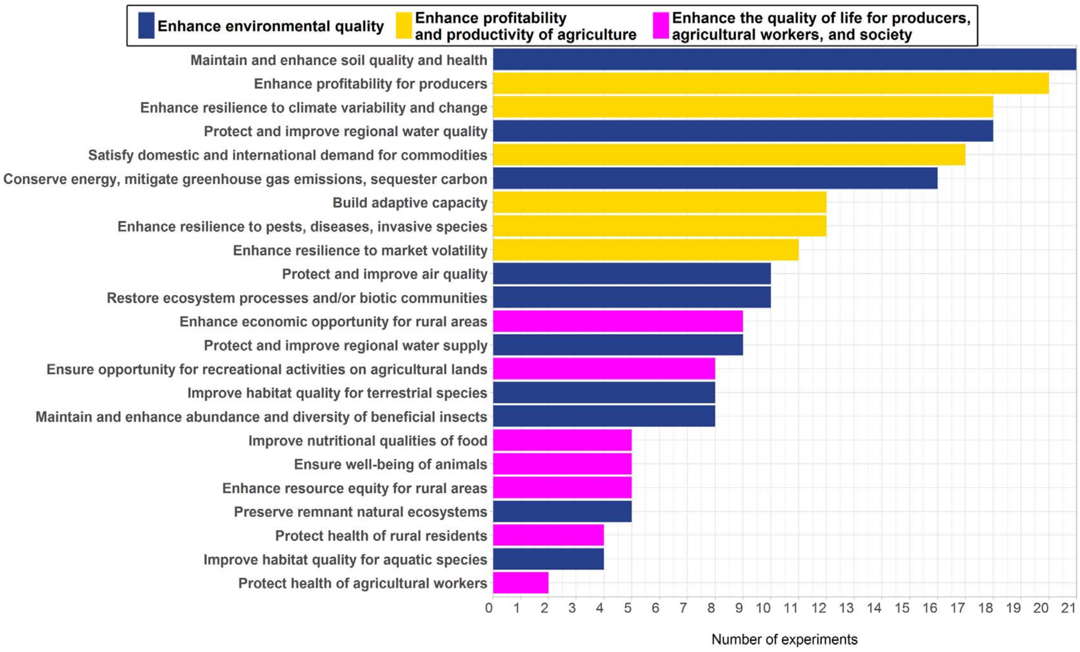

Figure 4. Scientists selected from among 23 'aspirational outcomes' in a multiple-choice question in the Aspirations Questionnaire. Bars represent frequency of selections across all experiments (supplement 4). Outcomes were categorized into themes corresponding with figure 3 and goals documented for LTAR and sustainable agriculture.

Four general strategies for sustainable intensification emerged across the aspirational treatments (figure 2). Most of the 15 practices are multifunctional in that they contribute to each strategy.

The 15 practices that support the strategies split evenly into three practice types (figure 2), but the types did not sort perfectly with the Common Experiment's three agricultural land uses. For instance, tillage management, a 'cropland management' practice, is under investigation in both pasturelands/grazed croplands and croplands (table 1).

Overall, the scientists perceived adoption lagging behind outreach for all practices except adaptive management planning, and adoption generally increasing with outreach (figure 5).

Reasons that adoption lags behind outreach which were present for six or more practices resolved into broad themes of costs, information deficits, and social norms (figure 2; figure 6).

Cropland management practices were generally rated highly for outreach (figure 5), and additional costs were regularly invoked to describe why adoption trails outreach (figure 6). Enterprise management practices were rated variably for outreach and adoption (figure 5). Again, reasons related to costs were used to explain discrepancies between the two ratings (figure 6). Three of the five grazingland management practices were rated relatively low for outreach and adoption (figure 5), with social norms and information deficits invoked to explain the ratings (figure 6). Although not captured graphically, trade-offs among economic, social, and environmental outcomes of practice implementation were also frequently mentioned during the synthesis process as important influences on practice adoption (also see Rodriguez *et al* 2008, Lubell *et al* 2011).

Discussion

Network-wide concerns about business-as-usual production

1. Costs of inputs

The economic and environmental costs of the fertilizers, fossil fuels, and infrastructure in business-as-usual agricultural production are well documented for the United States and other countries (e.g. Matson *et al* 1997, Tilman *et al* 2002). These costs are primary concerns for scientists across the network.

Through the survey, scientists in croplands and pasturelands conveyed concerns about soil erosion and water quality resulting from agronomic inputs, especially as management in LTAR regions affects several water bodies of national significance including the Florida Everglades, Chesapeake Bay, Lake Erie, the Mississippi River, and the Columbia River Basin (figure 1, table 1). Significant economic costs were also noted. Since 2012, for instance, for five commodities under wide investigation in the Common Experiment—corn, soybeans, wheat, cotton, and peanuts—fertilizer purchases represented 18%–42% of operating costs (USDA-ERS 2017).

LTAR's rangeland scientists expressed concerns about suboptimal forage production, suboptimal forage utilization by beef cattle, or both (table 1). Supplemental feeding represents, on average, 20% of

Figure 5. Rating for adoption plotted against rating for outreach (1 = none to minimal; 5 = extensive) for 15 practices in the aspirational treatments. Values represent the average of ratings submitted via the Aspirations Questionnaire (see methods, supplement 5). Summary statistics by practice and practice type are available in supplement 6.

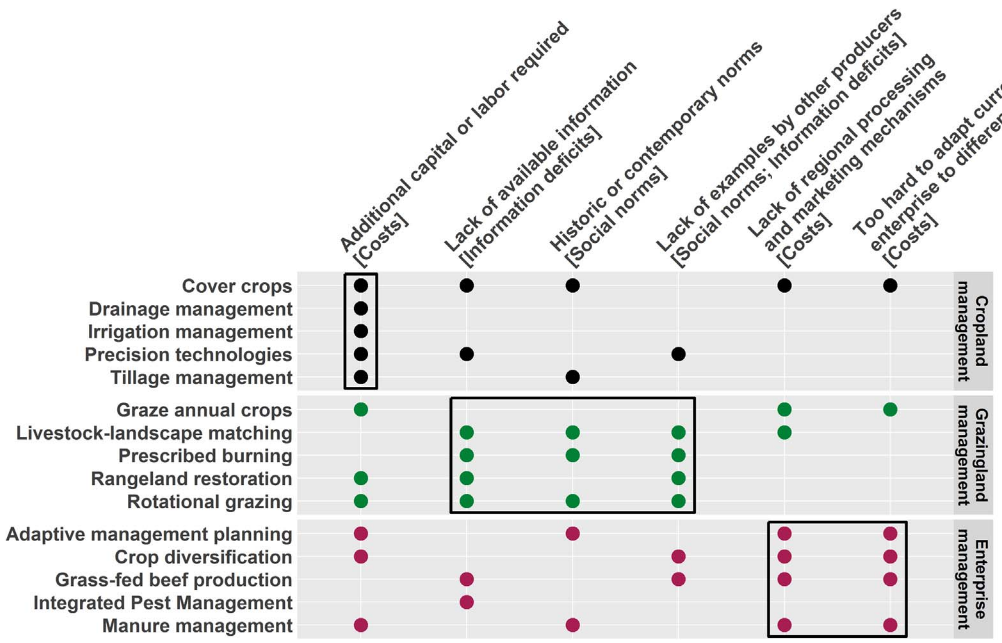

Figure 6. Reasons that adoption lags behind outreach for practices in the aspirational treatments. Reasons shown here were present for at least six of the 15 practices coded via the Aspirations Questionnaire (see methods, supplement 5). Broader themes identified through the synthesis process (figure 2) are noted in the brackets. Black boxes demonstrate patterns revealed by evaluating the reasons by practice type.

the total operating costs for cow-calf operations in the rangelands of the western United States (USDA-ERS 2017). Increased feed input costs due to suboptimal forage production or consumption can present significant economic hardships for ranchers (Holechek and Herbel 1986).

2. Costs of specialization, concentration, and uniform land management

Scientists network-wide expressed concerns about how business as usual seeks to overcome the inherent biophysical and socioeconomic variability of agricultural lands, instead of capitalizing on that variability to produce diverse suites of agricultural products and other ecosystem services.

During the past century, US farming systems have become increasingly specialized such that the number of commodities produced per operation has declined, and concentrated such that fewer farms are producing the nation's overall supply (Dimitri *et al* 2005, Hendrickson *et al* 2008). LTAR's cropland and pastureland scientists expressed concern that the decoupling of crop and livestock production has led to broken nutrient cycles and missed opportunities for portfolio diversification (Sharpley *et al* 2016, Liebig *et al* 2017). Further, they acknowledged that the tendency toward uniform agronomic management at the field scale has come at a cost of flexible, location-specific management, resulting in negative impacts to water and air resources, soil health and even profit.

LTAR's rangeland scientists appreciate that ranchers have always needed to adjust their management to cope with the intrinsic climatic variability of rangelands; however, concern was expressed about trends toward uniform styles of range and ranch management. Scientists from central Florida noted that fixed burning schedules can lead to suboptimal forage production and reductions in biodiversity in their region (Boughton *et al* 2013). In the Central Plains, maintaining set stocking rates and pasture rest schedules based on calendars—without adaptively changing plans based on current forage conditions and weather predictions—may reduce opportunities for matching forage availability with animal demand (Derner and Augustine 2016). Further, business as usual has championed livestock breeds that provide a uniform product for the beef supply chain, but those breeds can fail to capitalize on variable pasture resources in the American Southwest and Southern Plains, especially during drought (Anderson *et al* 2015, Scasta *et al* 2016). Across all rangeland systems, it was acknowledged that a mismatch of livestock type or management style with the inherent heterogeneity of the landscape can result in undesirable effects on production, vegetation, soils, and biodiversity.

3. Vulnerability to accelerating environmental changes

After decades of achievements in overcoming temporally variable threats to production, producers in LTAR regions and across the world are facing rapidly accelerating changes in climate, pest, and disease patterns (Lin 2011, Lipper *et al* 2014, Marshall *et al* 2014). Drought, flooding, and record high temperatures have increased in frequency and intensity, and reductions in global maize and wheat yields have already been attributed to these climatic changes (Lobell *et al* 2011). Simultaneously, pest, weed, and pathogen resistance can exacerbate vulnerability to mounting climatic variability. LTAR scientists across the network expressed concern about the vulnerability of business-as-usual production systems to these accelerating environmental changes.

General strategies, supported by 15 practices, to achieve aspirational outcomes

In response to their concerns about business-as-usual production, LTAR scientists are working with farmers, ranchers, and other agricultural stakeholders to evaluate alternatives. Collectively, the 21 aspirational treatments (table 1) reveal four general strategies designed to achieve the network's aspirations (figure 4) to advance sustainable intensification. Practices under investigation are multifunctional in that they support multiple strategies.

1. Reducing reliance on inputs through ecological intensification

All of LTAR's aspirational treatments are exploring *ecological intensification*: bolstering internal processes, mechanisms, and functions that directly or indirectly contribute to agricultural production to reduce reliance on external inputs (Robertson and Swinton 2005, Bommarco *et al* 2013). Production can be ecologically intensified by enhancing soil fertility, pollination, biocontrols, genetic diversity, and nutrient cycling (Power 2010, Rockström *et al* 2016), and most of the 15 practices under investigation are designed to promote such processes and functions. Broad network interest in ecological intensification is reflected in a universal commitment to maintaining and enhancing soil quality and health (figure 4, Doran 2002, Govers *et al* 2017).

2. Diversifying management to match land and economic potential

Most network locations are working to increase agricultural production and profitability (figure 4), and diversifying management is a prevalent strategy for achieving these outcomes sustainably. Tailoring management to match the spatial heterogeneity of soils and temporal variability of rainfall is under wide investigation, with crop diversification, livestock-landscape matching, precision management, and adaptive management as examples of practices supporting the approach (Herrick *et al* 2013, Derner and Augustine 2016). Further, several practices promote the integration of enterprises within and between regions for synergistic exchanges of resources (e.g. graze annual crops, manure management)—an approach increasingly recognized for its potential to advance sustainable intensification in the United States (Steiner and Franzluebbers 2009, Fedoroff *et al* 2010, Liebig *et al* 2017).

3. Building adaptive capacity to accelerating environmental changes

LTAR was conceived, in part, to help farmers and ranchers adapt to increasing variability in climate and related challenges associated with pests, diseases, and invasive species (Walbridge and Shafer 2011), and this emphasis was reflected in the survey. All 15 practices serve to build adaptive capacity in some manner. With an eye toward minimizing adverse impacts of agriculture on climate change, most experiments are also comparing greenhouse gas dynamics of their business-as-usual and aspirational treatments.

4. Managing agricultural landscapes for multiple ecosystem services

The ability to sustainably intensify agriculture depends largely on the non-commodity ecosystem services available for agricultural use now and into the future (Power 2010, DeClerck *et al* 2016). Two general models have emerged for sustaining necessary ecosystem services while increasing productivity in agricultural landscapes (Fischer *et al* 2008, Phalan *et al* 2011). One model, 'land sparing,' calls for designating some parcels for more intensive agricultural use while setting aside others as reserves for biodiversity maintenance and other related services. The other, 'land sharing,' emphasizes managing landscapes for both conservation and production outcomes, allowing for expansion of less intensive agricultural land uses depending on the situation (*sensu* Godfray and Garnett 2014). As the multifunctionality of agricultural lands is implicit in the agroecosystem concept (Altieri 2002), most of LTAR's aspirational systems are best described as 'land sharing' strategies: overall, the focus is less on regional land use planning and more on addressing how practices and overall management can protect and enhance ecosystem services on farms and ranches and the lands that surround them.

Overcoming barriers to adoption—new directions for sustainability research

Given the potential of the practices in the Common Experiment to advance strategies for sustainable intensification, it is important to ask why their adoption lags behind outreach (figure 5). LTAR scientists explained the lag as a function of costs, information deficits, and social norms (*sensu* figure 3), with the relative influence of these factors differing between practice types (figure 6). Trade-offs among environmental, economic, and social impacts of the practices were also identified as key issues influencing practice adoption. The development of strategies to overcome barriers to adoption of new practices constitutes a primary challenge for LTAR and other sustainability science institutions.

1. Costs

LTAR scientists generally consider cropland management practices to be widely promoted (figure 5) but lagging in adoption due to added costs (figure 6). Cover crops provide an instructive example. Intermittent cover crops can increase nutrient retention between cash crops, thereby lowering economic (and environmental) costs of fertilizers (Doran and Smith 1991, Meisinger *et al* 1991, Snapp *et al* 2005). However, extra labor, seed, and equipment requirements can increase costs by 2%–4% (Schnitkey *et al* 2016). Therefore, savings in fertilizer may be negated by added costs for management. Arguably, past research identifying certain benefits of cover crops has warranted extensive outreach about the practice; however, new knowledge about how to reduce costs for cover crop management is needed now.

Similarly, LTAR's enterprise management practices are increasingly recognized for certain benefits for sustainable intensification (Tilman *et al* 2002, Liebig *et al* 2017), but barriers to their adoption include costs related to regional processing and marketing (figure 6). Products from all of LTAR's aspirational systems can be considered 'sustainable,' 'green, or 'natural,' but a mismatch between niche products and existing processing and marketing mechanisms can prevent producers from achieving acceptable profits (Johnson *et al* 2012). Producer cooperatives may help overcome this barrier by filling processing gaps and advancing marketing opportunities though economies of scale (Gwin 2009). Depending on LTAR research results, producers adopting aspirational production systems may consider collectively marketing the potential of their products to sustain a variety of ecosystem services. In addition, many major food companies and non-governmental organizations are working to develop linkages with producers to improve agricultural sustainability (e.g. Maia de Souza *et al* 2017, Thomson *et al* 2017). LTAR may facilitate coordination of marketing cooperatives and corporate-NGO-producer partnerships, with added benefits of strengthening ties among stakeholders and expanding networked experimental research into the food system beyond farm and ranch gates (Macfadyen *et al* 2015).

While our synthesis suggests that added costs are primary considerations for producers considering adoption of cropland and enterprise management practices, net income from all agricultural production is generally low compared with other US professions (Fayer 2014). Accordingly, added costs and financial risks are key considerations for *all* producers (Tanaka *et al* 2011). Monetary assistance and incentives can help mitigate risks of adopting new practices (figure 3, Tanaka *et al* 2011, Boll *et al* 2015). Nonetheless, as exemplified by producers canceling USDA Conservation Reserve Program contracts when the price of corn increases (Kleinman *et al* in preparation), assistance and incentives for conservation-oriented practices are not yet consistently attractive or effective. These mechanisms may be improved by quantifying the monetary value of ecosystem services provided by business-as-usual versus aspirational management (Robertson and Swinton 2005, Brown and Havstad 2016). Such an accounting may help to ensure environmental, economic, and social equity among regions of the United States as the nation transitions to a new paradigm of sustainable intensification (Loos *et al* 2014, Robinson *et al* 2015). Further, equity *within* regions could be better understood through such an accounting. Most agricultural production takes place in rural areas, yet all Americans—urban and rural—consume the multiple ecosystem services provided by rural agricultural lands and the farmers and ranchers that tend them (Huntsinger and Oviedo 2014). Decades of out-migration have resulted in <20% of the US population residing in rural areas (Ratcliffe *et al* 2016, Cohen et al 2015). As a consequence, cities have increasingly become the centers of wealth while rural areas have remained relatively impoverished (USDA-ERS 2015). In addition, compared with urban areas, rural areas are at greater risk for economic losses due to climate change (Hsiang et al 2017). In light of these disparities, the flow of benefits from rural to urban areas should be quantified, and ways to adequately compensate rural producers for food production and other ecosystem services should be considered (*sensu* Gutman 2007).

2. Information deficits

Information deficits were frequently mentioned by LTAR scientists explaining the low outreach and adoption of grazingland management practices under investigation (figures 5 and 6; supplement 5). These observations might suggest that more basic research about potential benefits of these practices is needed before they can be widely recommended through outreach. For example, three experiments are evaluating the use of beef cattle that are postulated to be well-adapted to their local environments through smaller body sizes, earlier calving dates, or heritage genetics (table 1). While this approach is hypothesized to lower supplemental feed costs in the Southwest (Estell *et al* 2012) and reduce enteric methane production in the pasturelands of the Great Plains (Neel *et al* 2016), profitability may be compromised because the current beef cattle industry favors large and uniform body size at predictable times of the year (Scasta *et al* 2016). Such predictions about trade-offs between environmental quality and profitability are plausible, but as they have not yet been confirmed, more basic research is needed, including in the area of ecosystem service provision.

As discussed above, policy mechanisms to incentivize adoption of aspirational management approaches may be improved through ecosystem service valuation, but the accurate assessment of these values represents a critical information deficit. Spatially-explicit models that estimate service provision under different scenarios (e.g. Integrated Valuation of Ecosystem Services and Tradeoffs, 'InVEST'; Artificial Intelligence for Ecosystem Services, 'ARIES') could be especially useful for comparing the effects of management under aspirational versus business-as-usual paradigms as land uses and water availability change into the future. Scenario modeling could improve understanding of trade-offs among environmental, economic, and social effects of management under the two management scenarios (Nelson *et al* 2009)—knowledge identified as critical during our synthesis process. Further, such scenario modeling holds promise for extrapolating Common Experiment measurements to broader scales of agricultural organization. However, for such predictions to inform incentivization policies effectively, it will be imperative to quantify the uncertainty arising from extrapolating measurements across spatial and temporal scales and ecosystem service recipients (Hein *et al* 2006). With its significant spatial coverage and long-term trajectory, LTAR is in a unique position to partner with the modeling community to tackle these issues and even help to improve existing models. Synergistically, such modeling could help to unify how scientists across LTAR conceptualize ecosystem service flows, which could result in improved aspirational treatments as the Common Experiment evolves.

For any new information produced through modeling or other research efforts, effectively communicating that information will be key to advancing sustainable intensification. LTAR is poised to integrate voices from multiple disciplines to craft effective communication strategies for multiple sectors of agricultural stakeholders. For producers, trustworthiness of the source communicating information is paramount (Lubell *et al* 2014), and accordingly, LTAR is building on the strong tradition of the USDA Agricultural Research Service and other agricultural research organizations to conduct research in a participatory manner to maintain transparency and credibility. Increasingly, through emerging citizen science and open science platforms, producers and other stakeholders can engage in research directly, thereby expanding the interactive relationships between science support and producers (figure 3, Newman *et al* 2012, Herrick *et al* 2013). In addition, the USDA Climate Hubs are key partners for disseminating research results, with trusted connections with Cooperative Extension at land-grant universities and a proven track record of providing tools to help agricultural operations adapt to environmental changes (Elias *et al* 2017). To communicate with agricultural consumers at large, LTAR and other sustainability science institutions might consider locally appropriate, innovative technologies—such as software applications or 'apps' (Pitt *et al* 2011) and interactive displays in public spaces (Antle *et al* 2011)—that may improve overall agricultural literacy and ultimately inform consumer choices, a primary influence on producer decision-making (figure 3).

3. Social norms

Importantly, even if research reveals that LTAR's aspirational systems are optimal for production, profitability, and environmental quality, social norms could prevent their widespread adoption (figure 3). For instance, even if LTAR research demonstrates that using new livestock types can increase profitability and reduce impact to a given environment, longstanding norms tied to producer experiences and traditional use of particular breeds and sizes may prevail and ultimately prevent widespread adoption of the new types (Didier and Brunson 2004, Rodriguez *et al* 2008). Extending the Common Experiment questionnaires to producers could help illuminate how social norms and other factors such as social networks influence adoption of practices under investigation (Lubell *et al* 2013). Further, social networking technologies may help improve understanding of the interaction between public opinion and adoption of new practices and approaches (e.g. Barry 2014). Overall, understanding the influence of social factors on practice adoption and sustainable intensification will require increased, two-way collaboration and coordination among producers, agricultural stakeholders, and scientists from a diversity of disciplines (Lubell *et al* 2013).

Conclusion

The common experiment of the LTAR network seeks to produce new knowledge of agroecosystem functions and to understand how aspirational production systems may advance sustainable intensification in different regions of the United States. Network interactions can make research and discovery more efficient—several common themes emerge among the 21 local experiments, and working groups focused on these themes are likely to speed progress toward generally-applicable strategies and solutions (Carpenter *et al* 2009). Because the nature of sustainability challenges and innovations will evolve over time, and because our understanding of agroecosystems will also evolve with new technologies, models, and decision support tools, such efforts require long-term research investments. Importantly, investment toward adding new sites to the network will also be needed to fill gaps in our knowledge of regional agroecosystems.

One of the most important and least researched challenges for LTAR and other sustainability science networks is understanding how to overcome barriers to adoption of new practices. Partnerships among producers, policymakers, industry, and scientists should be strengthened to ensure that the merits of promising approaches are widely understood. These partnerships should also help LTAR researchers design approaches and communication strategies that are matched to local contexts and that account for the complex relationships between ecology, economics, and society. US LTAR and other long-term agroecosystem research networks will prove invaluable in our collective understanding of these complexities.

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