

# Advancing the Sustainability of US Agriculture through Long-Term Research

P. J. A. Kleinman,\* S. Spiegel, J. R. Rigby, S. C. Goslee, J. M. Baker, B. T. Bestelmeyer, R. K. Boughton, R. B. Bryant, M. A. Cavigelli, J. D. Derner, E. W. Duncan, D. C. Goodrich, D. R. Huggins, K. W. King, M. A. Liebig, M. A. Locke, S. B. Mirsky, G. E. Moglen, T. B. Moorman, F. B. Pierson, G. P. Robertson, E. J. Sadler, J. S. Shortle, J. L. Steiner, T. C. Strickland, H. M. Swain, T. Tsegaye, M. R. Williams, and C. L. Walthall

## Abstract

Agriculture in the United States must respond to escalating demands for productivity and efficiency, as well as pressures to improve its stewardship of natural resources. Growing global population and changing diets, combined with a greater societal awareness of agriculture's role in delivering ecosystem services beyond food, feed, fiber, and energy production, require a comprehensive perspective on where and how US agriculture can be sustainably intensified, that is, made more productive without exacerbating local and off-site environmental concerns. The USDA's Long-Term Agroecosystem Research (LTAR) network is composed of 18 locations distributed across the contiguous United States working together to integrate national and local agricultural priorities and advance the sustainable intensification of US agriculture. We explore here the concept of sustainable intensification as a framework for defining strategies to enhance production, environmental, and rural prosperity outcomes from agricultural systems. We also elucidate the diversity of factors that have shaped the past and present conditions of cropland, rangeland, and pastureland agroecosystems represented by the LTAR network and identify priorities for research in the areas of production, resource conservation and environmental quality, and rural prosperity. Ultimately, integrated long-term research on sustainable intensification at the national scale is critical to developing practices and programs that can anticipate and address challenges before they become crises.

## Core Ideas

- The LTAR network was established to enhance the sustainability of US agriculture.
- The LTAR "common experiment" compares business as usual with aspirational management.
- LTAR sites contribute research observations to the network's database.
- LTAR network research will support sustainable intensification strategies.

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\*Corresponding author (Peter.Kleinman@ars.usda.gov).

**G**LOBAL DEMAND for food, feed, fiber, and energy is increasing rapidly as the world's population approaches 9 billion people and lifestyles shift with demographic transitions spurred by economic development (von Braun, 2007). Agricultural producers in the United States now face unprecedented economic opportunity from new markets, but this comes amid increasing pressures to conserve natural resources, support rural economies, and enhance ecosystem services whose relationships to agriculture are not yet fully understood (Gold, 1999; Millennium Ecosystem Assessment, 2005; Woteki, 2012; Robertson et al., 2014). These opportunities and pressures must be treated as a single, multifaceted challenge—to advance agriculture that is economically, socially, and environmentally sustainable.

Sustainable agriculture must balance short-term management decisions with long-term planning so that production can adapt to changing pressures and demands and recover from periodic crises (United Nations, 1987; Ruttan, 1999). When applied to farming systems, sustainability implies financial stability, resilience to market and environmental shocks, resource conservation, family and community sustenance, and consistency with value systems (National Research Council, 2010). When applied

P.J.A. Kleinman, S.C. Goslee, R.B. Bryant, USDA–ARS Pasture Systems and Watershed Management Research Unit, University Park, PA 16802; S. Spiegel and B.T. Bestelmeyer, USDA–ARS Range Management Research Unit, Las Cruces, NM 88003; J.R. Rigby and M.A. Locke, USDA–ARS National Sedimentation Lab., Oxford, MS 38655; J.M. Baker, USDA–ARS Soil and Water Management Research Unit, St. Paul, MN 55108; R.K. Boughton, Univ. of Florida Range Cattle Research and Education Center, Ona, FL 33865; M.A. Cavigelli and S.B. Mirsky, USDA–ARS Sustainable Agricultural Systems Lab., Beltsville, MD 20705; J.D. Derner, USDA–ARS Rangeland Resources and Systems Research Unit, Cheyenne, WY 82009; E.W. Duncan and K.W. King, USDA–ARS Soil Drainage Research Unit in Columbus, OH 43210; D.C. Goodrich, USDA–ARS Southwest Watershed Research Center, Tucson, AZ 85719; D.R. Huggins, USDA–ARS Northwest Sustainable Agroecosystems Research Unit, Pullman, WA 99164; M.A. Liebig, USDA–ARS Northern Great Plains Research Lab., Mandan, ND 58554; G.E. Moglen, USDA–ARS Hydrology and Remote Sensing Lab., Beltsville, MD 20705; T.B. Moorman, USDA–ARS National Lab. for Agriculture and the Environment, Ames, IA 50011; F.B. Pierson, USDA–ARS Northwest Watershed Research Center, Boise, ID 83712; G.P. Robertson, Dep. of Plant, Soil and Microbial Sciences at Michigan State Univ., Hickory Corners, MI 49060; E.J. Sadler, USDA–ARS Cropping Systems and Water Quality Research Unit in Columbia, MO 65211; J.S. Shortle, Penn State Univ., State College, PA 16802; J.L. Steiner, USDA–ARS Grazinglands Research Lab., El Reno, OK 73036; T.C. Strickland, USDA–ARS Southeast Watershed Research Lab., Tifton, GA 31793; H.M. Swain, Archbold Biological Station, Venus, FL 33960; T. Tsegaye and C.L. Walthall (retired), Natural Resources and Sustainable Agricultural Systems, USDA–ARS, Beltsville, MD 20705; M.R. Williams, USDA–ARS National Soil Erosion Research Lab., Lafayette, IN, 47907. USDA is an equal opportunity provider and employer. Assigned to Technical Editor Rodney Venterea.

**Abbreviations:** LTAR, Long-Term Agroecosystem Research.

to agroecosystems, sustainability acknowledges management impacts on biodiversity, biogeochemical processes, and socioeconomic dynamics that frequently manifest at scales beyond the farm gate (for the purposes of this paper, *farm* refers to farms and other agricultural enterprises, including ranches). For agricultural industries, sustainability connotes brand and market preservation, adaptation to consumer priorities, and regulatory compliance. As defined by the US National Research Council (2010), a sustainable US agriculture would

- satisfy human food, feed, and fiber needs, and contribute to biofuel needs,
- enhance environmental quality and the resource base,
- sustain the economic viability of agriculture, and
- enhance the quality of life for farmers, farm workers, and society as a whole.

Agriculture in the United States is diverse, spanning gradients in scale, climate, physiography, ecology, economics, and culture (Zhang et al., 2007). These many dimensions confound uniform approaches to achieving sustainable production systems. Complications extend from local constraints to systemic factors that will not bend to simple solutions. Well-documented changes in environmental conditions (e.g., climate change, soil erosion, nutrient accumulation) present geographically uneven pressures on agriculture by disrupting historical norms, from lengthened growing seasons that also expand the ranges of pests to greater frequency and severity of extreme weather events that affect field management in many ways (Walthall et al., 2012). At the same time, farmers have little control over the price of their output. Farm gate sales account for only 15% (varying from 8 to 54%, depending on product) of the price of food in the grocery store (Schnepf, 2013). International markets influence local pricing; exports consume roughly 20% of US crop production. In addition, the loss of farmland to other uses, especially peri-urban development, remains a threat to production in some regions, with nearly half of the value of national farm output located in US counties under urban expansion (American Farmland Trust, 1994, 2015).

The combined demands for greater production and less environmental impact require scalable strategies that more efficiently invest resources for food, feed, fiber, and energy production. Such strategies must also mitigate trade-offs produced when concurrently pursuing production and environmental objectives. Thus, the Long-Term Agroecosystem Research (LTAR) network was established to conduct systems-level research integrating production, environmental, and rural prosperity objectives to provide a vision for ensuring the long-term sustainability of US agriculture. Here, we

- introduce the concept of sustainable intensification as a means of defining strategies for enhancing production, environmental, and rural prosperity outcomes from agricultural systems;
- describe the LTAR network as a program for developing, testing, and communicating technologies, practices, and information facilitating the sustainable intensification of US agriculture;
- elucidate the diversity of factors that have historically influenced the long-term sustainability of cropland,

rangeland, and pastureland agroecosystems in the United States; and

- identify priorities for research aimed at the sustainable intensification of US agriculture.

## Sustainable Intensification as a Process for Achieving a Sustainable Agriculture

In light of the increasing demand for protein-rich food and the need to conserve natural resources for future generations, there has been a call for *sustainable intensification*— increasing food security while shrinking the environmental footprint of agriculture, two broad objectives that can often be at odds (Garnett et al., 2013). Sustainable intensification has evolved rapidly as a concept, but, as with any overarching ambition, sustainable intensification has spent its early existence in a theoretical realm with limited application to real-world conditions (Petersen and Snapp, 2015). Sustainable intensification has been applied to many elements of agricultural production and consumption, from production in fields and farms to processing, distribution, markets, and waste recovery (Godfray and Garnett, 2014), and is a useful concept for linking broad, societal demands to local agricultural production systems, ideally enabling a diversity of strategies to ensure that these local systems will be sustainable over time and across multiple scales.

Early debate over sustainable intensification and a long history of research on sustainable agriculture highlights the need for flexibility in the application of sustainable intensification to agricultural development (Godfray and Garnett, 2014). A variety of tactics have been proposed: halting the expansion of agriculture into sensitive or marginal ecosystems; closing yield gaps on underperforming areas of production; increasing efficiencies in nutrient, water, and agrichemical use; reducing post-harvest losses (Foley et al., 2011); and expanding the consideration of non-commodity ecosystem services in decision making (Millennium Ecosystem Assessment, 2005). These tactics have been tested in various settings, but their success as part of large national or multinational campaigns to promote sustainable agricultural systems remains open to assessment. Not surprisingly, it has been argued that for sustainable intensification strategies to be achievable and equitable, new sources of revenue are needed beyond traditional income bases (Loos et al., 2014).

Sustainable intensification clearly shows potential to achieve national goals for agriculture. When applied to a nation as large as the United States, sustainable intensification strategies that simultaneously maximize yield and minimize environmental impacts will need to vary strongly across the nation's climatic, edaphic, political and socioeconomic gradients (Garnett, 2013). Underlying conditions vary considerably across the range of US production systems, pointing to the need for regionally defined objectives that meet local, regional, and national goals. While these goals may change with time, in the United States they have consistently fallen under the trifecta of (i) increasing production to meet growing national ambitions for food, fuel, feed, and fiber; (ii) conserving the nation's natural resources and protecting its environment; and (iii) promoting the prosperity of rural populations.

# The Long-Term Agroecosystem Research Network

In pursuit of sustainable US agriculture and in response to calls by the scientific community for long-term investments in sustainable agriculture research (Robertson et al., 2008), the USDA launched the LTAR network (Walbridge and Shafer, 2011). The LTAR network is grounded in empirical experimentation and coordinated observation that seeks to develop a national roadmap for the sustainable intensification of agricultural production in the face of a diverse range of agricultural stressors and expectations. Starting with research on the constraints to production, profitability, and non-commodity ecosystem services at field, operation, and watershed scales, the LTAR network is working to link locally defined advances in agricultural production to broader supply chains, impacts, and contexts. Anticipated products from LTAR include decision support tools, technologies, and management practices that can be directed toward the broader sustainable intensification of US agriculture.

The LTAR network is currently represented by 18 locations across the contiguous United States (Fig. 1). Historical experimentation and monitoring at LTAR locations averages 55 years, spanning 19 to more than 100 years (Table 1). Network science is grounded in local, empirical research, with a focus on connecting experimentation and monitoring to an understanding of the state and potential of US agroecosystems, recognizing that agriculture is also organized and influenced by specific industries, markets, and policies (Spiegel et al., 2018). The LTAR network's agroecosystems, which define the local conditions of inference, include a diversity of annual row cropping systems and grazing lands, representative of roughly 49% of cereal production, 30% of forage

production, and 32% of livestock production in the United States. As the USDA expands its investment in LTAR, new locations are being established (e.g., a California site, which is not represented here, was added to the network just prior to publication) to include broader geographic coverage and additional production systems. As LTAR network research evolves, new partnerships are anticipated to ensure LTAR's relevance to US agriculture as a whole and agroecosystems in particular (Walbridge and Shafer, 2011).

Operationally, the LTAR network is focused on topics of cropland and grazing land sustainability with regional or national consequence. At the core of LTAR is a common experiment, which contrasts "business-as-usual" management and "aspirational" management strategies that sustainably intensify production (Spiegel et al., 2018). All sites seek to test strategies that increase productivity and profitability of agriculture while reducing environmental impacts, with broader objectives refined locally to meet the realities and needs of producers, ecosystems, and communities. Common long-term measurements enable cross-site comparison, as well as integration of findings at broader spatial and temporal scales, supported by a suite of long-term databases for internal and external use (Kaplan et al., 2017). Computational modeling applied consistently to each network site (e.g., Arnold et al., 1998; Rotz et al., 2015) will serve to extrapolate findings and connect LTAR network hypotheses to sustainability outcomes for the nation's food, feed, fiber, and energy supply chains (Macfadyen et al., 2015). Strong ties to federal and state research, teaching, and extension programs across the United States ensure that research data and inferences will be disseminated and applied.

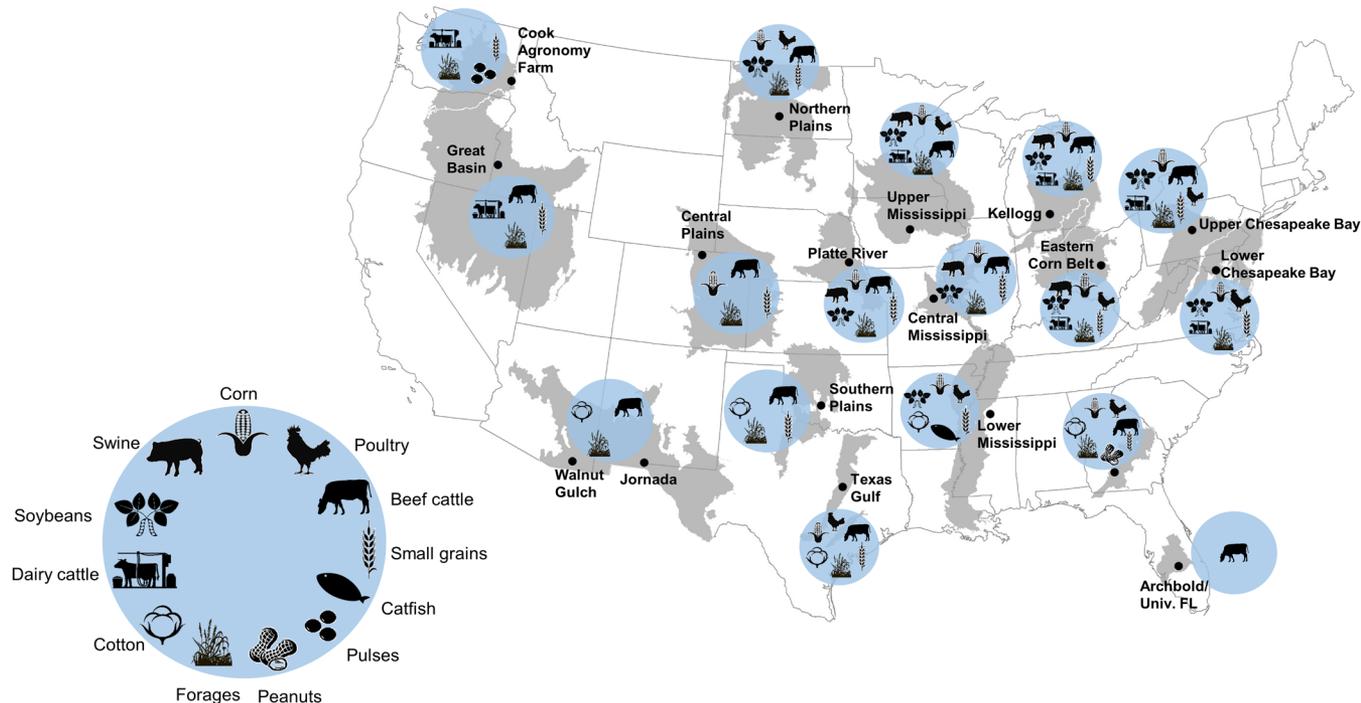


Fig. 1. The 18 LTAR network sites and the major agricultural commodities associated with their agroecological regions. Representation of agricultural commodities for each region corresponds with Table 1. Gray areas represent estimated regional inference spaces of the LTAR sites.

# Factors Affecting the Sustainability of Cropland Agroecosystems

Historical trends in US cropland agroecosystems highlight the developments that have propelled US productivity to today's record high levels, but they also illustrate the constraints and possibilities provided by information, culture, policy, and markets. The United States' 160 million ha of croplands have long been a foundation of the US economy, supporting its relationship with the world through trade and humanitarian support and enabling the growth of its urban populations. Since World War II, US croplands have undergone profound change in management intensity and productivity. Crop yields, a core measurement of

productivity, have increased roughly threefold since World War II (USDA Economic Research Service, 2016a) (Fig. 2).

Advances in fertilizers, crop breeding, pest control, irrigation, equipment, and drainage have all contributed to crop production increases. Mechanization has enabled economies of scale not possible under earlier agronomic practices (Tilman et al., 2002), while simultaneously eliminating the need to devote substantial land area to the production of feed (e.g., oat, *Avena sativa* L.) for draft animals. More recently, the precision farming tools of the modern information era are extending trends in productivity displayed in Fig. 2 (Gebbers and Adamchuk, 2010), as well as improving efficiencies in production that allow yield goals to be achieved with fewer inputs (Balafoutis et al., 2017). Further growth in productivity requires strategies that seek to optimize

**Table 1. General characteristics of LTAR network sites. Agricultural commodities listed for each region correspond with USDA National Agricultural Statistics Service (2012) data for the counties overlapping ≥50% with each regional footprint (Fig. 1). The products listed reflect both the region's largest contributions to the national yield and products under study by LTAR.**

LTAR network site	Year established	Focal production systems	Major agricultural commodities†	Cereal crops	Forages	Cotton	Livestock and poultry
				— % of national yield —			% of national sales
Archbold Biol. Station/ University of Florida	1941	Rangeland, pastureland	<b>Beef cattle</b> , citrus	0	0.5	0	0.6
Central Mississippi River Basin	1971	Cropland, pastureland	Beef cattle, swine, <b>corn, soybeans, wheat</b> , forages	2.2	0.9	0	0.8
Central Plains Experimental Range	1939	Cropland, rangeland	<b>Beef cattle</b> , corn, wheat, <b>forages</b>	4	2.2	0	6.2
Cook Agronomy Farm	1998	Cropland, rangeland	Dairy cattle, <b>small grains (wheat, barley)</b> , <b>pulses</b> , forages, oilseeds	1.7	1.8	0	1
Eastern Corn Belt	1974	Cropland, pastureland	Dairy cattle, poultry, swine, <b>corn</b> , soybeans, wheat, forages	4	0.7	0	1.7
Great Basin	1961	Pastureland, rangeland	<b>Beef cattle</b> , dairy cattle, barley, <b>forages</b>	0.9	5.9	0	2.9
Gulf Atlantic Coastal Plain	1965	Cropland, pastureland	Beef cattle, poultry, corn, <b>peanuts, rye</b> , vegetables, <b>forages, cotton</b>	0.2	0.2	9.2	0.4
Kellogg Biological Station	1987	Cropland, pastureland	Dairy cattle, swine, <b>corn, soybeans, small grains (wheat, oats, rye)</b> , forages	3.6	1.4	0	1.8
Lower Chesapeake Bay	1910	Cropland, pastureland	Dairy cattle, poultry, <b>corn, soybeans, small grains (wheat, barley, rye)</b> , forages	1.2	1.3	0	2
Lower Mississippi River Basin	1981	Cropland	Catfish, poultry, <b>corn, soybeans, wheat</b> , rice, sugar cane, <b>cotton</b>	3.2	0.7	20.6	0.7
Northern Plains	1912	Cropland, pastureland, rangeland	Beef cattle, sheep, <b>corn, soybeans, small grains (wheat, barley, oats)</b> , <b>forages, oilseeds</b>	3.7	2.5	0	0.8
Platte River/High Plains Aquifer	1912	Cropland, pastureland	<b>Beef cattle</b> , swine, <b>corn, soybeans, wheat, forages</b>	6.4	1.5	0	4
Southern Plains	1948	Cropland, pastureland	<b>Beef cattle, small grains (wheat), forages, cotton</b>	1.4	1.6	1.4	1.2
Texas Gulf	1937	Cropland, pastureland, rangeland	<b>Beef cattle</b> , poultry, <b>corn</b> , cotton, <b>small grains (wheat, oats), forages</b>	0.5	1.5	1.1	0.4
Upper Chesapeake Bay	1968	Cropland, pastureland	Beef cattle, <b>dairy cattle</b> , poultry, <b>corn, soybeans, small grains (wheat, barley, oats, rye), forages</b>	0.7	2.8	0	2.4
Upper Mississippi River Basin	1992	Cropland, pastureland	Beef cattle, dairy cattle, swine, poultry, <b>corn, soybeans</b> , oats, forages	15.1	3.8	0	6.8
Jornada Experimental Range‡	1912	Pastureland, rangeland	<b>Beef cattle, forages</b> , cotton	0	0.7	0.9	0.3
Walnut Gulch Watershed	1953						

† Research foci in bold type.

‡ The Jornada Experimental Range and Walnut Gulch Experimental Watershed share a region.

the interaction of crop genetics with environmental limits and management options, making genetics  $\times$  environment  $\times$  management a central organizing principle of LTAR sustainable intensification research (Hatfield and Walthall, 2015).

The greater productivity of US agriculture has been a boon to the US consumer, as grocery store prices for farm commodities have fallen by roughly two-thirds since World War II. And since 1960, the fraction of disposable income spent by US consumers on food has fallen from 16 to 10% (USDA Economic Research Service, 2016b). Many of the practices and technologies responsible for the nation's yield increases have required greater inputs, with total farm expenditures for inputs having increased nearly an order of magnitude since World War II (USDA Economic Research Service, 2016b). From the 1940s to the present, net returns to farm operators declined roughly threefold (Henderson et al., 2011), pressuring farmers to increase economic efficiencies (e.g., by increasing landholdings). At the same time, farmers are responding to societal demand for noneconomic priorities, from natural resource conservation to food safety to nutrition (Nowak and Korsching, 1998), as well as changing demand for alternatively grown foods, such as organic foods. Government commodity, insurance and conservation programs have helped to buffer these pressures, with total payments to farmers increasing nearly 18-fold since 1960 to \$16.9 billion in 2015 (McFadden and Hoppe, 2017). Cropland research sites in LTAR's network are exploring a range of opportunities to augment farm income without resorting to fencerow-to-fencerow crop cultivation, from commercially acceptable strategies to lower energy, fertilizer, and pesticide purchases (bioenergy crops [Coffin et al., 2016], improved manure nutrient use [Rotz et al., 1999], diverse crop rotations and pest control alternatives [Teasdale et al., 2005]) to strategies that augment commodity quality and value (improving organic production systems [Cavigelli et al., 2013], new crop rotations and commodities [Karimi et al., 2017]) to more efficient use of agricultural landscapes (watershed strategies to target crop production and conservation practices [Tomer et al., 2015a,b]).

Over the 20th century, gains in production intensity have been accompanied by specialization of cropland farming. This trend has increased cost efficiencies (Winsberg, 1982) while reducing on-farm crop diversity. From 1900 to 1945, individual US farms produced four to five commodities; by 1970, the number of commodities per farm declined to an average of three, and by 2000 to approximately two (Dimitri et al., 2005). Across the 18 LTAR locations, corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) are most widely grown (Fig. 3). Even in regions with small farms historically growing more diverse crop rotations, corn and soybean

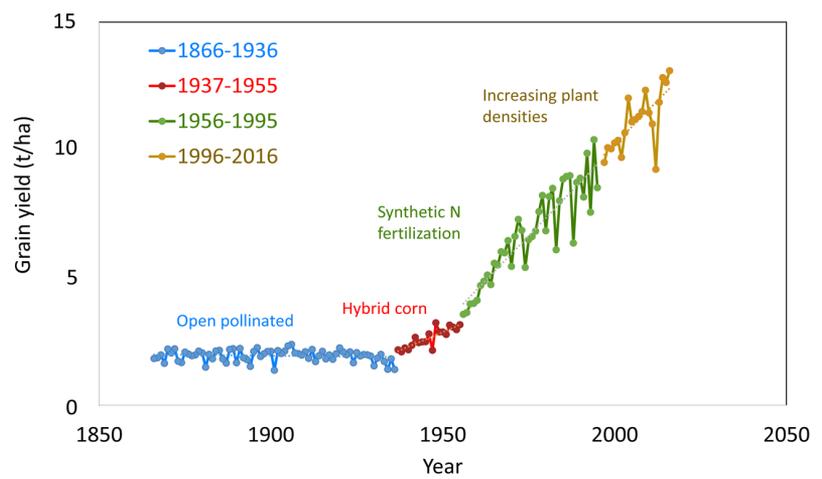


Fig. 2. Historical US corn grain yields. Adapted from Duvick (2005) and USDA National Agricultural Statistics Service (2012). Courtesy of H. Poffenberger.

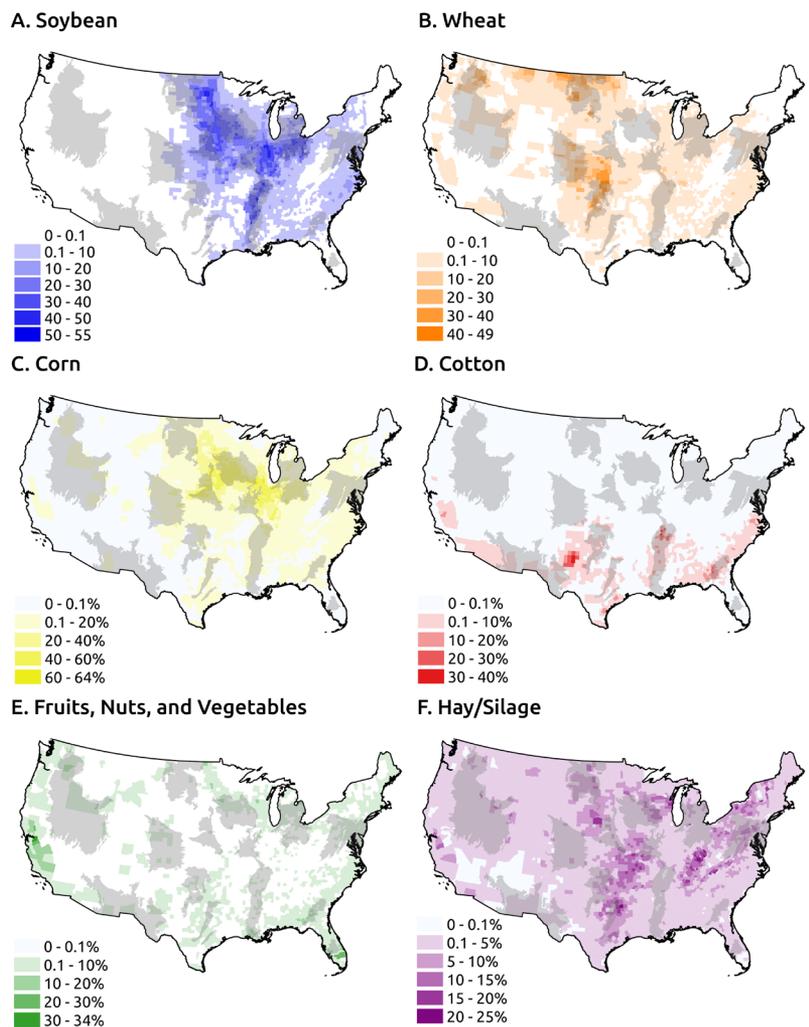


Fig. 3. Percentage of land in the conterminous United States dedicated to each crop in 2012 by county. Adapted from USDA National Agricultural Statistics Service (2012). Category "Fruits, Nuts, and Vegetables" includes citrus and non-citrus fruit, berries, vegetables harvested, tree nuts, peanut, sugarbeet, and sugarcane. Gray areas represent estimated regional inference spaces of the LTAR sites.

comprise substantial amounts of the rotation (Jones and Farley, 2016). Corn and soybean currently account for 58% of the total cropland area of LTAR's agroecosystems. It is now understood

that the loss of diversity introduces vulnerabilities to the nation's crops from stressors such as pests, weather, markets, and potentially, soil health. This is perhaps best exemplified by the 1970 and 1971 infestation of southern corn leaf blight [caused by *Bipolaris maydis* (Y. Nisik. & C. Miyake) Shoemaker], resulting in an estimated economic loss of \$1 billion across the United States (roughly \$6.5 billion in today's value). The average yield loss across the United States was 20 to 30%, but losses in parts of LTAR's eastern Corn Belt region were as high as 50 to 100% (Bauer, 1972; Ullstrup, 1972). Today's dependence on a limited set of herbicide-resistant corn and soybean hybrids has, in turn, spurred the evolution of herbicide resistance in weeds, most notably Palmer amaranth (*Amaranthus palmeri* S. Watson) and waterhemp [*A. tuberculatus* (Moq.) Sauer] (see Case Study 1). Thus, LTAR's sustainable intensification research emphasizes strategies to diversify cropping systems (intercropping, cover crops [Varvel, 2006]), as well as alternative approaches to weed management (Nord et al., 2012).

Although a majority of US crops are grown in agroecosystems where both crop and animal production occur, the specialization of agriculture has increasingly separated their management. As illustrated by LTAR's agroecosystems, animal production systems are often geographically separated from the major cropping systems that serve as the source of feed. This uncoupling of systems results in flows of resources, particularly nutrients, that can accumulate around areas of livestock production and, over time, contribute to an array of environmental concerns (Sharpley et al., 2013). Cropping systems, particularly corn- and soybean-dominated systems, are primarily dependent on synthetic fertilizers for crop nutrition. On average, only 5% of the nation's cropland is fertilized with manure (USDA Economic Research Service, 2009), although local rates of cropland manure application can be considerably higher (e.g., approximately 17% of Iowa cropland receives manure [Iowa State University, 2014]). Yet, a majority of US soybean and corn is fed to farm animals (Denicoff et al., 2014). Since animals metabolize less than one-third of the

nutrients in feed, the majority of nutrients in corn and soybean they eat neither appears on the plates of US consumers nor is returned to the cropland where the feed originated (Elser and Bennett, 2011; Lanyon, 2000). Instead, these nutrients enrich animal manure, which, in turn, is typically applied, often in excess, to farmland near animal production areas where it may contribute to air and water quality degradation that can take decades to reverse (Sharpley et al., 2013). To elucidate the impact and management of manure nutrients in uncoupled cropland and animal production systems, LTAR network research relies on system-level analyses at farm, watershed, and regional scales (Rotz et al., 1999; Liebig et al., 2004; Nearing et al., 2011; Collick et al., 2016). Indeed, more efficient cycling of manure nutrients and substitution of manure nutrients for mineral fertilizers in cropping systems is a major focus of sustainability research in one-third of LTAR's 18 network sites (Spiegel et al., 2018), recognizing that such recoupling of production systems will ultimately require major changes to infrastructure, policy, and management if it is to be achieved (Liebig et al., 2017).

The modern conservation movement was born, in large part, out of concerns about cropland farming in the first half of the 20th century: the Dust Bowl of the Great Plains in the 1930s, the general loss of productivity from farmland, impacts to water and air, and impairment of a host of ecosystem services that benefit rural communities in the United States (Bennett and Chapline, 1928; Leopold, 1949). Conservation activities compete with other priorities on US croplands, principally those derived from the pursuit of profitability but also priorities derived from belief systems and local cultural practices and made possible by constantly evolving technologies (Ervin and Ervin, 1982; Knowler and Bradshaw, 2007). All LTAR network locations have witnessed major historical declines in the extent of conservation set-asides (e.g., buffer strips and idle land), the principal policy tool used to protect soil and water as well as to provide habitat for pollinators and wildlife (Kremen et al., 2002; Swinton et al., 2007; Lark et al., 2015). When commodity prices soared after

## Case Study 1 Central Mississippi LTAR Site

Straddling the Mississippi River, LTAR's Central Mississippi agroecosystem occupies the glacial till plains of northern Missouri and western Illinois. Average yields doubled with the advent of the Green Revolution, from 2.6 Mg ha<sup>-1</sup> in 1950 to 5.2 Mg ha<sup>-1</sup> in 1975. Over the same time, agricultural employment declined from 33% to less than 15% of the labor force in the region, even while cropland expanded by nearly 10% (USACE, 1975). During the 1970s and early 1980s, mean debt of Missouri farmers nearly tripled (Missouri led the nation in farm bankruptcies in 1985), prompting many small- to mid-sized farms to abandon integrated crop-livestock production for more specialized and profitable grain production systems (Demissie, 1986). Since that period, farming systems in the Central Mississippi region largely retained their separate specialized grain and livestock production systems.

In recent decades, multiple new pests have presented broader challenges to agriculture in the region. Glyphosate-resistant soybean and corn have simplified weed control and have helped to expand no-till cropping systems with associated erosion control benefits. However, weeds such as Palmer amaranth and waterhemp have recently become resistant to glyphosate and are aggressively invading fields where glyphosate is the principal herbicide (Ward et al., 2013). Growing 2 to 6 cm daily, a single Palmer amaranth plant produces up to 1 million seeds, spreading quickly and reducing yields by as much as 79% for soybean. Current strategies for effective control of infested fields involve diversified approaches to herbicide selection and, once the weed is established, deep, inversion tillage, which is considered anathema to soil conservation objectives.

Sustainable intensification strategies in the Central Mississippi agroecosystem seek to address yield gaps as well as to ensure greater stability in yields over the long term in the face of climate change. Key opportunities at the farm level include greater adoption of precision management and variable rate application technologies. These technologies are also expected to drive reductions in both greenhouse gas emissions and nitrate losses to ground and surface waters. The persistence of soil conservation concerns and the evolving paradigm of soil health highlight opportunities for both improving productivity of farm soils and reducing off-site impacts through practices such as reduced tillage and use of cover crops.

2008, economic incentives to grow grains, particularly corn, exceeded the national average rental of \$140 ha<sup>-1</sup> by USDA's Conservation Reserve Program. In 2012, there was a net loss in nearly every LTAR region of Conservation Reserve Program contracts, as even marginal land was converted to commodity production (Fig. 4; Lark et al., 2015). Acknowledging the primacy of economics in determining conservation outcomes, a major theme of LTAR's sustainable intensification research is to define landscape management strategies that increase the productivity of prime cropland while finding economically viable alternative land uses for marginal lands that also reduce negative environmental impacts (Spiegel et al., 2018).

Across the United States, cropland agriculture is the single greatest consumer of fresh water, a pattern that has not changed since early settlement times. Indeed, in much of the western United States, settlement and cropland establishment required irrigation development. Given irrigation's potential to increase crop yield and quality, reduce pest pressures, precisely deliver nutrients, and buffer against the uncertainty of weather, irrigation can be found in nearly all LTAR cropland agroecosystems. Today, irrigation represents about two-thirds of the nation's groundwater use, with some of the greatest expansions occurring after World War II through the early 1980s (Maupin et al., 2014). Extraction of groundwater in some of the nation's most productive agricultural regions exceeds groundwater recharge, resulting in long-term declines in water levels (Reilly et al., 2008). Regions represented by LTAR's Central Plains, Southern Plains, and Platte River/High Plains sites, which account for 11% of US irrigated crop production (Gollehon and Winston, 2013), all rely on the Ogallala High Plains aquifer, which is declining in many areas. Even in the humid Lower Mississippi River valley, rapid increases in demand for irrigation from the Mississippi River valley alluvial aquifer since the 1980s have resulted in

major groundwater declines in some areas. To address the sustainability of irrigated agriculture, LTAR network sites in arid and humid regions alike are pursuing new water management strategies (Baker et al., 2012), from precision sprinkler irrigation systems to water-conserving cropping systems to large-scale managed aquifer recharge.

The relationship of agriculture to rural communities in the United States has changed over time, reflecting trends in globalization, agricultural policy, and major demographic shifts. With increasing mechanization, greater efficiencies in production, and the growth of urban job opportunities, farm populations decreased from nearly 40% of the United States population in 1900 to approximately 25% of the population in 1940 to only 1% after 2000 (Dimitri et al., 2005; USDA Economic Research Service, 2016a). While wages for US farm laborers have grown more than other farm inputs during that time, strong competitive pressures exist to minimize labor costs to ensure the low cost of agricultural products. In 2012, hired farm labor wages averaged \$10.80 h<sup>-1</sup> (USDA National Agricultural Statistics Service, 2012), 40% below the US median wage. As US farmers have aged (average age is currently 58 years compared with 42 years for the nation's workforce as a whole), dependence on contractual labor has dramatically increased, as has the cultural diversity of rural communities (USDA Economic Research Service, 2016c). Agricultural land ownership has also changed dramatically in the United States (Fig. 5). From 2006 to 2015, cropland values in the United States increased from \$5,400 to \$9,900 ha<sup>-1</sup>, respectively, serving as a major barrier to recruitment of new farmers (USDA National Agricultural Statistics Service, 2016). In LTAR's eastern Corn Belt region, almost half of cropland is rented or leased (USDA National Agricultural Statistics Service, 2012; Reimer et al., 2012), and rental agreements requiring the maintenance of soil fertility levels have interfered with local

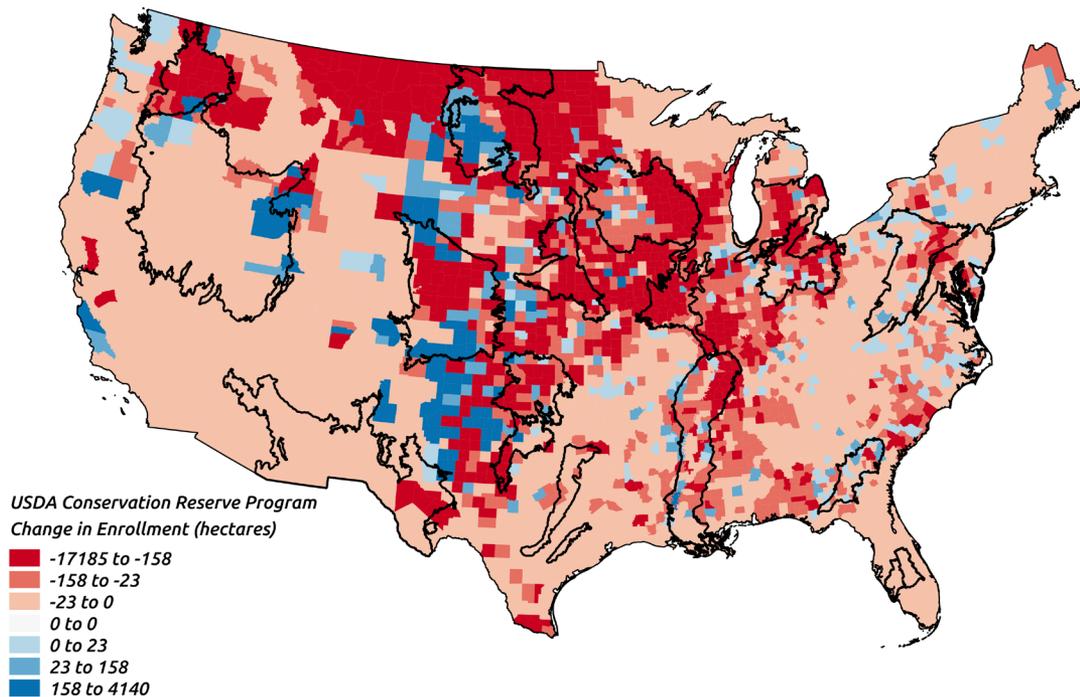


Fig. 4. USDA Conservation Reserve Program changes in enrollment by county from 2013 to 2014. Adapted from USDA Farm Service Agency (2017). Contracts expire on 30 September, and most new contracts begin 1 October. Black polygons represent estimated regional inference spaces of the LTAR sites.

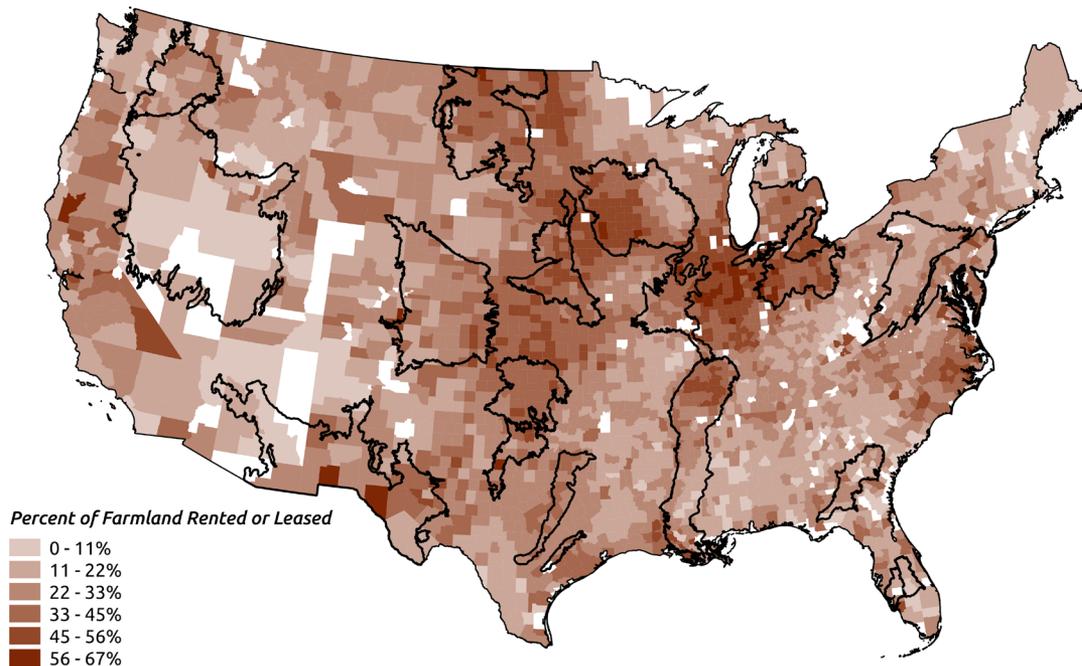


Fig. 5. Percentage of US farmland rented or leased by county, 2012. Adapted from USDA National Agricultural Statistics Service (2012). Black polygons represent estimated regional inference spaces of the LTAR sites. Data were not available for counties colored white. Black polygons represent estimated regional inference spaces of the LTAR sites.

water quality mitigation efforts (King et al., 2017). Sustainable intensification strategies must take into account the myriad of social and economic factors that simultaneously influence adoption of new practices, alter expectations of rural workforces, shift market opportunities, and change rural life in other ways.

## Factors Affecting the Sustainability of Grazing Agroecosystems

Grazing agroecosystems include both rangelands and pasturelands and constitute the single most extensive land use in the conterminous United States, accounting for 319 million ha, approximately 40% of the land area of the 48 contiguous states (Fig. 6). Grazing lands are typically associated with areas that are unsuitable or undesirable for crop production (e.g., poor soils or low rainfall), although prime cropland may also be grazed profitably. Opportunities for sustainable intensification of grazing agroecosystems include strategies aimed at balancing both animal and forage productivity, strategies that offer access to premium markets (e.g., organic, grass-fed), and strategies aimed at ensuring long-term resilience in the face of uncertain climatic, fire, and biotic stressors. Notably, grazing agroecosystems provide key opportunities to recouple animal, forage, and feed production systems and therefore must ultimately be linked to cropland strategies. Sustainable intensification of grazing lands must look beyond the scale of individual management units (fields, paddocks) and even individual enterprises to consider the production potential and non-commodity ecosystem services of the surrounding landscape, as well as opportunities for optimizing interacting regional and national animal feed production systems. Although rangelands and pasturelands differ in core management approaches and ownership patterns, both provide a wealth of non-commodity ecosystem services—freshwater

storage, soil carbon storage, habitat for flora and fauna, and aesthetics—that should be considered in sustainable management strategies (Havstad et al., 2007; Sanderson et al., 2012).

## Rangelands

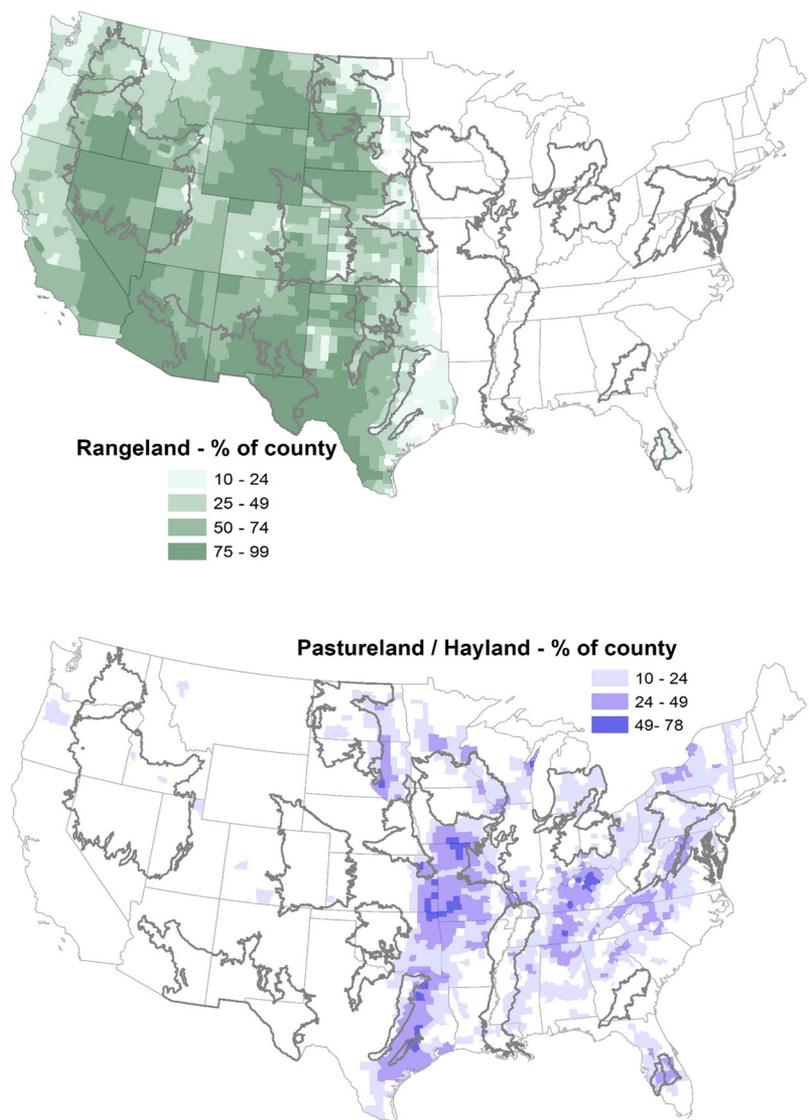
America's rangelands—the uncultivated grasslands, shrublands, and savannas that cover about one-third of the contiguous 48 states—span LTAR's desert, mountain, Great Plains, and subtropical coastal ecosystems (Fig. 6) and supply approximately 10% of the total feed needs for US beef, sheep, and goat production (Havstad et al., 2007). As rangelands are, by definition, managed as semi-natural systems (Society for Range Management, 1998), options to sustainably intensify production are constrained relative to pasturelands and croplands. Ranchers are particularly susceptible to the vagaries of weather and markets, resulting in economic returns that vary widely with drought, supplemental feed availability, feedlot grain prices, and consumer demand (Torell et al., 2010). In addition, depending on the relative importance of private and public lands in the regional portfolio, ranchers' access to a land base sufficient for livestock forage requirements are complicated by rising private land costs and by difficulties retaining leases on public land as agency mandates change (Tanaka et al., 2005; Brunson and Huntsinger, 2008). Nonetheless, opportunities exist to improve rangeland production and profitability while sustaining rangeland ecological integrity for long-term production. The LTAR network rangeland sites are evaluating strategies that simultaneously increase forage utilization, reduce environmental impacts, and enhance preparedness for accelerating climate variability, including collaborative adaptive grazing management (Derner and Augustine, 2016), breed selection (Anderson et al., 2015; Neel et al., 2016), grass finishing (Diaz et al., 2015), and

innovative prescribed burning practices (Derner et al., 2009; Boughton et al., 2013).

Many of the rangeland regions represented by LTAR have undergone profound shifts in vegetation during recent centuries, and opportunities for sustainable intensification are closely tied with these regional histories. The regional agroecosystems represented by the Great Basin, Jornada, and Walnut Gulch sites have experienced dramatic plant invasions, altering biodiversity, forage availability, soil health, and hydrology (see Case Study 2). A principal focus at these sites is to evaluate whether ecological restoration can improve both forage availability and biodiversity (Bestelmeyer et al., 2018; Goodrich et al., 2015; Williams et al., 2016). Elsewhere, LTAR's Floridian rangelands have been profoundly altered by large-scale manipulation of water and fire regimes, changing the extent of grasslands, composition of habitat, and accompanying diversity (Bridges, 2006). There, LTAR is evaluating strategies to return subtropical rangelands to a graminoid and forb-dominated system that is expected to improve livestock grazing capacity and protect populations of native species. At LTAR's Central Plains site, grasslands can accommodate heavy stocking of cattle due to co-evolution of grasses and bison (Milchunas et al., 1988; Porensky et al., 2016). However, to protect a comprehensive array of ecosystem services, LTAR is evaluating adaptive strategies that account for preferences of grassland birds and other valued taxa (Derner et al., 2009). The LTAR network's sustainable intensification strategies for rangeland emphasize seeking to reconcile the long-term stability of grazing production with the protection of the non-commodity ecosystem services that are desired from these systems.

## Pasturelands

Pasturelands include both rainfed eastern humid regions and western arid regions where irrigation of pastures is common (Fig. 6). From an agronomic management standpoint, pasture maintenance and infrastructure are often neglected compared with more intensive cropland management, resulting in lost opportunities to produce forage less expensively than purchased feed (see Case Study 3). As with rangelands, a prime challenge with pasturelands is matching the availability of high-quality forages to animal demands as pasture forage availability and quality vary spatially and temporally (Franzluebbers et al., 2012). The dominance of cool-season species in pastures of LTAR's northern agroecological regions results in mid-summer lulls in forage yields and quality that are amplified by drought. In arid regions, irrigation of pastures is necessary to maintain production. Aggressive harvesting of forages can deplete soil nutrient reserves, damage forage species, and result in long-term problems such as early decline of grasses (e.g., orchardgrass [*Dactylis glomerata* L.] die-off) or lower nutritional quality (Jones and Tracy, 2015). As with rangelands, LTAR's pastureland sites are evaluating strategies to extend grazing periods and to improve forage yield and nutritional



**Fig. 6. Rangelands and pasturelands in the conterminous United States as percentage of county. Rangelands are defined as "Shrub/Scrub" + "Grassland/Herbaceous" in the 17 western states and Florida; pasturelands are defined as "Pasture/Hay" in all states (National Land Cover Database [Homer et al., 2015]). Gray polygons represent estimated regional inference spaces of the LTAR sites.**

quality during periods of low productivity. Strategies range from using stockpiled forages in the dormant season (Riesterer et al., 2000) to interseeding new species into established pastures (Bartholomew and Williams, 2010).

The management of pastures is complex, with concerns ranging from the invasion of noxious weeds and outbreaks of plant pests and pathogens to the difficulties matching timing of peak production of forage grasses with peak needs of livestock (Sanderson et al., 2012). In LTAR's Southern Plains and Archbold/University of Florida agroecosystems, the emergence of woody weed species has plagued graziers, while burgeoning populations of wild mustard (*Brassica* spp.) and the new invasive bermudagrass stem maggot (*Atherigona reversura*) are reducing forage production in the Gulf Atlantic Coastal Plain. These complex problems require multipronged mitigation strategies that include regular burning, adaptive rotational grazing, weed scouting, and breeding pest-resistant forage varieties to enable timely responses. Yet, when properly managed, pastures are

often seen as an important component of landscape strategies aimed at integrating crop and livestock systems (Liebig et al., 2017) and improving ecosystem services from pollinator habitat (Sanderson, 2016) to soil health (Hammac et al., 2016) and water quality enhancement (Endale et al., 2011). Even though the dominant species in US pastures are not native (Sanderson et al., 2012), pastures can increase farm and landscape habitat diversity, especially in areas with extensive row-crop production (Egan and Mortensen, 2012; Russo et al., 2013). Pastures can also be leveraged to add value to livestock products, particularly in contrast with confinement operations (Hafla et al., 2013).

## Sustainable Intensification of US Agriculture and the LTAR Network

Research to understand and enable sustainable intensification of US agriculture must encompass the breadth of demands placed on the nation's agroecosystems, considering not only production factors and environmental impacts but also human nutrition, economic development, and public policy (Garnett, 2013). For the LTAR network's 18 agroecosystem regions, spanning nearly one-third of the land area of the 48 contiguous states, interdisciplinary research into sustainable intensification addresses four themes simultaneously at multiple spatial and temporal scales: (i) increasing production to meet growing national ambitions for food, feed, fiber, and energy; (ii) conserving the nation's natural resources and protecting its environment; (iii) promoting the prosperity of rural populations; and (iv) developing a vision for sustainable intensification of US agriculture that weighs both national and local opportunities and costs.

## Increasing Production to Meet Growing National Ambitions for Food, Feed, Fiber, and Energy

To achieve national objectives for greater productivity, LTAR network research embraces the approach of genetics  $\times$  environment  $\times$  management (Hatfield and Walthall, 2015), integrating science across these three major areas of investigation, developing and vetting production strategies, and then extrapolating with models to justify the evolution of agriculture. To ensure sustainable outcomes, research to advance national agricultural productivity also considers the ensuing resilience of new systems to multiple concurrent threats.

Yield increases cannot be expected universally. In some cases, opportunities to increase commodity yields can close yield gaps (Godfray et al., 2010). In other cases, the production of a commodity may be close to its local ceiling, but productivity and profitability increases within the local agroecosystem may still be possible. Therefore, central to the LTAR network's extrapolation of findings from empirical and modeled research is the determination of appropriate expectations for increasing productivity and profitability across US agroecosystems. This requires the evaluation of strategies that extend beyond the field and farm gate, including forecasting opportunities to maximize productivity and other outcomes at regional scales (Coffin et al., 2018).

## Conserving the United States' Natural Resources and Protecting Its Environment

For commodity production and farm profitability to enhance, rather than compete with, non-commodity ecosystem services, a comprehensive understanding of agroecosystem processes is required. Developing this understanding requires basic science, often without an immediate applied outcome. However, there are a plethora of ecological studies with no tie to the realities

### Case Study 2

#### Jornada Experimental Range and Walnut Gulch LTAR Sites

Raising livestock on expansive rangelands has been central to postcolonial culture in the US Southwest (Morrisey, 1951). The industry grew with Spanish settlers during the 17th and 18th centuries, briefly declined in the mid-19th century, and became important again during civil wars in the United States and in Mexico. By 1870, enormous herds of cattle were arriving via newly expanded railroads, funded by investors in the east (Sayre, 2009). Since then, cattle numbers have peaked several times to over 1 million—in 1890, during World War I, and again in 1920—but the count in Arizona and New Mexico combined fell to 900,000 by 1990 (Fredrickson et al., 1998).

The arid to semiarid rangelands that supported livestock through these cycles have undergone well-documented changes in social-ecological characteristics. Over the past century, following early episodes of severe overgrazing coupled with drought, the perennial grass cover that was once predominant has been replaced by shrubs. Regional beef production has declined overall. The value of ranches and the incomes of people managing them are increasingly decoupled from livestock production because alternative uses of rangelands are increasing, particularly exurban development and recreation. Even though stocking rates have declined dramatically compared with the beginning of the 20th century, grassland recovery has been limited or absent in many areas. Ongoing shrub encroachment, soil erosion, and biodiversity loss affect a variety of ecosystem services, including forage provision, air quality, hunting, and other recreational opportunities.

Significant opportunities exist to increase food production and rural incomes in the rangelands of the desert Southwest. From the standpoint of controlling and reversing shrub invasion, novel mechanical removal and herbicide treatments show promise, with the intention of increasing forage availability and quality for cattle while stabilizing soils and maintaining habitat for wildlife. In addition, recent research on alternative cattle breeds has identified potential advantages with Raramuri Criollo cattle, a biotype with 500 years of adaptive history in the Chihuahuan Desert (Anderson et al., 2015). Compared with the British crossbred cattle raised in the region, Criollo cattle typically range more widely across desert pastures, a behavior that may help to overcome some of the economic and environmental problems associated with localized overgrazing in the desert. With focus on specific breeds and sustainable management practices, there are also opportunities to expand grass finishing, sustainability branding, and local direct sales. These practices can lower input costs and increase commodity value.

of management whose recommendations do little to advance agriculture (Sharpley et al., 2016). Therefore, research must link commodity and non-commodity ecosystem services to realistic management options relevant to local contexts. Through systematic measurement using common protocols, LTAR network research will enable context-specific processes to be compared across the national spectrum of LTAR sites.

Over the long term, LTAR is seeking to diversify strategies for agriculture at field, landscape, and regional scales, recognizing that some desired outcomes are easier to achieve than others and that current paradigms for intensification of commodity production tend to promote homogenization within industries and within regions, rather than diversification. As a result, there is a need to understand the constraints placed by markets and policies to adapt innovative strategies for the enhancement of ecosystem services.

### Promoting the Prosperity of Rural Populations

Through its place-based representation at multiple sites, the LTAR network is equally focused on ensuring that the national pursuit of greater commodity production benefits local agricultural communities. Benefits will be achieved not only through greater profitability of farming systems and improved environmental quality but also through changes that support vibrant rural community institutions and economic infrastructures while ensuring equitable access to natural resources and reducing health risks to rural residents. At a minimum, research to advance productivity and profitability must understand and seek to overcome the social and economic barriers to change. To ensure that change is sustainable, connections must be made to rural workforces, rural quality of life, and rural economies (Perdue, 2017).

At the heart of research on the full spectrum of ecosystem services provided by agriculture is an understanding that there are net benefit inequities between the providers (rural) and

beneficiaries (rural and metropolitan) of agricultural ecosystem services and that trade-offs in production and environmental quality that emerge from management and policy decisions substantially affect rural health and prosperity. These trade-offs apply to all forms of agricultural production (Cavigelli et al., 2013; Swain et al., 2013). Sustainable intensification strategies must leverage such research outcomes to ensure that trade-offs are fully understood and considered.

### Developing a Vision for Sustainable Intensification of US Agriculture That Weighs Both National and Local Opportunities and Costs

National calls for greater commodity production must account for the diversity of US agroecosystems to find opportunities for intensification strategies that can be sustained over the long term without collateral deterioration of resources, non-commodity ecosystem services, and rural prosperity. At local levels, efficient implementation of sustainable intensification requires targeting technological, management, and logistical/infrastructure changes in areas offering opportunities for greater productivity, new products and markets, and enhanced non-commodity ecosystem services. At another level, national strategies for sustainable intensification enable flexibility in expectations of different agroecosystems, distinguishing between where and how productivity gains can be made, and assessing when and where nondetrimental impacts at some scales may accumulate to result in a substantial detrimental impact at another scale.

Agriculture today reflects the outcome of historical shifts in management in which ambitious goals meet with challenges to production potential, profitability, resource availability, cultural norms, and other factors beyond the control of a single farmer or rancher. As policies, markets, and populations change demands on US agriculture, there is little question that US agriculture can rise to the challenge, but the application of national expectations must

### Case Study 3 Upper Chesapeake Bay LTAR Site

Falling within the ancient Appalachian mountains of the mid-Atlantic, LTAR's Upper Chesapeake Bay location brushes against the population corridor of the United States' eastern seaboard. Pastures are a ubiquitous feature of rural and suburban landscapes alike, accounting for 14% of the total land area and 73% of agricultural land. While certain farming populations, such as plain sect (Amish and Mennonite) farmers, rely heavily on pastures, pasturelands are largely relegated to less-productive agricultural soils, and their management is often neglected. A large amount of pastureland is maintained by small beef and hobby farmers. Small horse farms, each with a few animals, are so numerous that horses are estimated to generate nearly 10% of the manure dry matter in the 166,000-km<sup>2</sup> Chesapeake Bay watershed (which includes LTAR's Upper and Lower Chesapeake Bay agroecosystems). Pastures offer opportunity to reduce expenses on forage inputs. Indeed, grazing is a significant component of nearly all dairy systems found in the Upper Chesapeake Bay region, including on many large confined operations in which dry cows and heifers are typically grazed.

Substantial opportunities exist to improve use of pasture forages, lessen farm dependence on purchased feeds, and improve the contribution of pastures to multiple ecosystem services. A significant niche now exists for pastured dairies, with animal welfare, health benefits, and taste contributing to premiums received by some dairy producers, particularly those participating in direct marketing. Sustainable management of pasturelands includes the need to adopt practices that mitigate the impact of grazing cattle on the environment, especially through control of manure storage and distribution (Egan et al., 2015). Traditional practices, such as allowing direct access to streams, can affect not only water quality but many local ecosystem services and can even adversely influence animal health (James et al., 2007). Under Chesapeake Bay mitigation activities, streambank fencing and riparian corridor restoration have been priorities, but they can impose significant costs and management difficulties to grazers, including impeding access to certain areas of the farm, imposing demands for watering infrastructure, and providing opportunities for invasive plants to flourish. These are largely manageable problems, but they require additional planning and management requirements that are unwanted by small farmers with limited time and resources. Given the narrow profit margins and limited flexibility of small farms in the region, innovation is needed to devise strategies for graziers that can accommodate both provisioning and non-provisioning ecosystems services (e.g., Moechnig, 2007).

reflect local realities, understanding that different approaches will be required across regions and production systems.

The LTAR network is uniquely poised to support the sustainable intensification of US agriculture, providing the data (Kaplan et al., 2017), as well as the inferences, needed to inform producers, the public, and policymakers on options and implications. The land base provided by the LTAR network can provide test beds to evaluate new cultivars, breeds, and methods under actual production conditions with careful monitoring of not only yields but on- and off-site production effects, as well as the potential and requirements for new products and markets. Ultimately, a balance of local and national concerns is expected to support well-reasoned strategies for sustainable intensification that reflect the broad diversity and national ambitions of US agriculture.

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