Long-term network research for the next agricultural revolution

Interwoven into society as a source of food, nutrition, livelihoods, and monetary resources, agriculture shapes and depends on the environment. Threats to modern agricultural landscapes include climate change, soil degradation, eutrophication, and loss of wildlife habitat. Farmers and ranchers are working to mitigate these threats within financial and social limitations, but new technologies and quantitative targets are essential to guide the transformation of modern agriculture (Hunter *et al.* 2017). Agriculture also faces increasing demands from growing populations, rising wealth, and concomitant changes in food preferences that impact the entire food system, from food production to food and waste distribution (Ramankutty *et al.* 2018). While the previous agricultural revolution focused primarily on increasing crop yields around the globe, the next agricultural revolution must maintain and/or increase production while conserving natural resources for future generations and improving human well-being (USDA 2020). There is a continued need for increasing yields in some areas of the world as an important strategy for addressing land pressures and reducing environmental costs (Jayne and Sanchez 2021). In the next agricultural revolution, novel sustainability strategies must become realized (Meynard *et al.* 2017) through adoption of individual practices or through transformation of entire food production systems, all in the context of rapid global change. The varied technologies required to achieve this goal are captured in the concept of "sustainable intensification" (Pretty 2018) and are central to the science goals of the US Department of Agriculture (USDA) (USDA 2020).

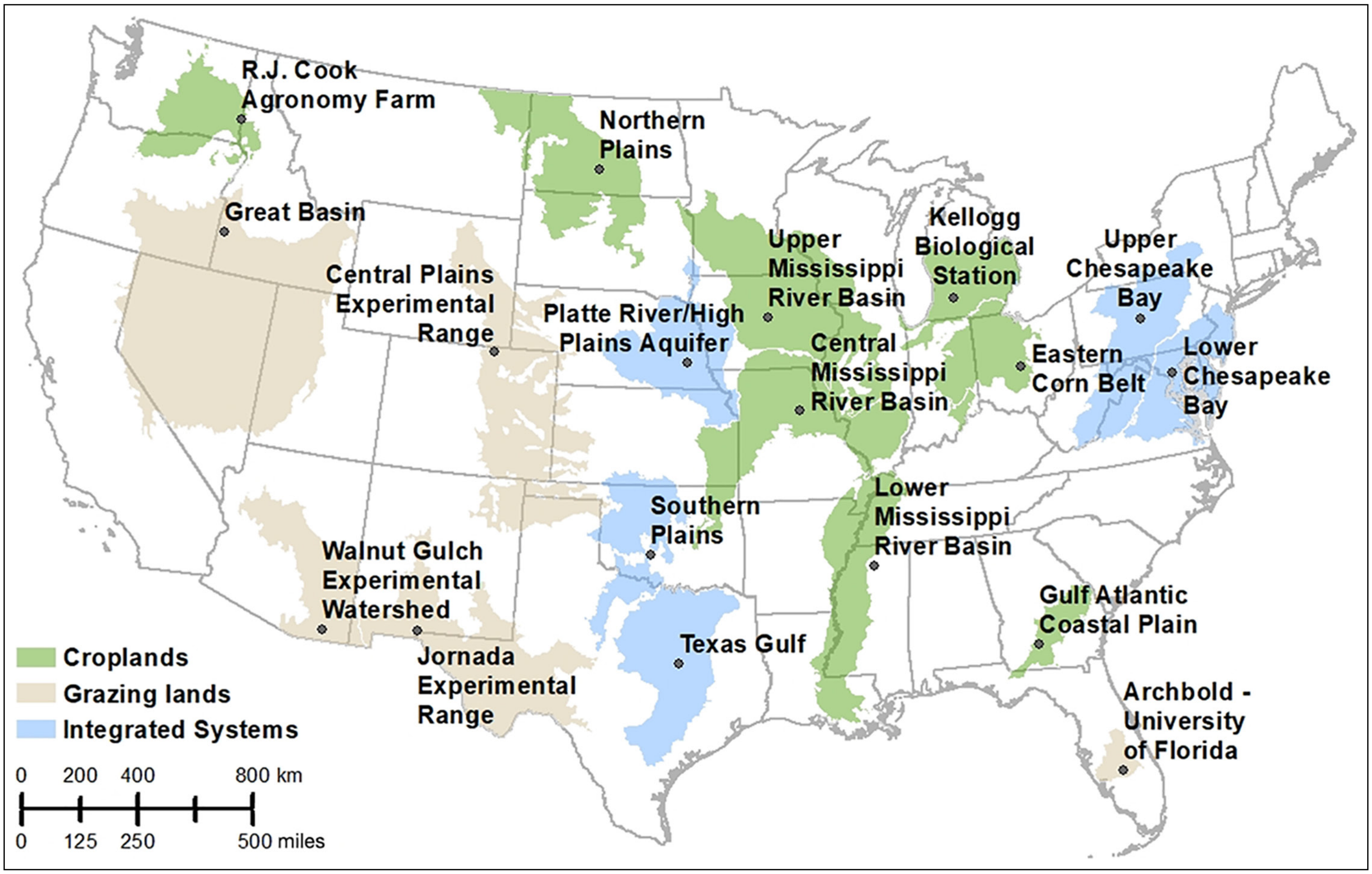
How do we sustainably intensify agricultural systems? Success depends on understanding the social and ecological elements of agroecosystems across multiple scales and using that knowledge to introduce innovations that farmers and ranchers adopt. In response to that demand, the Long-Term Agroecosystem Research (LTAR) network (https://ltar.ars.usda.gov) was proposed in 2008 (Robertson *et al.* 2008) and established in 2014 by the USDA's Agricultural Research Service (ARS). With LTAR, ARS sought to promote coordinated, cross-site, transdisciplinary research, and the co-production of science with agriculture's many stakeholders. Policy makers, federal and state agencies, producers, and environmental groups are engaged with a variety of strategies, including collaborative adaptive management (Wilmer *et al.* 2018), workshops (Bentley Brymer *et al.* 2018), listening sessions, field days, on-farm research, and many other forms of outreach.

LTAR comprises 18 sites across the US (Figure 1). Collectively, current sites represent ~49% of cereal production, ~30% of forage production, and ~32% of livestock production systems of the US (Kleinman *et al.* 2018). Each site uses long-term, place-based science to develop and test meaningful strategies for farmers and ranchers. As a network of diverse agroecosystems, LTAR-based research will fill the need for foundational social and ecological information to allow development of context-dependent sustainable intensification strategies. Within the greater food system, LTAR work is focused on food production (although LTAR scientists also seek to understand how sustainable agroecosystems interact with all food system components), and future directions will include life-cycle assessments. The network is intended to last at least 30 years to develop and test innovations over timeframes that provide insight into agriculture's response to climate change.

LTAR employs several approaches to promote network-level research. The centerpiece is a coordinated "common experiment". Each experiment contrasts site-specific "business as usual" scenarios with one or more management systems hypothesized to advance sustainable intensification. An early LTAR assessment laid the groundwork for identifying general strategies to advance sustainable intensification and potential barriers to practice adoption (Spiegal *et al.* 2018). Ongoing efforts are identifying network-level common indicators representing three domains of sustainable intensification outcomes: production, environment, and rural prosperity. A major challenge is to define measurable indicators of rural prosperity: the ability of rural communities to build capital in human, financial, physical, and social realms (Emery and Flora 2006). Rural prosperity is a culturally dependent, multidimensional variable composed of well-being, fulfillment of basic needs (mental, physical, social), and the ability to mitigate risk and future vulnerabilities across individual and community scales. Network-wide indicators will enable scalable evaluations of the benefits of innovations and monitoring of national progress toward sustainability goals.

LTAR working groups serve to enhance collaboration among the network's more than 300 scientists. Currently, LTAR has 20 cross-site working groups focused on methods, technologies, models, communication, or network-level research questions (https://ltar.ars.usda.gov/research). Examples of ongoing network research projects include wind erosion prediction (Webb *et al.* 2017) and replacement of commercial fertilizers with livestock manure nutrients.

LTAR prioritizes the integration of human dimensions with agronomic and ecological research. This is essential to understanding how society can viably transform agriculture to achieve the next agricultural revolution. Human dimensions research illuminates why agricultural innovations are adopted (or not), while also helping to expand the scope of sustainability goals. As innovative systems are being developed and assessed, engagement with stakeholders is fast becoming a primary LTAR network strategy (Wilmer *et al.* 2018). A social–agroecological systems approach represents a radical departure from the disciplinary silos of past agricultural research. Because the number of biophysical scientists involved in LTAR



USDA

Figure 1. The Long-Term Agroecosystem Research (LTAR) network currently represents 18 agroecological regions across the US, with plans for growth aimed at representing the diversity of agriculture in the US. Map based on data from https://doi.org/10.15482/USDA.ADC/1520632 and Bean *et al.* (2021).

dwarfs the number of social scientists, integration has been challenging, but early career social scientists should be encouraged by future opportunities.

To ensure that network research is widely used, LTAR prioritizes open data. Like the sites of its sister network, the Long Term Ecological Research (LTER) network, LTAR sites have embedded data managers who work together to manage data consistent with the FAIR (findable, accessible, interoperable, and reusable) vision. LTAR sites have data streams initiated before LTAR was established – in some cases dating back more than 100 years – that are leveraged for network analyses; for example, a recent study provided a baseline to understand how water budgets shift in response to changes in management practices or varying climate (Baffaut *et al.* 2020).

Data from LTAR complement those of other national networks, such as the National Ecological Observatory Network (NEON) and LTER. The addition of LTAR to the "network of networks" enables cross-site syntheses of ecological theory across gradients of climate, management intensity, biodiversity, and nutrient cycling, and will enable scientists to learn more about natural and human ecosystems across the US and beyond.

A science network focused on the next agricultural revolution is more important now than ever. Climate change is altering agricultural production; markets are evolving under globalization and changing consumer demand; marginal lands are being converted to intensive production; and perturbations, such as the COVID-19 pandemic, are disrupting food production and distribution. LTAR network research on sustainable intensification will need to connect to policy efforts to manage and reduce food waste, shift diets, and ensure equitable food distribution and security (Herrero *et al.* 2020). LTAR is an investment in the security of our food systems, natural resources, the environment, and the well-being of those who produce and consume agricultural products – that is, everyone.

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FrontiersEcoPics

The ghost shrimp strikes back

The ornate reef sea snake (*Hydrophis ornatus*) is a venomous – and understudied – marine reptile. Off the coast of Japan's Iriomote Island, *H ornatus* have been observed probing into burrows in sandy or muddy substrates, in search of fish. Gobies (family Gobiidae) are one of the snake's most common prey items and often reside or seek refuge within shrimp burrows. What would happen if a sea snake encountered a shrimp while foraging for a goby?

While scuba diving near Iriomote Island at a depth of 8 m, one of us (KY) witnessed an unusual sight: an *H ornatus* with the detached left claw (cheliped) of a large ghost shrimp (*Glypturus armatus*) latched onto its head. The cheliped had damaged the snake's cephalic scales and caused a hemorrhage behind its left eye. Although alive, the snake barely moved during the encounter with the observer, even when physically touched.

We speculate that this sea snake had recently inserted its head into a shrimp's burrow while foraging, and the shrimp – a detritus feeder – pinched the snake as a response to expel the intruder from its burrow. The wounded snake probably then thrashed to escape from the burrow, causing the cheliped to break off from its owner. Whether the snake or the shrimp recovered from their respective injuries is unknown. Our observation not only demonstrates that certain shrimp are able to harm one of the goby's main predators but also leads to additional questions. How does the risk of injury by shrimp affect, if at all, the foraging behavior of sea snakes? Do gobies actively select shrimp-occupied burrows based on the degree of protection provided by the host shrimp?

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