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COMMENTARY

Toward the next angiosperm revolution: Agroecological food production as a driver for biological diversity

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Flowering plants once drove a global shift in insect–plant–animal relationships and supported an increase in biodiversity, energy flux, and productivity throughout terrestrial ecosystems. We argue here that angiosperms could once again contribute to biodiversity within landscapes, if agroecosystems, and the plants within them, can be managed for multifunctional benefits. The potential for farmland to support biological diversity is understood and well-argued in the literature. We take this long-standing conversation and frame it within a longer evolutionary context, bringing attention to how modification in 2 key areas of our current food production system could support this goal. First, a move toward crop and grazing landscapes that more closely align with regional food webs can lead to observable improvements in community wildlife abundance. Second, we can re-expand the genetic base of our food, fodder, and cover crops, in particular by using crop wild relatives, through the use of wide crosses, genome-assisted selection, and participatory breeding. Agriculture as it is now widely practiced utilizes a narrow sliver of total angiosperm species diversity and within-species genetic diversity on a large amount of land. Change to this status quo requires coordination across tightly interlinked policy areas. It will also require social change. Farmers should be supported to transition through nudges throughout their social network. This necessitates a significant shift in our collective culture to value growing and consuming the flowering crops that can trigger an angiosperm revolution of the Anthropocene.

Keywords: Agroecology, Biodiversity, Participatory breeding

Approximately 100 million years ago, flowering plants took advantage of their impressive acquisition of advantageous traits to take over our Earth's landscape. As Pangea was breaking apart, angiosperms used their newfound ability to distribute pollen and fruit, produce natural insecticides, shut down during adverse conditions, and developed a remarkable 10-fold increase in leaf veining and photosynthetic power to spread across the then humid planet (Brodribb and Feild, 2010; Chaboureau et al., 2014). Benton et al. (2021) argue that this time can be called an "Angiosperm Terrestrial Revolution" (ATR), as angiosperms not only exhibited rapid diversification themselves, but they acted as a driver of broader terrestrial biodiversity, facilitating evolution and diversification in a huge range of organisms, including fungi, insects, spiders, birds, and mammals. As the authors state:

> *The rise of angiosperms triggered a macroecological revolution on land and drove modern biodiversity in a secular, prolonged shift to new, high levels, a series of processes we name here the Angiosperm Terrestrial Revolution.* (2021, p. 1)

Angiosperms' diversity created opportunities for surrounding organisms and drove new plant–insect and plant–animal relationships. The resulting increased productivity raised overall energy flux on the Earth and also supported an expansion of highly productive tropical forests.

Around 10,000 years ago, the human species first domesticated a select number of angiosperms to begin the agricultural revolution and an irreversible shift toward deforestation and new types of agroecosystems (Diamond, 1987; Vandermeer et al., 2002; DeFries et al., 2004). As agricultural practices progressed and developed over the years, humans have been able to select for, and now breed, flowering plants to produce food for our ever-growing population. Plants used for crops often have bigger seeds, reduced branching, larger fruits; many of these plants are no longer able to exist in the wild. The novel crops and habitats we have created have also supported the evolution of pests and pathogens (e.g., Chen et al., 2018), as

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well as led to rapid coevolution in humans for processing this new diet.

We are currently cultivating only about 150 of the 30,000 edible angiosperm species and of the approximately 370,000 total angiosperm species (Milla et al., 2018). Approximately half of our cropland is dedicated to growing only 3 angiosperm species—wheat, maize, and rice. Since both rice and wheat are grown in largely separate climates, most continents have half their farmed land devoted to only 2 angiosperm crops (Food and Agriculture Organization [FAO], 2022). On average, our diets include more grain than recommended, and intake of refined grains in processed foods has steadily increased (USDA ERS, 2017; USDA and HHS, 2020). An equal driver of this land use is our high levels of meat consumption, with, for example, up to 40% of maize used for feed in the United States (USDA ERS, 2023). Diets do differ across regions; however, this grains-based foundation is nearly universal. What then has been the cost of this narrowing down of diversity in our cultivated plants? Agricultural land used for crop production and livestock grazing covers approximately 38% of the Earth's surface (Ramankutty et al., 2010; FAO, 2020; ESRI, 2022). This radically alters the habitats of the fungi, insects, and birds that historically benefited from highly productive, energetic, and interlinked ecosystems supported by hundreds of thousands of angiosperm species (Tscharntke et al., 2005; Benton et al., 2021).

The shift toward relatively simplified, larger scale, industrial monocultures, along with agricultural commercialization and trade policies, has resulted in more homogenous landscapes and has contributed to the loss of global biodiversity. This trend has not proceeded uniformly across the globe. Temperate northern countries have created the most uniform and least biodiverse agricultural landscapes; however, some areas of the tropical "global south" have also moved in this direction in recent decades, resulting in more similarity *between* regions (Foley et al., 2005; Kremen and Miles, 2012; McGranahan, 2014; Martin et al., 2019; Raven and Wagner, 2021). These trends in agriculture are one of several concurrent threats to biodiversity globally, which also include deforestation, chemical, light and sound pollution, and climate change (Wagner et al., 2021). Land use change for residential use also plays a role, including habitat disruption through urbanization, as well as suburban sprawl devoted to monoculture lawns. In the United States, this interspersed yet large grass "biodiversity wasteland" totals more than 16 million hectares, approximately one-third of the size of land planted to grain crops there (Manley and Peronto, 2016; FAO, 2022).

Global biodiversity trends are being closely monitored by the scientific community. A planetary boundary framework can be used to analyze the state of key Earth system (ES) processes and to track our risk for crossing critical thresholds, which lead us out of the stable Holocene epoch into the more uncertain Anthropocene (Steffen et al., 2015). The framework highlights the importance of "biosphere integrity" as a core ES process, defining it as a combination of *functional* and *genetic* diversity. While it is challenging to identify a clear-cut threshold for something as complex as functional diversity, agreeing on proxies that can show global and regional trends can be helpful to motivate research, debate, and policy. The *Biodiversity Intactness Index* (BII) is used as a proxy for the maintenance of functional diversity, and anything greater than a 10% reduction in BII may put longer term function of ecosystems at biome scales at risk[1] (Steffen et al., 2015; Newbold et al., 2016). Our global mean BII was estimated in 2016 to have decreased by approximately 15% (Newbold et al., 2016). Turning to genetic diversity, using the proxy of extinctions per million species-years (E/MSY), we are seeing 100–1,000 E/MSY, whereas Steffen et al. argue that our goal should be <10 E/MSY. Therefore, using this framework, we have already reached the zone of high risk for both of these metrics (Steffen et al., 2015). Are we heading toward Earth's "sixth mass extinction" as explored in Barnosky et al. (2011)?

With this conundrum in mind, we would ask what role our collective management of flowering plants might play in securing our planet's biological diversity? This is not an entirely new question. Since the industrialization of agriculture, scholars, policymakers, as well as groups of farmers have been asking whether we can produce food efficiently with reduced environmental harm or, going further, in harmony with the surrounding ecosystem. In a related line of thought, if we need to produce more food for a growing population, what combination of protecting natural areas and improving environmental management of working lands will enable us to achieve our biodiversity needs in different regions (Perfecto and Vandermeer, 2010; Pearce, 2018)? The question above takes this longstanding conversation and frames it within a longer historical and evolutionary context. The area of land under human management has grown from none to approximately 60% of habitable land today (ESRI, 2022). The diversity in our working and residential landscapes has become dangerously narrow and also progressively less native. Over this same time period, however, our scientific knowledge and technical tools have grown exponentially, and we therefore have the opportunity to drive the *next* angiosperm revolution, this time one that is human led. Given the extent of land devoted to farming, and consequentially to the production of cultivated flowering plants, agriculture, and crucially, farmers, can be an integral part of this "revolution."

We propose that modification in 2 key areas of our current food production system could support this goal. First, a move toward more diverse crop and grazing landscapes to support healthier agroecosystems would allow for local and regional increases in functional biodiversity and landscape mosaics that promote the movement of wildlife, as suggested by Liebman and Schulte (2015) in the original article in this forum, and by many others, in particular (Jackson et al., 2010; Perfecto and Vandermeer, 2010; Kremen and Miles, 2012; McGranahan, 2014;

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[1] The Biodiversity Intactness Index measures the relative abundance of originally present species compared to the abundance in the absence of human land use effects.

Gwinner and Neureuther, 2018). Following our evolutionary framing, we shift the perspective slightly on this already well-articulated principle and focus on how farms can play a positive role in ecological food webs. In doing so, we reveal a gap in the farm-level technical support needed to help farmers make the most tailored and therefore effective changes. Second, we can re-expand the genetic base of our food, fodder, and cover crops, in particular by using crop wild relatives (CWRs), through the use of wide-crosses, genome-assisted-based breeding, and participatory breeding. There is growing evidence that hybridization has contributed to speciation and diversification among angiosperms (Mallet, 2007; Soltis and Soltis, 2009; Abbott et al., 2013), as well as to the origin and diversification of our crops (e.g., Warschefsky et al., 2014). This will allow us to begin to reverse the genetic erosion that has been carried out over thousands of years in our quest for agricultural efficiency and higher productivity. We will expand on the potential benefits and obstacles of both approaches in the following, as well as discuss how movement in multiple areas, including seed selection, farm management, agricultural advising, policy-setting, and consumer preference, all in the same direction, may help us to gain much-needed momentum.

Supporting biodiversity by viewing agroecosystems as part of regional food webs

When humans use and modify land for the purpose of food production, there is typically a resulting decrease in native biodiversity and an altering of natural ecosystem function. Our population of approximately 8 billion depends on agriculture for its survival, and therefore, trade-offs in the services provided by different land use types are a necessary balancing act. The trade-off is not an all-or-nothing situation; a farm's impact on regional biodiversity depends on how a farm is managed. Biodiversity is multidimensional, a "structured hierarchy across spatial, temporal and taxonomic scales" (Leibold and Chase, 2017) and can be measured in each, and across, these dimensions (Mittelbach and McGill, 2019a). While trends in biodiversity are often measured in wild landscapes, the same principles apply to land that is actively managed by people, such as farms and rangelands (Tscharntke et al., 2005). Organisms require habitat to live, migrate, breed, and feed. If agricultural sites are sufficiently hospitable, organisms can at minimum rest and feed if not complete full life cycles, and these "patches" of landscapes then contribute to healthier regional biodiversity (McGranahan, 2014).

As discussed above, angiosperms have the ability to modify ecosystem function through their photosynthetic capacities, high transpiration rates, adaptability, efficient and diverse reproductive structures, and ability to coevolve and mutually stimulate evolutionary change with pollinators and herbivores (Lidgard and Crane, 1990; Benton et al., 2021). Historically, angiosperm diversity has driven ecosystem diversity and, in turn, ecosystem productivity. Field experiments have established that ecosystems with higher biodiversity exhibit higher productivity, both at the local or farm-level scale (van Ruijven and Berendse, 2005), and in nonexperimental monitoring of landscapes. Here, the impact of biodiversity has proved to be as important to overall productivity as drivers, such as climate, topography, and land cover (Oehri et al., 2017), at least until a leveling off point is attained (Mittelbach and McGill, 2019a). Higher levels of biodiversity and productivity also contribute to system resilience. Species richness and functional diversity together influence *response diversity*, which is a measure of the range of responses by organisms that are possible within the system to any given disturbance (Tscharntke et al., 2005; Cardinale et al., 2012; McGranahan, 2014).

At the farm level, decisions around types of crops or animals, management of noncropped areas, the size of the operation, the timing of rotations and land cover, and the way inputs are chosen and applied all play an important role in how each farm site fits into and contributes to the broader regional landscape mosaic. Breaking this down, drawing from McGranahan (2014), Lengnick (2022), and Mittlebach and McGill's *Community Ecology* (2019b), crop and livestock choice affect *species diversity*, or the number of different types of species existing in any given area. Species diversity is also impacted by what is growing in the natural or perennial areas on a farm that are not harvested, as well as by the "associated" diversity, such as soil microorganisms, insects, and wildlife (Vandermeer and Perfecto, 1995; Perfecto and Vandermeer, 2008). If species diversity is measured at the farm-level or similar scale, it is known as *alpha diversity*. Each region is made up of many separate local sites, and the difference in species composition between sites in a given region is the *beta diversity*, and so the relative difference of a farm's species to that of neighboring land impacts beta diversity. The number of species in the entire region is the *gamma* diversity (see **Figure 1**). The term *region* is used in an ecological sense in this discussion, defined as the area in which speciation and extinction processes operate and in which species form communities (Mittelbach and McGill, 2019c). The scale of a farm or rangeland determines how significant an impact it has on gamma diversity and overall *habitat connectivity*. Very simply, larger farms that are homogeneous exact a higher cost to gamma diversity. However, there are additional aspects of biodiversity beyond species counts that facilitate healthy ecosystem functions. Productive farms that more closely mimic the surrounding native vegetation, whether prairie, forest, or rainforest, are better able to contribute to connected habitats in the region. Horizontal and vertical diversification on the farm impacts *functional diversity*, which measures the difference in the *function* that groups of species with similar traits perform within an ecosystem, as well as the *trophic complexity* and energy flow up and down the food chain. Biodiversity in an area fluctuates throughout the course of a year with the seasons. Farms that resemble the seasonal shifts in vegetation in their surrounding natural landscape will better support regional biodiversity. Finally, decisions around farm inputs are consequential for the health of surrounding organisms and soil and water quality, therefore impacting ecosystem health (Kremen and Miles, 2012; Liebman and Schulte, 2015). Genetic diversity underlies these other levels of biodiversity, being essential

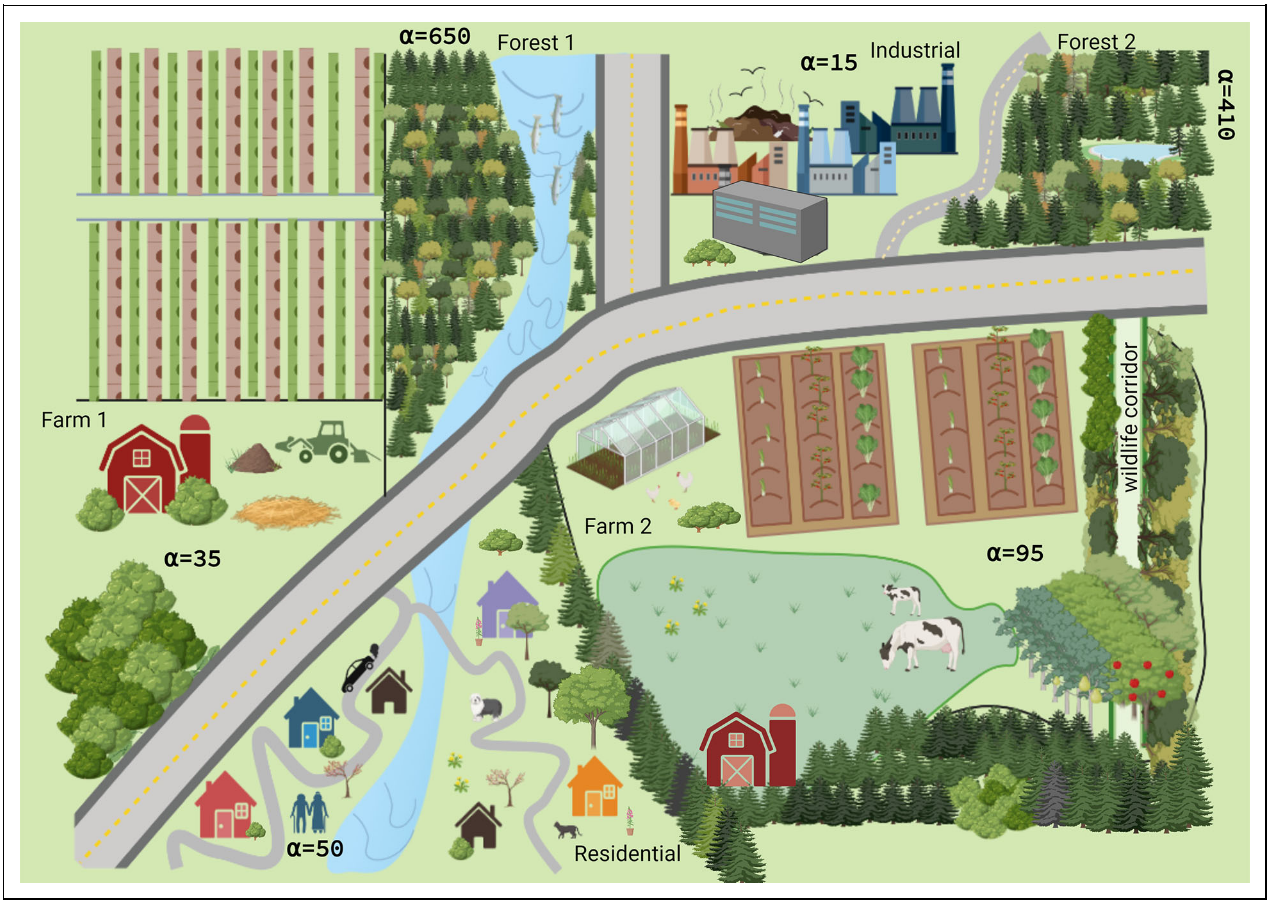

Figure 1. The figure illustrates a simplified regional landscape, which includes 2 farms. The visual is intended to underscore the ideas discussed in this section. The alpha diversity numbers here are for example only and would vary in a real setting. Most of the species in these counts were not possible to picture, in particular, all of birds, insects, and microorganisms. This mimics what a person could easily see, or not see, when at a site and observing quickly. Sites in the region include (1) Farm 1, which grows 2 crops, with an alpha diversity = 35, (2) Forest 1, which includes a river and extends beyond the figure, with an alpha diversity of 650, (3) Industrial area, alpha diversity = 15, (4) Forest 2, which extends beyond the figure, alpha diversity = 410, (5) Farm 2, which grows 3 in-field crops, 2 crops under a high-tunnel, and 2 tree fruit crops, is also raising cows and chickens and has forested buffers on two sides as well as a corridor suitable for wildlife transit on the right, with an alpha diversity = 95, and (6) Residential area, alpha diversity = 50. The on-farm alpha diversity measurements include managed species, wild perennial plants and trees, and associated diversity, such as microorganisms, insects, and wildlife. The farms are shown during the growing season, and alpha numbers would change during the offseason. The beta diversity is the relative difference of one site's species to that of a neighboring site. For example, if Farm 2 shares 20 species in common with Forest 2, the beta diversity would be (95 − 20) + (410 − 20) = 465. The gamma diversity is the number of unique species in the entire region. The sum of the unique species in each site would be (650 + 15 + 410 + 95 + 50 + 35 = 1,255). However, there would be shared species between sites, and in particular, the forested areas would likely have substantial overlap in species, and the gamma diversity may, for example, be around 700. Created by Chelsea Gilgan and Sara Delaney with BioRender.com.

to the development of species diversity and functional diversity. Shifts away from monocultures of genetically uniform crops can thus help sustain greater species and functional diversity. Further aspects of genetic diversity will be discussed separately in the following section.

Each of the types of biodiversity above is interconnected. Populations of any given species are never *evenly* spread across even a small area. Organisms clump in favored areas and move and migrate to other favored areas. If you take any bounded area, you can measure the number of different species within that boundary. However, you cannot scale that diversity measure linearly as you look at larger and larger areas. Instead, the curve showing the relationship between total species and area is logarithmic in shape. The abundance of each unique species in a site also follows a nonlinear distribution, as most species are rare, but a few will be very common (Mittelbach and McGill, 2019c). Understanding these relationships and how they interact is important for making comparisons and for continuing our explorations into what contributes to ecosystem productivity.

> *Ecologically, alpha, beta, and gamma are all just limited views onto a larger complex underlying reality of how individuals of different species are arrayed across space. The fact that each view captures only a piece of the total picture should not fool us into thinking they are independent.*
> (Mittelbach and McGill, 2019c, p. 17)

This coupled and dynamic nature of species relationships means that the attributes of a single site will contribute to several diversity metrics. If a change is made on a farm site, such as an addition of plant varieties or habitat plantings, it may lead to straightforward benefits and also to across-scale systemic changes. This same complexity complicates decisions regarding farm management trade-offs, advising farmers, and designing and measuring the benefits of policy and incentive programs.

Farms, as managed habitats for flowering plants, have a unique ability to influence surrounding ecosystems. Flowering plants *created* the productive and resilient landscapes that we know today. Starting in a broadly tropical climate, forests were gradually formed over approximately 50 million years, and our tropical forests remain the most biodiverse and productive ecosystems today (Malhi, 2012; Mittelbach and McGill, 2019c). The Earth cooled and continents shifted, but the foundations for our complex food webs had already been put in place. Taking this historical view can reframe the conversation around diversified agriculture, and we argue that it points to 3 ways a farm can be a contributor to the creation of productive regional landscapes today: (1) through the cultivation of more indigenous plants and animals, focusing on what can be called "place-based agriculture," (2) through more closely mimicking the surrounding natural vegetation throughout the year by adding sustained ground cover, perennials, and wild areas on managed farms, and (3) by considering the role of the cultivated angiosperms and their interactions with insects and the impact of farm practices on the survival of these interconnected species.

Farm managers can move toward agroecosystems that more closely resemble the surrounding native landscape through small shifts or more radical changes. A starting point is to shift mindset to a *place-based agriculture* strategy, in which the ecology of the locale is used to determine what is grown and how it is grown, rather than forcing crops to perform through the use of costly inputs (Bormann and Kellert, 1991; Marsden, 2012; McGranahan, 2014; Isaac and Martin, 2019). This can be achieved in any of our food production systems, including grains, fruits and vegetables, and rangelands. In the large-scale homogenous maize and soy row-crop systems of the U.S. Midwest, for example, farmers are experimenting with the relatively minor adjustment of integrating indigenous perennial prairie plants into approximately 10% of their farmland, in the long-term and ongoing STRIPS experiment (Liebman and Schulte, 2015; Moore, 2021). A more radical shift would mean having a larger proportion of cultivated plants on a farm be native to that area. The case

Case study: Place-based agriculture and consumer mindset in one community—Foxtrot Farm

Foxtrot Farm, managed by Abby Ferla, sits on approximately 4 acres in the hilly region of northwest Massachusetts in the Northeast United States. The certified organic farm produces perennial and annual herbs, vegetables, and fruits as well as cut flowers. Before 2017, the land was in pasture for over 100 years and included a dairy operation in the 1960s (A. Ferla, personal communication, 19/10/2022; Foxtrot Farm, n.d.).

Abby and her team have a very intentional approach to managing the farm, which focuses on working with the character of the land and the natural ecosystem. They choose crops and varieties based on their hardiness in that area to minimize the need for inputs. The farm does not use tillage, with an aim to capture carbon, improve the organic matter and microbial life of the soil, and increase water retention.

The business runs around a "Healing Foods CSA," which provides "climate-resilient, high nutrient foods" to its members. Membership in this CSA includes not only a weekly share of produce but also a newsletter, a suggested weekly meal plan with recipes, and a DIY kit for a seasonal apothecary pantry item. The farm also hosts workshops and potlucks for community members that focus on seasonal, place-based eating.

In the 2023 season, Foxtrot was growing approximately 60 different types of culinary and medicinal herbs, 39 vegetables, 4 types of berries, 2 types of fruit trees, as well as corn for flour and cut flowers. Products included what Abby refers to as "wild, ancestral foods," such as wild greens, nettles, milkweed, hawthorn berries, and elderberries (A. Ferla, personal communication, 28/04/2023).

Foxtrot farm is situated in a relatively rural area between hardwood forest and wetlands, although there are commercial and residential areas within a 30 km radius, including a major transit corridor. Abby does not personally feel that her farm is significantly adding to the biodiversity of their ecosystem, given the high diversity in the surrounding natural areas. While a study has not been carried out there, it would be safe to say their small farm parcel is not disrupting habitat connectivity and is in fact increasing beta diversity in the region. The staff pay attention to insects and other wildlife and have observed 6 different species of bees as well as monarchs on the farm. They also time the mowing of their fields to support nesting of Bobolinks, a migratory bird with a declining population.

The farm tries to work "within" the local ecosystem and, additionally, feels confident that they are contributing to the biodiversity of their CSA member's gut biomes (A. Ferla, personal communication, 28/04/2023).

study in the following profiles a small organic farm in the northeast of the United States that prioritizes wild ancestral foods for both their climate resilience and their ability to contribute to more diverse diets.

It is worth noting from this example how much effort the farm has put into customer education and engagement to make their unique business model feasible. The influence of customer demand and markets on the ability of farmers to make shifts in production will be expanded on in our conclusion.

Agricultural systems can better support the creation of productive landscapes by more closely matching surrounding vegetation patterns throughout the full year. Wild, unmanaged land generally always has some ground cover. Farms can mimic this by growing cover crops or perennials. In a tropical climate, this means growing drought-tolerant cover crops in the dry season. In temperate climates, cover crops need to be grown through the cold winter months. Cover crops provide additional benefits to a farm, including enhanced soil quality and structure, improved water infiltration, and erosion reduction. However, they add a task and expense to farm management and can be challenging to work into a seasonal rotation. Temporal heterogeneity can be improved further through the incorporation of trees and other perennials. Agroforestry brings a wealth of on-farm benefits, such as water regulation, improved soil quality, and carbon sequestration and also increases to species and functional diversity (Asbjornsen et al., 2014). Perennials can be integrated with crops such as with strip or intercropping, in buffer strips or hedgerows, or in larger areas of natural vegetation within and next to the farm. Farmers can also plant perennial food crops. Fruits, cacao, and coffee are already prevalent; however, more could be done with food trees, such as chestnut, macadamia, and breadfruit (Clark and Nicholas, 2013; Toensmeier and Herren, 2016), perennial grains, such as Kernza or perennial sorghum (DeHaan and Van Tassel, 2014; DeHaan and Ismail, 2017), and perennial legumes and vegetables through breeding as discussed in the following. Livestock producers can practice silvopasture or create more heterogeneous grassland landscapes through patch-burn grazing management (McGranahan, 2014; Burbi and Olave, 2018). Arguably, the most multifunctional agroecosystems are farms that integrate locally adapted grains, fruits, vegetables, perennials, and small livestock in one system and maintain varied year-round vegetation, such as in tropical home gardens, edible forest gardens, or permaculture systems (Soemarwoto and Conway, 1992; Jacke and Toensmeier, 2005; Delaney, 2014; Ferguson and Lovell, 2014). The following case study showcases how one community organization in Nicaragua is supporting farmers to convert to this type of system.

These types of operations do not however lend themselves easily to commercialization. They are more practical, and common, in tropical regions, and in communities where subsistence agriculture is prevalent; however, aspects of this approach are widely applicable.

Case study: Farmers in Nicaragua "get married" to new home garden techniques

Farming is a way of life for most families in rural Nicaragua. Many Nicaraguan farmers are growing maize and beans, and sometimes a cash crop like coffee, using the methods they learned from their parents and grandparents. However, after decades, this can lead to soil degradation and progressively lower yields. When combined with new challenges such as the increasing frequency of droughts and extreme weather, families experience food insecurity.

One long-standing community organization, the Council of Protestant Churches in Nicaragua (CEPAD), works across the country to provide sustainable agriculture training, "walking alongside" communities for several years, so that they can take the time needed to transition (CEPAD, 2021; H. Blandon, personal communication, 15/05/2023).

CEPAD's agriculture program focuses on helping households produce a high-yield, diverse harvest from a small amount of land, using techniques that are in-tune with their local environment. Their aims are cross-cutting: poverty reduction, nutrition, conservation of biological diversity, and "cultivating farmers' knowledge."

They provide an umbrella of practices to choose from in their trainings, which include the use of polyculture and crop rotation. Many farmers grow up to 15 crops, including maize, cassava, yucca, potatoes, beans, plantain, banana, citrus, pineapple, many types of vegetables, as well as keeping animals, after working with CEPAD. They give trainings on cover crops, zero tillage, integrated pest management, live fencing, reforesting peripheries, on-farm water management, and use of livestock manure for organic fertilizer. Finally, CEPAD works with communities to choose seed varieties, with a preference toward native species and those which contribute to diversity, ground cover, and animal habitat, sometimes helping farmers start local nurseries.

CEPAD staff leading this program report that they see their program supporting farmers not only with more food for their families but also home gardens that are contributing to soil and water health. They see more beneficial insects and birds around their homes and have found that farmers can maintain crops even through the driest months of the year. Food production remains the first priority, but as this aim is achieved, participants are also motivated to take care of the "whole creation."

The staff attribute these changes to the long-term support that CEPAD provides, and their training of trainers process, which allows farmers to first see through demonstration, test out ideas, and then share with neighbors. They explain that farmers eventually "get married" to the agroecological techniques. The multiyear relationship building and engagement is key here, much like with any marriage (H. Blandon, personal communication, 15/05/2023).

Figure 2. *Calleida punctata*, a species of ground beetle in North America, moving along a flower. Image drawn by Makaila Bailey.

Third, and perhaps most importantly for the creation of productive landscapes, farm management can consider individual species on their land, their interactions with each other, and with those in the habitats bounding the farm. Looking back to the ATR outlined above, a crucial aspect was the way in which angiosperm diversity triggered subsequent diversity expansions in groups of insects through a wide array of plant–insect mutualisms. It is these mutualisms that will be focused on here. This focus is justified, as insects alone account for one-third to one-half of global biodiversity (Stork et al., 2015), yet are facing dramatic declines in numbers and species due to, in part, exposure to agricultural chemicals and monoculture land management (Sánchez-Bayo and Wyckhuys, 2019). Angiosperm–insect pairs are at a nexus of food webs, sitting between soil organisms, such as fungi, bacteria, and worms below, and herbivores including birds, amphibians, and even more insects above. Here, we will use one example for illustration: the interactions of flowering plants with the order Coleoptera, the Beetles (**Figure 2**). Beetles saw a pronounced expansion during the ATR and are now the most diverse living clade. This makes them "central to understanding insect evolution" (Benton et al., 2021, p. 7). Beetles were the first pollinators during the ATR, before the arrival of bees or butterflies. Within Coleoptera, the *Carabidae*, or ground beetles, are the largest family, numbering up to 40,000 species described globally (Kromp, 1999). Ground beetles are often plentiful in a farm or garden and are typically considered a "beneficial" insect. Many ground beetles are predators, eating caterpillars, slugs, or if generalists, anything they can find. Some also eat seeds, including weed seeds. They are also food for a range of predators including other beetles, spiders, ants, lizards, toads, and ground-feeding birds. Due to their central role in an ecosystem, ground beetles can be used as a bioindicator of broader insect diversity and therefore ecosystem health in agricultural landscapes (Pizzolotto et al., 2018).

A farm can, at a general level, implement practices that support habitat for ground-dwelling insects, many of which are discussed above. These include cultivating flowering plants that resemble other vegetation in the region, reducing soil disturbance, particularly during known beetle breeding times, maintaining soil cover, in this case for habitat, and providing plentiful food, such as caterpillars, by reducing or eliminating crop pesticide applications. However, if a farm wants to understand more specifically how it is contributing to, or hindering, regional biodiversity, they cannot simply look for the presence of beetles in the soil during field monitoring. Monitoring needs to be more intentional, and farms may require technical assistance. In a variety of on-farm studies, pitfall traps have been used to catch beetles over time and across a study area. Species identification after trapping provides information about behavior of the beetle, the spread of that species across the farm and over time, and the relative abundance of that species on the farm compared to surrounding areas. Ecologists may also categorize trapped insects based on characteristics such as body or wing size in order to group based on functional roles. Analyzing which functional types of beetles are thriving on a farm versus elsewhere can show how a farm is affecting the region.

Two farms are profiled as case studies in the following to showcase efforts to identify how farmland fits in with regional insect diversity.

In considering those cases, it is noteworthy that the farms are working collaboratively with a research team and receiving technical support from ecologists. There are also likely to be farms that are closely tracking insect and even ground beetle diversity independently that have not published their work. In any case, this level of specificity in monitoring and identifying a farm's role in the insect diversity of its surrounding food web is rare. However, to be confident that a given farm decision is in fact having a positive impact on the farm and supporting that particular food web, this is the type of detail that is required. To move in this direction, ecology expertise should be much more commonly built into agricultural advising programs, as well as conservation incentive program structures. A commitment to ongoing collaborative monitoring will also be needed to capture changes resulting from climate change related shifts in species ranges.

Case study: Research partnerships reveal the need for specificity in understanding farms' contribution to ground beetle conservation

Farm-research collaboration in the Hudson Valley

The Hudson Valley Farm Hub (HVFH) is located on 1,500 acres in New York State in the Northeastern United States. The farm hub is a nonprofit venture which began in 2013, with a goal of building resiliency in the regional food system. The organic farm has a focus on soil health, and grows grains, cover crops, and vegetables in rotation (HVFH, 2023b). The Farm Hub has been partnering with the neighboring Hawthorne Valley Farmscape Ecology Program and they now have an active research collaborative (HVFH, 2023a).

The collaborative takes a population ecology approach to "investigate agroecology topics on biodiversity and crop production." The team includes up to 10 ecologists, focusing on everything from soil and insects to turtles and birds. Their overarching research questions are (1) How can on-farm habitat conservation or creation help support regional biodiversity? and (2) How can such conservation or creation contribute to farm production?

Through their years of research at the Farm Hub, as well as at other area farms, the ecologists have found that the answers to these questions are incredibly nuanced. When looking at on-farm habitat conservation, they found that the type of habitat needed is specific not only to the type of insect life, such as beetles versus bees versus spiders, but also within each type, different species each have unique requirements (Vispo et al., 2018).

The ecologists have identified 260 species of ground beetles in the county and of those have found 48 in a 2017 study on 3 farms. However, only 5 of those were most commonly found in the crop fields and pastures, and those were different from the common species found in the woods and "brush" areas. The ecologists on the team plan to continue this research by looking at the traits of the ground beetles found on the farms versus those in the wooded areas and to consider how functional diversity within this insect family is being supported, or at minimum preserved, by the farms.

Considering farm management practices on olive plantations

Insects such as ground beetles can potentially thrive in a perennial orchard environment, and a number of studies have recently looked at how varying management practices and farm systems on olive plantations impact ground beetle diversity (Pizzolotto et al., 2018; Jiménez et al., 2023).

One study in Italy set up monitoring at 17 sites that were situated within 3 different natural vegetation types—evergreen, deciduous, and lowland mixed forests. The sites also differed in their management approach, from (a) periodic mechanical tillage to (b) periodic tillage except under tree rows where grasses were allowed to grown freely, and (c) entirely covered with spontaneous vegetation and mowed in the spring (Pizzolotto et al., 2018).

Perhaps surprisingly, they did not find a direct linear effect between frequency of soil cultivation and functional diversity of ground beetles across the sites. They identified a total of 62 ground beetle species, with 5 being very common in all sites, and 11 that they determined were characteristic of olive plantations, all of which were small, had high dispersal power, and an opportunistic feeding strategy. Species typical of forested areas and open habitat were coexisting on the farms. They also found more autumn breeders, due to the disturbance of breeding grounds during spring mowing.

The authors suggest that the olive groves are complex agroecological systems, and when combining the human-induced practices with the many background variables of the surrounding ecosystems, it is not possible to "disentangle" generalized cause and effect interactions. Instead, land managers in this region could focus on the beetle distribution in their specific site and optimize management practices to support species that may prey on a pest such as the olive fly (Pizzolotto et al., 2018).

One olive farm that is proactively tailoring their management practices to support beneficial insect species is Myrolion Farm in Greece, which produces organic extra virgin olive oil. Myrolion is working to boost insect diversity through planting "floral margins" and precision use of pesticides. They also adjust their pruning and harvesting to protect reptile and bird habitat (Myrolion, 2023). They are part of a larger EU-funded project, Novaterra, which is focused on reducing pesticide use while maintaining commercial viability (Novaterra, n.d.)

Challenges

A variety of challenges currently stand in the way of any rapid shift in our global food production systems to larger scale polycultures and more diverse multifunctional agroecosystems. These challenges are present at varying scales, from the farm, up to global markets and policy, and some are more easily changeable than others.

At the farm level, the first is the additional time and thought needed to manage a diverse system, from input ordering, to scheduling seed starting and planting, to managing harvest dates and sales (Morel et al., 2020). The second is the difficulty of mechanizing systems with multiple crops, which prevents farmers from intercropping even 2 crops together at larger scales (Morel et al., 2020; Ditzler and Driessen, 2022). In addition, farm managers who are interested in shifting from conventional monoculture production need to do so slowly and strategically in order to preserve yields, building up soil health and natural pest suppression as external inputs are gradually reduced (Reganold et al., 1990). This type of shift may also necessitate a shift in the mindset and even identity of the farm owner (Bell, 2004; Soini Coe and Coe, 2023). This often requires a broad range of social support to sustain.

At the system level, in industrialized settings, agricultural infrastructure and markets are not set up for handling diverse product streams at the scale needed to consistently supply our supermarket aisles (Bowman and Zilberman, 2013). Larger wholesale buyers do not typically purchase a diverse selection of products from a single farm, and they may even discourage on-farm practices that benefit biodiversity. In one study in California, large-scale growers reported that their buyers cited food safety concerns when banning the use of compost or adding habitat through hedgerows (Esquivel et al., 2021). Farms therefore need to independently find buyers that value a diversified or biodiversity-friendly mix, which may push them toward selling to CSAs, at farmers markets or local retail, or negotiating a larger contract with a restaurant or a wholesaler that favors these growing methods. Within this system, the level of consumer demand for a wider variety of produce and willingness to try more native foods can also be either a key constraint or an opportunity.

In the area of farm finance and incentives, a number of the countries with the largest influence on our global agricultural landscapes, including the United States, China, Brazil, and Australia, currently have agricultural policies in place which actively discourage more diverse production (Bowman and Zilberman, 2013; Wang et al., 2015; Lengnick, 2022). At the same time, many countries, including some of those above, have for decades experimented with policies aimed at reducing the environmental consequences of food production, some with the specific aim of conserving biodiversity or wildlife. Evaluations on the impact of environmental agriculture policies are sparse and have shown mixed results and varying levels of farmer participation (Morris and Young, 1997; Reimer and Prokopy, 2014). Studies also highlight a mismatch between uptake of practices that would be most effective for promoting biodiversity on cultivated land and those that are more widely adopted and funded (Toombs and Roberts, 2009; Basche et al., 2020). In terms of policy specifically aimed at biodiversity conservation, given the discussion above, it is inherently challenging to get this right.

A biodiversity-focused agricultural policy framework must be selective about what is incentivized. As discussed above, there are a variety of agricultural practices that can potentially support different aims. Two recent global meta-analyses highlighted an overall positive impact of crop diversification on biodiversity and ecosystem services (Tamburini et al., 2020; Beillouin et al., 2021); however, both also point to the degree of impact changing with type of practice. Beillouin et al., for example, found that the benefit to biodiversity increased progressively within a selection of diversification practices, with variety mixtures providing the lowest impact and agroforestry the highest.

A recent study in Europe found that less intensively cropped, more heterogeneous landscapes achieved higher biodiversity and multifunctionality scores, but noted that when choosing an analysis scale, zooming out captured more diversity across the landscape (Stürck and Verburg, 2017). Defining boundaries is a well-known challenge in ecology, and it has been found that the correct scale to measure ecosystem functioning is that of the *regional* ecosystem, as that is where "species interact and where we expect biodiversity to most strongly affect the functioning of ecosystems." Both smaller and larger boundaries are inappropriate (Mittelbach and McGill, 2019a, p. 54). Drawing boundaries for measuring the impact of practice or policy requires scientific expertise as well as local knowledge.

Finally, each regional context is unique. In some cases, such as the approximately 170 million acre U.S. Corn Belt where BII measures less than 60% (Newbold et al. 2016), the negative environmental impact of current land-use is so significant that any move toward the types of on-farm biodiversity discussed above would improve the multifunctionality of this region (Bittman, 2014; McGranahan, 2014). In other cases, the landscape is already more heterogeneous, and trade-offs between crop yields, habitat, and other land uses must be considered carefully.

The following case study illustrates 2 different agri-environmental policy efforts in Europe, which show how regulations can influence farmer behavior in possibly unexpected ways.

As can be seen in these examples, there is a need for careful monitoring to understand the impacts of agri-environmental policies. Monitoring should ideally be done over long enough time scales to capture change and also needs to be undertaken at the landscape scale. In the United States, the US Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) Conservation Effects Assessment Project (CEAP) is an effort in this direction. CEAP conducts assessments of conservation efforts on croplands; however, these are focused on a different, and also important aim: measuring impacts of farm practices on water quality (USDA, 2022). CEAP also assesses the benefits of working land conservation efforts to wildlife, often through regional single-time studies on priority species or groups. Relatively few of these studies focus on cropland impacts to date, with some exceptions (Evans et al., 2014; Brofsky and King, 2021; Natural Resources Conservation Service [NRCS], 2021b; Shirley and Janke, 2023). In addition, building on science that supports measuring the impacts of conservation efforts at wider scales (Gallant et al., 2011), the NRCS Working Lands for Wildlife (WLFW) effort targets conservation of indicator species and brings together communities across a region to proactively address threats to both biological communities and working lands sustainability (NRCS, 2021c, 2021d, 2021e). Longitudinal impact studies are being done on this work. While they cannot use a sampling and modeling approach to extrapolate in the manner done for water quality

Case Study: The EU CAP and new UK schemes, different ways of encouraging diversification

In Europe, the EU undertook a "greening reform" of the Common Agricultural Policy (CAP) which went into effect in 2015. One of the measures asked farms to meet crop diversification standards, with an aim of enhancing biodiversity in member states. However, the bar was set far too low, with medium to large farms only required to cultivate 2 or 3 crops, respectively, and small farms exempt all together (Pe'er et al., 2014).

In a recent study on the effects of the new CAP in Sweden, it was found that on average, while the mean annual diversity index did increase from the very low levels of the previous 10 years, it is still lower than in the early 2000s. Many farms had already achieved the 2015 diversity goal before the policy came into effect. In addition, measuring functional diversity simply as diversity across different botanical families, the research team found that this *functional* diversity actually decreased post-2015, which can be explained by many larger farms choosing to "diversify" by adding related crops. Further, measuring functional diversity this way does not yet measure it in "ecologically informed ways," which would use the traits of crop species, and their niches in the food web (Schaak et al., 2023, p. 7). The authors suggest that adding stronger functional requirements to the policy is essential to meet biodiversity targets.

In contrast, post-Brexit, the UK needed to put in place its own environmental policies outside of the CAP. In 2023, the Department for Environment, Food and Rural Affairs (Defra) enacted 3 new, or updated, environmental land management schemes, including the "Sustainable Farming Incentive," which focuses on soil organic matter and multispecies cover crops, and "Countryside Stewardship," which focuses on increasing pollinator, bird, and other wildlife habitat through in-field grass strips, bird-friendly plants, and adding successional areas, scrub, and hedgerows. They are tiered to help farms thoughtfully transition their management practices and farm design. The "Landscape Recovery" scheme also supports larger scale collaboration between farmers, foresters, and private landowners to restore landscapes for threatened species (Defra, 2023).

It is too soon to evaluate the impact of these new schemes, either in their design or perhaps more importantly, how many UK farmers will enroll. Previous Countryside Stewardship schemes have seen low participation (Morris and Young, 1997). There is, however, evidence from a 10-year study on one large conventional farm in England where they tested the environmental impacts of the previous environmental stewardship policies. This farm applied promoted practices, at a high standard and with expert advice. Results show successful conservation of birds and butterfly species over time, compared to similar farms not using those practices. The authors stress how important the technical support was in this farm's success and suggest that the country needs improvements in training and tools for farmers (Redhead et al., 2022). This study was funded by Defra, and the agency is also using further scientific evidence in designing the current schemes (McGregor, 2023).

assessment given the complexity of biodiversity, they have demonstrated impact (NRCS, 2021a).

Programs that target wildlife conservation on croplands could potentially have even greater influence if they were more closely linked with farmer incentive programs. For example, NRCS programs such as the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (NRCS, 2023) could prioritize select practices and habitat based on the biodiversity targets in that area, which is currently done with WLFW-EQIP funds. However, this more strategic approach only represents approximately 15% of total spending in this program (B. Costanzo, personal communication, 01/06/2023). This may lead to better aligned funding as well as higher enrollment, if farmers can see the cumulative results of their actions over time (Thompson et al., 2022). With challenges at each of these scales in mind, a key consideration is whether we might be able to shift our food production strategies at the speed and magnitude needed to address our biodiversity challenge. Here, we need to discuss how angiosperm diversity might be enriched through strengthening genetic diversity.

Supporting angiosperm diversity through genetic diversity

With recent advances in breeding, including both gene editing and genomic selection, we are now able to introduce genes from distantly related taxa into targeted crop species, as we search for useful adaptations for food production in our future climate (Liu et al., 2021). We are also increasingly able to harness polygenic adaptations from CWRs and to neo domesticate wild plants to create crops able to provide food, fiber, and fuel as well as ecosystem services (e.g., von Wettberg et al., 2020).

Throughout the history of angiosperms, hybridization has been an underappreciated driver of diversification (e.g., Mallet, 2007; Soltis and Soltis, 2009; Abbott et al., 2013) alongside diversifying selection in different regions. Although once viewed as just a branching, diversifying process, via genomic investigation, we are increasingly finding that in many taxa, particularly angiosperms, hybrid speciation can be an important process (Vallejo-Marín and Hiscock, 2016). Since the advent of human agriculture, hybridization has been a similarly important process for the diversification of crop species. Some crops are the direct result of hybrid speciation, such as lemon and grapefruit (Wu et al., 2018), while many others have diversified by introgression from close relatives, like date palms (Flowers et al., 2019) and mangoes (Warschefsky and von Wettberg, 2019). Much of the first 10,000 years of agriculture involved domestication of new crops, followed by their movement to new regions as farming spread (Abbo et al., 2014). Many crops diversified as they spread, through new mutations as well as hybridization with wild relatives. In some cases, hybridization with wild relatives adapted to distinct environmental conditions beyond those experienced by the crop in its center of domestication may have been critical to expansion or survival of the crop in new conditions.

The last century has seen considerable erosion of genetic diversity (e.g., Esquinas-Alcázar, 2005; Khoury et al., 2022). Mechanization and intensification favor uniform stands of single crop species, replacing traditional polycultural systems with the potential to overyield monocultures and provide yield stability in the face of variable conditions. Breeding research and development increasingly met the demands of modern systems, thereby homogenizing crops over vast areas (Ditzler and Driessen, 2022; Mastreta et al., n.d.). However, breeding in some regions replaced long traditions of farmer seed saving and stewardship, where informal seed systems included farmers saving and using an extensive diversity of seeds, generating an important evolutionary service for agricultural systems.

With the power of new genomic tools and an improved understanding of the social dynamics through which farmers select seed, it is possible to speed the reversal of these losses. We can (1) breed across climatic gradients and soil-type gradients, introducing diversity across space; (2) breed for intercropping and polycultures; (3) neodeomesticate species adapted to particular conditions, including agriculturally marginal habitats; and (4) put farmers back into the process of selecting and stewarding crop diversity through participatory breeding. None of these approaches necessarily entail significant declines in yields.

Using molecular tools to breed for expected shifts in climate is widely mentioned in the current crop breeding literature (e.g., Galluzzi et al., 2020; Kamenya et al., 2021; Snowdon et al., 2021) and will be necessary to maintain, let alone increase, yields of current agricultural systems. For example, molecular tools coupled with expanded collections of wild diversity provide a basis for improving a number of traits in chickpea (von Wettberg et al., 2018). These tools can be used to breed for more diverse agroecosystems, be they perennial and/or polycultural. Perennial systems have reduced disturbance and keep live roots in soils for more of the year than annual systems. Although there is debate about their capacity to approach the yield of annual systems (e.g., Crews and DeHaan, 2015; Smaje, 2015; Soto-Gómez and Pérez-Rodríguez, 2022), the benefits for perenniality for ecosystems are numerous. Polycultures have the potential to overyield monocultures and have greater resilience and stability. However, as noted above, most agricultural polycultures require manual harvest. For areas where mechanized agriculture dominates, breeding can facilitate the adoption of polycultural systems by creating crop pairs that can be co-harvested, such as grain cereals and legumes (Annicchiarico et al., 2019). However, the challenges of aligning maturity times across environmental gradients for 2 or more crops are inherently challenging.

Neodomestication can create new crops that better match species adapted to particular biomes, such as the perennial grain and oilseed crops developed by The Land Institute and partners to mimic the prairies of North America (e.g., Pimentel et al., 1986; Glover et al., 2010; Crain et al., 2022). Although still subject to debate about their yield and feasibility (e.g., Loomis, 2022; Cassman and Connor, 2022), these systems may provide multifunctional benefits in a range of settings, increasing agricultural diversity and resilience alongside annual monocultural systems (e.g., Ryan et al., 2018). Genomic selection (e.g., Jannink et al., 2010; Xu et al., 2020) and gene editing (e.g., Chen et al., 2019; Jansing et al., 2019) will be essential to speeding up the improvement of these systems to allow rapid fixation of alleles impacting critical agronomic issues like seed shattering that limit the use of wild relatives of crops and to meet the disease and pest pressure that plague them.

Hybridization among crops and wild relatives can create new forms as well, with similarities of existing crops but with new traits. Efforts to breed perennial rice, wheat, and sorghum are based on this approach, using distantly related perennial relatives of crops as sources of genes controlling perennial growth habits (Soto-Gómez and Pérez-Rodríguez, 2022). Hybridization has been a particularly important but historically underappreciated driver of diversity in many tree crops, such as date palms (Flowers et al., 2019), citrus (Wu et al., 2018b), apples (Cornille et al., 2014), and mangoes (Warschefsky and von Wettberg, 2019).

Less effort has gone into perennial legumes, but many of our leading legumes (soybeans, common beans, and chickpeas, as examples) have at least some perennial wild relatives, and a few cultivated legumes have perenniality in their cultivated genepool (i.e., pigeonpea, winged bean). Fully perennial agroecosystems will need cereals, legumes, oilseed crops, vegetables, and fruit to all come in perennial forms. Participatory breeding has proven highly successful in parts of the global south (e.g., Ashby, 2009; van Etten et al., 2019). Although sometimes viewed by breeders as an approach at odds with contemporary breeding, there is inherently no reason molecular tools cannot be used to support farmer-led participatory breeding, and doing so could bring in valuable local and historical knowledge of overlooked varieties and traits. Participatory breeding puts crop genetic diversity in the hands of farmers, enabling them to diversify crops to suit their climate, cuisine, and culture. As occurred over the first several millennia of agriculture, farmer selection has the potential to again support an increase in agricultural diversity.

One of the most successful examples of participatory breeding is "Seeds for Needs" wheat improvement program in Ethiopia, started by Bioversity International (now the Alliance of Bioversity and CIAT; Coto et al., 2019; Fadda et al., 2020). This program put genebank-preserved accessions of wheat in the hands of Ethiopian woman farmers, allowing them to uncover diversity for a range of agronomic traits from disease resistance to grain quality. The program has had benefits beyond increasing diversity, improving food security for participants (Gotor et al., 2021). This program was replicated beyond Ethiopia (e.g., Fadda et al., 2020). In the following case study box, we examine the potential of participatory breeding in the global north, where these approaches have not been used to the same extent.

Case study: Participatory breeding for culturally meaningful crops

Although developed in the global south, participatory breeding programs can be equally successful in the global north. An example of this is "ultracross" populations, which originate from crosses of many (20 to over 80) distinct parents. The Utopian Seed project, with distribution assistance from several nonprofits and seed companies (Southern Exposure Seed Exchange, the Utopian Seed Project, Two Seeds in a Pod, Experimental Farm Network, and Ujamaa Cooperative Farming Alliance), is developing new ultracross varieties of culturally meaningful crops like collard greens (The Heirloom Collard Project, n.d.), okra (Experimental Farm Network, 2023), and sorghum.

These crops have cultural histories in the Southern United States tied to the African Diaspora, but cultivars for use by small growers with potential for community-based selection are not widely available. The ultracross populations, which are a mix of many distinct parents, began by selecting diverse accessions for culturally meaningful crops from the U.S. National Plant Germplasm System, community seed keepers, and seed companies. Traditionally, farmers from historically marginalized backgrounds have had limited access to genebank accessions. Ultracrosses bring these accessions and their crosses, to farmers through seed company sales, and through distribution by the Utopian Seed Project and the Ujamaa cooperative farming network. Farmers who agree to grow ultracrosses may plant out multiple accessions, allow them to intercross, and save seed from selected plants.

The ultracrosses become a highly diverse mixed population, which can be immediately sold to gardeners and growers, but that can also be saved and selected upon in subsequent generations. The high diversity of these ultracrosses allows any grower who wants to save seed to develop distinct new varieties out of underutilized genebank diversity. These mixes have only been available for a few years at the time of writing, so time will tell how effective they are at maintaining diversity in the hands of small-scale cooperative growers, and how effective they may prove to be at maintaining the diversity present in the original genebank accessions. More information is available from Southern Exposure Seed Exchange (2020), UCFA (2023), Walton (2023), The Heirloom Collard Project (n.d.), and Utopian Seed Project (n.d.).

A way forward

The magnitude and pace of the biodiversity crisis demands that we employ both the landscape and genetic levers we have described for agriculture to serve as a means of diversification. We should first acknowledge the importance of flowering plants to overall ecosystem productivity and resilience, and with that recognize the impact of our food production choices—which currently utilize such a narrow sliver of total angiosperm species diversity and within-species genetic diversity on such a large amount of land. With this in mind, we argue that progress will be faster and more effective if farmer technical support, incentive programs, and policies in agriculture, food systems, and biodiversity are discussed within the context of this interlinked system.

Others have begun this conversation, although the pieces have been fragmented and not enough progress has been made. Magrini et al. (2018), for example, argue that we need a "co-evolution framework to address the interconnected transition of agriculture and food systems" to break out of our "lock-in" to the major cereal crops that dominate our food system. They argue for public institutions to support shifts in both production and consumption toward more sustainable options such as pulses. This could be furthered through a proliferation of community-based efforts toward place-based eating such as is being done at Foxtrot Farm, above.

In another thread, agriculture and biodiversity are discussed together. Banks (2004) suggests bringing together agriculture and conservation biology, work by Kremen and Miles (2012), clearly lays out the case for the ecological benefits of diversified agriculture, and then again showing how this can lead to a more secure and just food system (Kremen et al., 2012). McGranahan (2014) argues that we need to bring together the sciences of farm-level agroecology and landscape ecology and strive for multifunctional agroecosystems. This idea, at its core, has been considered within agricultural practice since its beginning and has persisted in some pockets of what may be called "traditional" or indigenous culture around the world. It entered academic literature at least 100 years ago, if not before, as, for example, in this call to consider agricultural in the Midwest in the context of the prairie ecosystem (Weaver, 1927), and the academic conversation has continued, escalating more recently as environmental pressures increase (Zhang et al., 2007; Perfecto and Vandermeer, 2008; Jackson et al., 2010; Kremen and Merenlender, 2018; Schattman et al., 2023).

Biologists and chemists looking at ESs and striving to reverse our genetic diversity crisis would benefit from closer collaboration with plant breeders and geneticists and a more participatory modern plant breeding effort. Modern breeding has largely been done for farmers, without their direct involvement in selecting new cultivars. However, for most of the history of agriculture, farmers were the critical stewards of crop diversity, generating much of our landrace diversity through divergent selection on family farms. New molecular tools have incredible power to select among crop diversity, and including farmers in these processes will allow them to return to a key role in protecting diversity (Zimmerer et al., 2023; Mastreta et al., n.d.).

Our behavior is ultimately influenced by what we as a society choose to measure. The contributions of crops have traditionally been ignored by biodiversity assessments. Including nonnative and managed species growing on unprotected land in biodiversity assessments would be one step in helping to move us in the necessary direction

(Schlaepfer, 2018; Wolf et al., 2022). Two recent examples point to progress in this area. In 2019, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) approved a global assessment, which specifically addressed the importance of conserving agricultural diversity, and in 2022, a successful negotiation at the UN Biodiversity Conference in Montreal added a target on the contribution of agriculture, fisheries, and forestry to biodiversity to the Global Biodiversity Framework (CBD, 2023). Global agriculture databases, such as that maintained by the FAO, could also go beyond tracking commodity groups and track use of cultivars, varieties, and landraces, as suggested by Martin et al. (2019).

Finally, better connected research and policy work will take us part of the way there; however, in the end, farmers will be making decisions about how to manage their land and their businesses. As most farmers are not currently operating with biodiversity promotion as one of their primary goals, we are looking for a broad-sweeping change in farming paradigms. A farm owner is *required* to think first about production, growing enough to feed the family or keep the business open necessarily comes before everything else. Ghazoul (2007, 2008) notes how this needs to be considered when asking farmers to provide ecosystem services, even those services like soil quality and pollination that also help the farm in the long run. Jackson et al. (2010) point out how a farm is often stuck in the "here-and-now," rather than moving toward the long-term planning and landscape-level view that can help them manage uncertainty. However, for a farmer to think more broadly and consider other functions their farm may have beyond annual food production, they need multipronged support to ensure profitability while making a transition (Schattman et al., 2023). We would argue that many, if not all, farmers do possess a land stewardship ethos, but it cannot surface if basic business goals are not first satisfied.

Beyond financial and logistics support, moving to a farming-for-food webs mindset is a mental and social change. As also discussed in Jackson et al. (2010) and by many others more broadly in relation to farmer adoption of new practices (Pretty, 2002; Oreszczyn et al., 2010; Wood et al., 2014; Bourne et al., 2017; Prager and Creaney, 2017; Delaney, 2023), a farmer's attitude is influenced by their social network. If a farmer is going to move in any given direction, research has shown that multiple, repetitive nudges from within their broader social network are required as they progress through the adoption or innovation process (Pannell et al., 2006; Strimling et al., 2009; Altman and Mesoudi, 2019). The new type of farming, in this case biodiversity-focused, needs to become normalized for them and their social group, which includes other farmers, friends, neighbors, family, customers, advisors, and even ideally lenders and policy setters. This type of repetitive and encompassing social "pressure" is helpful for any sort of change. It is particularly necessary for the type of multipractice, if not systemic change that is required for a farm to effectively support the health of regional food webs (Foster and Rosenzweig, 1995; Hassanein, 2000; Bell, 2004; LaCanne and Lundgren, 2018; Soini Coe and Coe, 2023).

One additional aspect that may help to speed this transition in society more broadly is how it is framed, and within that, the particular words that are used. Coming back to the benefit of taking an evolutionary frame on this issue—we can more often include words that bring up that which we value as part of our natural and cultural history, such as "flowers," "butterflies," "birds," "bees," "wildlife," and "land," which have the additional benefit of being things that everyone can see. We can also talk of "collective caretaking" and "protecting our community," to tap into the power of collective efficacy (Jugert et al., 2016; Hayhoe, 2021), and, to align with trends in home gardening such as "rewilding," "planting native," and creating "backyard sanctuaries" (Goddard et al., 2013; Penick, 2013; Manley and Peronto, 2016; Lofthouse, 2021; Roach, 2022; Audubon Society, n.d.). These are broadly apolitical and positive goals that can potentially enable conversation between farmers, gardeners, and consumers, as well as politicians and scientists.

If this broad group can come together at the same table to find ways to measure, promote, and support more diverse agroecosystems, we may in fact be able to trigger the angiosperm revolution of the Anthropocene.

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