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FEATURE

Sustainable and regenerative agriculture: Tools to address food insecurity and climate change

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The United States plays an important role in addressing both food insecurity and climate change. Agriculture sits at the nexus of these two issues, which some have called "wicked problems" due to their pernicious effects and the complexity of their causes and their solutions (Rittel and Webber 1973). While public and policy discussion often concentrate on the role agriculture may play in contributing to climate change, it also has great potential for climate adaptation and mitigation. This is because some agriculture systems have the potential to adapt to climate change using selective management approaches, while also providing mitigation benefits (Shakoor et al. 2022). Through agriculture we have unique opportunities to help mitigate climate change in ways not possible in other industries or systems.

As one of the largest agricultural economies in the world, it is imperative that the United States strive to limit the degree to which agriculture contributes to climate change, leverage best practices so that farms help mitigate climate change, and ensure food security in the United States and globally. We can rise to these challenges by investing in research that advances climate adaptation and mitigation approaches for agriculture, using both established and new federal policies and programs. These solutions can work for farms, for consumers and communities, and for the environment.

THE PROBLEMS WE FACE

The challenge to achieve universal food security has escaped the United States thus far. Someone is considered food secure when nutritious food is consistently available, accessible, in a form they can and want to use, to the degree that they can lead a healthy and active life (Coleman-Jensen et al. 2021). However, more than 1 out of 10 people in the United States is classified as food insecure. Recently, the USDA has introduced a new focus on nutrition security, which highlights the intersection between food insecurity and diet related disparities and diseases (USDA 2022). Food and nutrition insecurity is directly affected by social, economic, and environmental disruptions and disasters. The National Food Access and COVID Research Team has shown that in many places across the country, food insecurity spiked as a result of the COVID-19 pandemic (Niles et al. 2021). Households with children under the age of five, and Black, Indigenous, and communities of color experienced greater rates of job loss, and an associated decline in food security, during this historic period (Clay and Rogus 2021; Ohri-Vachaspati et al. 2021; Niles et al. 2021; Rogus et al. 2022).

The COVID-19 pandemic is one example of a disruption that can have disastrous consequences for the most vulnerable among us and their ability to feed themselves; climate change also poses threats to our domestic food security, and global food security as well (Gregory et al. 2005). For example, when heavy rainfall caused a significant flood at the Abbott Nutrition plant in Sturgis, Michigan, the damage exacerbated shortages of specialty infant formula across the country (Jaffe 2022). This event highlights that farms are not the only part of the food system that are vulnerable to climate change. From food production to food waste, and all the steps in between, disruptions driven by climate change have tangible consequences.

We offer two examples of how changes in the climate have affected different agricultural industries in the United States. First, increased average temperatures are associated with a decrease in yield in staple grains (Asseng et al. 2015; Zhao et al. 2017). It has been shown that a 1°C (1.8°F) increase in average temperature leads to an 8% to 10% decrease in corn (*Zea mays* L.) yield, and a 9% decrease in rice (*Oryza sativa* L.) yield (Abrol and Ingram 1996). To put this into context, the National Atmospheric and Oceanic Administration reported in June of this year that average temperatures have increased 0.32°F (0.18°C) per decade since 1981, and in 2021 the surface temperature of Earth was 1.51°F (0.84°C) warmer than the 20th-century average, which was of 57.0°F (13.9°C). It was also 1.87°F (1.04°C) warmer than the pre-industrial period (1880 to 1900) (Lindsey and Dahlman 2023). In other words, the climate has already changed enough for us to start to see decreases in crop yields, if all other things are held constant. The decrease in grain crop productivity has not been noticeable to many due to technological advances brought about by agricultural research in precision agriculture, irrigation, and improved crop genetics. However, if temperatures continue to increase, as we anticipate they will, it is unclear how long these improvements will continue to offset the biophysical limits of crops. Indeed, some argue that we have already exceeded technology's capacity to buffer crop yields against climate change (Ray et al. 2019).

A second example of how climate change has a notable effect on US agriculture can be found by looking at non-citrus tree fruit. Increasing minimum temperatures affect fruit bearing trees, such as apples (*Malus domestica*), peaches (*Prunus persica*), pears (*Pyrus* spp.), and plums (*Prunus* subg. *Prunus*) (Luedeling 2012). Warm periods in the spring (sometimes called a false spring) can cause early bud development. When these false springs are followed by killing frosts, they can decimate a year of fruit production, as was the

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case in Michigan in 2012 (Linder and Campbell-Arvai 2021), in West Virginia four years in a row between 2014 and 2018, and in many other parts of the Northeast and upper Midwest. This phenomenon also affects perennial fruit crops like wild blueberries (*Vaccinium* spp.) (Tasnim et al. 2021). Meteorologists have coined the term "weather whiplash" to describe rapid temperature swings. This is just one of the ways in which climate change affects perennial tree fruit and other fruit, but it illustrates how we must look beyond annual average temperatures and consider how climate (often talked about in 30-year or more time frames) affects weather patterns (anything shorter than 30 years). As Daniel Ward, a cooperative extension pomologist from the Rutgers Agricultural Research and Extension Center, has said, "It's not about whether farms lose a crop in any given year, but about how many years a farm can sustain losses" (Ward, personal communication).

These are just two simple examples, but each agricultural sector in every region of the United States will be affected by climate change in some way, and many already are struggling. This is a long-term problem. Even if we were to stop putting greenhouse gasses into the atmosphere today, we would see temperatures increase throughout this century and beyond, with cascading effects on precipitation and other weather patterns (Archer 2007). These weather patterns, in turn, affect the balance of agroecosystems, which are composed of communities of plants (cultivated and not cultivated), insects and animals (pests, beneficials like pollinators, and humans), diseases (affecting plants, humans, and other animals), and, importantly, the interactions between all of these. The need to adapt to climate change is here and will likely intensify as the century progresses. There are many uncertainties associated with what the future holds. However, we know enough right now to support farmers as they adapt to a changing climate, build resilience into their farm operations today, and anchor thriving US agricultural industries.

We can do this through unwavering support for sustainable and regenerative agriculture. To farm sustainably means that we grow food, fiber, and fuel in a manner that does not undermine our ability to do so in the future (Harwood 1990). Specifically, sustainable agriculture reduces the use of inputs by improving efficiency, prioritizes use of sustainable inputs when inputs are necessary, is based upon ecological principles, and connects consumers and producers (Gliessman 2015). To farm regeneratively is to do this in a way that has a positive effect on natural resources; this term is often used in the context of sequestering carbon (C), improving soil health, or improving water quality through agricultural management activities (Newton et al. 2020). Specific practices guided by these principles include reduced or no tillage, cover cropping, crop rotation, and integration of livestock into cropping systems. These practices also have the added climate mitigation co-benefit of sequestering C in soil when they are implemented over an extended period of time (Lal 2004, 2015; Cooper et al. 2021). Other agricultural practices, such as managing manure (through biodigestion and flaring) and amending animal feed (to improve digestibility of ruminant feed, so livestock like cows will produce less enteric methane [CH_4]), alternative wetting and drying of fields (in rice production), and using only the most efficient fertilization practices have the benefits of reducing nitrous oxide (N_2O) and CH_4 emissions (Chadwick et al. 2011; Løvendahl et al. 2018; Runkle et al. 2019). These two greenhouse gasses are 298 and 25 times more powerful than carbon dioxide (CO_2) over the first 20 years in the atmosphere, respectively (USEPA 2015, 2016).

Climate change adaptation is not a straightforward task, there is no one "right" way to do it, and it is likely not to be the same approach forever. Rather, the best adaptation practice for any given farm depends on the particularities of that farm and how those change over time. Adaptation could mean consistently developing and testing a new practice or suite of practices. It could also mean changing an existing practice that may have worked previously but no longer does so, or discontinuing something that isn't working at all (Montes de Oca Munguia et al. 2021). Take the example of a small- or medium-scale dairy operation. In this example, a hypothetical dairy farmer could make one or more small changes to improve profitability (and maintain economic and ecological viability) in the face of climate change: they could change their feed ration, investing in new herd genetics, or shift to selling heifers instead of milk; they could make large-scale changes that fundamentally alter the business, such as shifting to value-added processing and becoming a cheese maker; they could significantly increase their land base or size of their herd; or even exit farming. This illustrates the point that adaptation can manifest in many different ways depending on the farmer, the operation they run, and the context in which they are running it. Additionally, when a farmer adapts to change by trying something new, the change rarely is isolated to one practice or improvement. Land management, whether cropping, ranching, or forestry, is highly dynamic.

Prior to very recently, support for farms to pursue and fully adopt sustainable and regenerative practices has been provided in a limited way by federal programs, and in a patchwork way by states. For example, state programs in Maryland, Pennsylvania, New York, and Vermont have offset the cost of cover crop seed (Bowman and Lynch 2019; Chami 2020; Wallander et al. 2021). Support has also come from research and outreach organizations like federal research agencies, agricultural experiment stations, and cooperative extension services. Private industry has also stepped in to supply information through private certified crop consultants and others who provide for-profit services (Kelemen 2022). These efforts are excellent examples of how to move forward and expand adoption of sustainable and regenerative agriculture, and they have provided valuable opportunities to try out new, climate-centered outreach and education programs and incentives. However, these efforts have been piecemeal and are not universally accessible to US food, fiber, and fuel producers across regions and at diverse farm scales (Chandra et al. 2017). For agriculture to meaningfully contribute to addressing climate change, we need a unified, federal approach.

SOLUTIONS

To design and deliver agriculture-based solutions to address food security and climate change, we must ask ourselves two questions. First, "What are the primary threats to agriculture posed by climate change, and to what degree will US farms be affected?" We have already given examples of a few of these threats, but wish to emphasize that solutions must be tailored to specific challenges, and that the needs of different agricultural industries will vary. The second question is "What tools do we have at our disposal to promote agricultural practices that are good for farmers, ecosystems, and the national and global food supply?"

Both the challenges climate change poses to agriculture and the solutions to these challenges are nuanced. A great deal is already known about where we should invest and what we should do to efficiently support farmers as they adapt to a changing climate. We should invest in practices to reduce CH_4 and N_2O emissions, and sequester C (Lal 2004). Grassland conversion to row crops should be avoided, more cover crops should be planted in rotation with cash crops, and we need to invest in alley cropping and nutrient management (Fargione et al. 2018). We must invest in sustainable use of water resources, whether that is through efficient irrigation, water source development, or growing crops that require less water overall (Pretty 2008). Perhaps most importantly, we need to drastically reduce our use of fossil fuels in food production (and in food systems overall) by investing in renewable energy sources, developing and adopting widespread energy efficiency practices, and by using fertilizers judiciously and only when and where needed. These principles are applicable to farms of all scales, from tiny to large; organic and non-organic; serving local, national, and global markets.

Ultimately, farmers are the ones who make decisions about what practices do and do not make sense for their operations. In spite of overwhelming evidence that the use of regenerative agriculture practices (e.g. reduced or eliminated tillage, cover cropping, crop rotation, and integration of livestock) can improve climate resilience while increasing profitability, many farmers have not yet adopted these practices. For example, cover cropping was used on less than 13% of cropped farms in 2017, according to the USDA Census of Agriculture (USDA NASS 2019). Of course, this leads to the obvious question—why? Recent meta-analyses show that farmers with positive environmental attitudes, who identify as land stewards, and who have positive perceptions of a practice are more likely to use that practice (Lu et al. 2022). A lack of one-on-one support may help explain why adoption of some regenerative practices remains low (Piñeiro et al. 2020). Additionally, not everyone is yet aware that change is necessary. This is changing, however. More and more often, farmers are taking note of drought, heat, and shifts in seasonal temperatures, and all of these changes are leading these communities to realize that they cannot continue to farm in the same way as their predecessors (Kelemen 2022).

Of course, farms must be profitable to be sustainable. A recent study of wheat (*Triticum aestivum* L.) producers in Kansas shows that agricultural practices like cover cropping, reduced tillage, and crop rotation can often be seen as a financial risk, one which some growers are willing to take and some are not (Kelemen 2022). This study and others demonstrate producers' desire for education and technical support when it comes to how to integrate regenerative agriculture practices into their existing farm management approach. Farmers can more effectively transition to regenerative and sustainable management when they have access to educational programs that are regionally specific, including support from technical service providers who have knowledge of both the practices in question and the region's growing conditions, and peer support and knowledge exchange with and from other farmers who are also using regenerative practices.

Farmers would also clearly benefit from financial assistance, either in the form of payments for ecosystem services, or broader, more accessible cost-share style payments. Ecosystem services are defined as "the benefits that people derive from functioning ecosystems" (Ash et al. 2005), and include things like clean air, clean water, and a regulated climate. Payments for providing these services through agriculture would mitigate the risk of farming in a new way while often simultaneously working to mitigate climate change. In addition, farms using practices that provide these agricultural and ecosystem benefits are more resilient to the effects of climate change, as these practices generally require less water, fewer fossil fuel-based inputs, and potential improvements to soil health.

How to best structure payment for ecosystem service programs is a matter of great debate. First and foremost, there must be a robust and universally adopted system for quantifying ecosystem services among diverse agricultural regions and operations (Bennett et al. 2021). This ensures payments are objectively determined and tied to the actual delivery of services. For now, ecosystem service payment programs have the difficult task of garnering farmer interest and participation. It should be noted that farmers may be deterred from participating in voluntary payment programs that have high transaction costs, which includes the administrative burden of applying to a program and complying with program rules (Del Rossi et al. 2021). However, these programs could be a useful tool for expanding adoption of regenerative practices, which could contribute to widespread climate adaptation and mitigation (Biggs et al. 2021). Payments will likely increase some farmers' interest in these practices, though for others payments will not incentivize adoption (Kelemen 2022). Some producers see payments as a bridge, and after the benefits of the practices are realized the payments may no longer be necessary. Farmers in our studies are highly motivated to improve profitability and soil health on their farms, two overlapping and intersecting motivations that can be leveraged through policy as a win-win for agriculture, food security, and the climate.

However, when it comes to quantifying public goods like C sequestration, scientific assumptions must be clarified and measurement reliability should be addressed to ensure that payments are fair and equitable (Schröter et al. 2021). Programs that pay for ecosystem service outcomes (e.g. the amount of C sequestered) will likely be less efficient to run than programs that pay farmers directly for practice use, due to the cost of verifying ecological outcomes. This does not diminish the need to assess ecosystem service provision over time at the landscape scale, but rather allows us to allocate valuable resources (i.e., time and funding) toward incentivizing adoption and long-term use of sustainable and regenerative agriculture. Compensating farmers for the ecosystem services that they generate is an important tool in our climate change response toolkit, especially where farmers need financial support to make the transition to more regenerative practices. More research should be conducted, however, to assess the effects of payment duration on the length of time farmers are willing to keep using these practices (Thompson et al. 2021). This is especially important for practices that must be maintained over long periods of time in order to realize ecosystem service benefits (e.g., no-tillage and soil C sequestration).

The efficacy of farming practices known to be sustainable and regenerative has been explored and evaluated across the country, on a variety of important food crops and at a wide range of scales (Fargione et al. 2018). The value of this research is difficult to overstate, and it's very important to advocate for continuation of funding that supports further research in this vein. Indeed, it's been shown that the use of sustainable and regenerative practices can improve yields and increase soil health and quality (Yang et al. 2020). The economic benefits to farms and society are variable, and more work is needed to ensure that farmers are able to reap the benefits of sustainable and regenerative practices. These practices provide ecosystem services to the public; however the costs are largely privately held by the farmers (Rejesus et al. 2021). This is true whether we are looking at a 0.2 ha (0.5 ac) community garden in Brooklyn, a 16 ha (40 ac) vegetable farm in Maine, or a 4,000 (10,000 ac) wheat and cattle farm in Kansas. What regenerative farms have in common is that they strive to keep plant roots in the ground, keep the soil covered, minimize soil disturbance, and increase microbial diversity and soil organic matter and C, and by doing so provide a template for farming into the future. It is in our shared interest to support them in this important work.

WHAT'S NEXT?

In order to help farms adapt to climate change in a meaningful way, we must heavily invest in agricultural research, and leverage and expand educational programs, technical assistance, and financial assistance for farmers. Additionally, it is crucial to invest in professional development opportunities for agricultural advisors, defined as anyone who provides professional services and information directly to farmers. This entails developing sector-specific, regionally specific, and tailored offerings for both farmers and advisors. Some of this work has already begun through the recent increases in funding for conservation planning of the USDA Natural Resources Conservation Service (NRCS), and the Risk Management and Farm Service Agencies. For example, proposed conservation stewardship bundles would integrate suites of agricultural climate mitigation practices into the NRCS Conservation Stewardship Program, and the support for multiple agroforestry centers would complement the existing National Agroforestry Center in Lincoln, Nebraska. These two recommendations are among several well-considered and research-based approaches recommended by the Select Committee on the Climate Crisis in their June of 2020 report (Caston et al. 2020) and also included in the Agriculture Resilience Act (H.R. 2803) put forward by Congresswoman Pingree of Maine. Passage and funding of the initiatives included in the Agricultural Resilience Act would accelerate our ability to adapt to and mitigate climate change through agriculture.

We must listen to farmers about what works best for them, while ensuring that the tools and programs we offer are flexible enough to make room for innovation and new ideas. This means broadening access to programs in the 2023 farm bill and beyond that support both established and new farmers (Jablonski et al. 2022), and expanding the scope of existing programs to ensure broadscale participation. By doing so, we can make greater progress toward eliminating structural exclusion that has historically limited the participation of women, Black, Indigenous, and farmers of color in federal agriculture programs (Van Sant et al. 2022). This entails reevaluating the amount of time that farmers are eligible for programs and recognizing that on-farm changes that contribute to climate adaptation and mitigation will occur in stages and at all scales.

Farms of all shapes and sizes should be acknowledged for their contributions to climate change adaptation and mitigation. Farmers are thinking about and addressing climate challenges today: from designing energy-efficient greenhouse systems built into the sides of hills, to developing their own equipment for small-scale no-till systems, farmers were always trying to think about the climate problem in a new way. Private companies are also beginning to bring significant resources to bear on understanding and addressing the climate change challenges faced by growers in their industries. For example, General Mills is one of the first companies in the United States to pilot a payment for ecosystem services program, coupled with an intensive one-on-one education program and technical support for farmers, and Wyman's (the largest retailer of wild blueberries in the United States, and the second largest frozen fruit brand) has recently invested in a new research partnership with the Maine Agricultural and Forest Experiment Station to investigate the effects of increasing temperatures and changing precipitation on small fruit crop performance and health. These efforts demonstrate a recognition that new opportunities are coming online, where private, public, and institutional partners can work together across scales to address climate change and food security. These partnerships should be fostered and celebrated, so we can move together toward better outcomes for our country and the planet.

CONCLUSION

There is no question that more can be done to ensure that farmers are engaged and supported to pursue climate adaptation and mitigation projects. Sustainability, regenerative practices, and climate change adaptation and mitigation look different in different regions, in rural areas and urban areas, in different agricultural sectors, and for farms of different scales. These differences are driven by the particular pressures farmers face, and their social, ecological, and economic contexts. Support for farmers who wish to pursue sustainable and regenerative agriculture in different regions, sectors, and scales can include continued support for critical research to expand the climate toolbox, direct funding to producers, technical assistance, outreach and education, and peer-to-peer learning. We have many established mechanisms for offering this kind of support, though these mechanisms should be made more robust if we are serious about facilitating a widespread transition to climate adaptation and mitigation across the country. To make additional progress, we need to adopt the kind of initiatives that have been put forward by Congresswoman Pingree in the Agriculture Resilience Act, explicitly integrate climate adaptation and mitigation into farm bill conservation programs, and maintain climate change as a priority in this critical legislation.

We also must ensure that federal agriculture programs and other tools for adapting to climate change are available to all who steward the land (Furman et al. 2014). In addition to being a matter of science, climate change is invariably a racial, gender, and economic justice issue, as the negative effects of climate change will fall disproportionately on those who can least afford it (Timmermann 2021). The time to build equitable access to federal support into the farm bill and other programs is now; doing so will reduce barriers to accessing that support, specifically for programs that address agriculture and climate change.

What is at stake if we fail to address these issues, with the level of nuance and specificity that different types of farms require? We have an instructive example in the disrupted supply chains associated with the COVID-19 pandemic and recent extreme weather events, which significantly challenged our ability to get food to those who need it. To minimize the future harm to our country, we should bring federal policy to bear on extending and expanding how US agriculture adapts and mitigates climate change. The health and well-being of our people and the agroecosystems that feed us demand it.

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