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RESEARCH ARTICLE

The potential of nature-based solutions to reduce greenhouse gas emissions from US agriculture

Thomas L. Daniels[1]

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Abstract
Climate change is the main environmental challenge of the twenty-first century. The United States is the world's second-largest producer of annual greenhouse gases (GHGs), and agriculture contributes about 10% of the USA's emissions. This study evaluates the literature and potential of nature-based solutions to reduce GHG emissions from US agriculture, which has been characterized as "industrial agriculture." The US experience has global relevance. Nature-based solutions in US agriculture include: (1) changing the crops and livestock that farmers produce; (2) changing how farmers grow food by using regenerative or climate-smart agriculture practices, such as soil and water conservation and improved manure and fertilizer management to build up soil carbon and enhance productivity; (3) changing where food is grown; (4) enabling the sale of carbon offset credits from farmland owners to GHG emitters; and (5) enabling the sale of development rights by farmland owners to "preserve" farmland for agricultural uses and avoid the conversion of farmland to residential and commercial development. The potential reductions in GHG emissions from nature-based solutions appear to be 40–50%. So, nature-based solutions will not eliminate all GHGs from US agriculture. But the reduction in methane and nitrous oxide are especially important. The global challenge is how to profitably produce more food to feed a growing population while sustainably reducing GHGs and improving soil carbon health within a changing climate.

Keywords Regenerative agriculture · Greenhouse gas · Nature-based solution · Farmland

1 Introduction

Climate change caused mainly by human activities has become the paramount environmental challenge of the twenty-first century (IPCC 2018, 2021). Increasing global temperatures portend more frequent and intense storms and more prolonged droughts and heat waves which threaten the ability of farmers to produce food to feed a growing world population (Gowda et al. 2018, p. 392). The Paris Agreement of 2015 set a goal to keep the rise in average global temperatures to well under 2 C degrees from pre-industrial levels (UNFCCC 2015). The sixth assessment report of the IPCC noted that widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred and the likelihood of keeping average temperatures below a 1.5 C increase is fading (IPCC 2021). In short, the need to mitigate climate change has become increasingly urgent (The White House 2021, p. 13).

Food systems generate one-third of the world's anthropogenic greenhouse gas emissions (GHGs), with agricultural land use and the loss of farmland accounting for more than 20% of GHGs (Crippa et al. 2021, p. 198, UN FAO 2021, p. vii). So, if the world is to reduce GHGs, the dominant industrial food production model will need major changes. Industrial agriculture features heavy machinery powered by fossil fuels, the use of chemical nitrogen fertilizers, and Confined Animal Feeding Operations which produce huge amounts of manure (Philpott 2020, p. 8; Sharma et al. 2022, pp. 7, 9). Often industrial agriculture works against nature by depleting soil carbon and reducing organic matter through plowing and a lack of cover crops (Philpott 2020, p. 6). Moreover, methane from livestock and manure and nitrous oxide from nitrogen fertilizer and manure are major sources of GHGs and reducing these GHGs is especially urgent (US EPA 2022, p. 5–1).

The industrial model of agricultural production appears unsustainable at a time when there is a clear need to: (1)

✉ Thomas L. Daniels
thomasld@design.upenn.edu

[1] Department of City and Regional Planning, University of Pennsylvania, Philadelphia, PA, USA

reduce the use of fossil fuels to mitigate climate change; (2) increase carbon storage and sequestration in soils to maintain soil productivity and to offset GHG emissions; and (3) reduce methane and nitrous oxide emissions that contribute to climate change (McNunn et al. 2020, p. 1; Roesch-McNally et al. 2017, p. 206; UNCCD 2022, p. 25; UN FAO 2021; US EPA 2022, p. 5-1).

This special issue of *Socio-Ecological Practice Research* explores the promise and limits of nature-based solutions to reduce GHGs and to adapt to climate change. This paper focuses on five nature-based steps that the USA's farmers and ranchers can take to decrease GHG emissions. The USA's experience is relevant to other countries in the search for ways to modify industrial agricultural operations to mitigate GHG emissions while maintaining agricultural output. Socio-ecological practice involves the application of ecological knowledge and wisdom to solve problems through an iterative process of planning, design, implementation, and management (Xiang 2016, p. 53). The goal is to "bring about a secure, harmonious, and sustainable socio-ecological condition serving human beings' need for survival, development, and flourishing" (Xiang 2019, p. 7). Socio-ecological practice can serve as a guiding principle for reducing GHGs from agriculture. Ecologically, farming with nature to build up soil health and sequester carbon is far more sustainable than farming against nature with a heavy reliance on chemical fertilizers and irrigation (UNCCD 2022, p. 25). In addition, social changes will be needed in consumer diets and in a willingness to provide government financial support for a transition to climate-friendly food production.

Nature-based solutions (NBS) are defined as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits" (Bauduceau 2015, p. 7). To date, NBS have been more popular in Europe than in other countries as judged by the resulting green infrastructure projects (La Rosa et al 2021, pp. 329–330).

NBS in agriculture have three guiding principles: "sustainably increasing agricultural productivity and incomes, adapting and building resilience of people and agri-food systems to climate change, and reducing and/or removing greenhouse gas emissions where possible" (UN FAO 2021, p. vii). NBS in agriculture feature regenerative or climate-smart practices, such as no-till farming and cover crops to enhance the productivity of soils by storing and sequestering carbon, and the careful management of fertilizers and manure to decrease methane and nitrous oxide emissions (Keestra et al. 2018; Lehner and Rosenberg 2021; McNunn et al. 2020, p. 1, Sharma et al. 2022, p. 7, UNCCD 2022, p. 27, UN FAO 2021).

This study seeks to ascertain the potential of NBS to reduce greenhouse gas emissions from US agriculture. The study presents a review of the literature to evaluate the potential for NBS in five areas: (1) changing the crops and livestock that farmers produce; (2) changing how farmers grow food by implementing regenerative, climate-smart practices; (3) changing where food is grown; (4) enabling the sale of carbon offset credits by farmers to GHG emitters in return for greater carbon sequestration; and (5) enabling the sale of development rights by farmland owners to retain land in farming and thus avoid the conversion of farmland to residential and commercial development.

2 Global agriculture and greenhouse gas emissions

Cropland and grazing lands cover more than 11 billion acres or almost 40% of the Earth's land area (UNCCD 2022, p. 25). Agriculture contributes about one-fifth of global greenhouse gas emissions (Crippa et al. 2021, p. 198, UN FAO 2021, p. vii). In 2007, livestock alone was responsible for 5% of anthropogenic carbon dioxide emissions, 44% of methane emissions, and 53% of nitrous oxide emissions (UN FAO 2013, p. 15). From 1990 to 2015, the global food system—including food production, packaging, distribution, and waste experienced a 12.5% increase in GHG emissions (Crippa et al. 2021, p. 199). In 2015, China, Indonesia, the USA, Brazil, India, and the European Union accounted for 51% of GHG emissions from agriculture (ibid.). Sources of GHGs from agriculture vary among countries; for example, rice is a leading food crop and a main source of methane emissions in many developing countries (ibid.). Nitrous oxide emissions are somewhat higher in developed countries because of the greater use of chemical fertilizers.

Among developed countries, GHG gas emissions from food systems remained fairly steady between 1990 and 2015, whereas GHGs in developing countries—mainly China—nearly doubled, in part from greater mechanization and increased food production (ibid., p. 200). This suggests an increasing need for farmers in developing countries to adopt climate-smart practices in how they produce crops and livestock and what they produce.

2.1 US agriculture and greenhouse gas emissions

Agricultural land covers about 900 million acres of the US, comprising more than 56% of the nation's privately held land (USDA 2019). The quality of the agricultural land varies greatly from low-productivity rangeland in the West to the deep fertile soils of the Midwest Corn Belt. The US is a leading agricultural nation, accounting for about 7% of the world's $5 trillion in annual crop and livestock output, and producing almost one-quarter of the world's grains—corn, rice, and wheat—and nearly half of global soybean output (Gowda et al. 2018; Nieuwkoop 2019; USDA 2021c). The US is a major exporter of feed grains, which reflects in part the heavy concentration on the production of grain for domestic livestock, a major source of GHGs from agriculture. Overall, the US has a small trade surplus, and fruits and vegetables, which are associated with low GHG emissions, are the leading food imports (USDA 2021d).

The structure of US agriculture is also important to recognize. There are more than two million farms in America, with a farm defined as capable of generating at least $1,000 a year in gross sales of food or fiber (USDA 2019). About 97% of US farms are family-owned and operated. Large farms with annual sales of more than $500,000 a year make up 141,000 farms or just 7% of all farms, but they dominate agricultural production, accounting for more than 81% of total farm output (USDA 2019). On the other end of the spectrum, 1.3 million farms produce less than $10,000 a year in gross sales (ibid.). These are typically hobby farms where the owners earn the large majority of their income away from the farm. Small commercial farms have increasingly focused on niche markets such as organic vegetables, fruit, and meat. In between the large and small farms are the medium-size farms with sales of $100,000–$500,000. The number of large farms has been gradually increasing; and small farms have become more numerous. But the number of medium-size farms has declined; a few have become large farms but most of the loss has been from medium-size farms exiting agriculture (Philpott 2020, p. 178). These trends are likely to continue.

The USA accounts for about 12% of the world's annual production of greenhouse gases, second only to China, and has emitted more GHGs over time than any other country (UN Environment 2018, p. 6). In 2020, the USA generated a net of 5.2 billion tons of GHGs of which about 10% came from agriculture (Sharma et al. 2022, p. 7; US EPA 2022, pp. ES-4, 5-1). Between 1990 and 2020, US emissions from agriculture rose by 8%, from 552 million metric tons to 595 million metric tons (US EPA 2022, p. 5-2).

US overall GHG emissions in 2020 came from carbon dioxide (79%), methane (11%) nitrous oxide (7%), and fluorinated gases (3%) (US EPA 2022, p. ES-7). But the sources of GHGs from agriculture were quite different. In 2018, carbon dioxide emissions made up 12.3% of emissions from agriculture, 36.2% came from methane, and nitrous oxide was the leading GHG at 51.4% (USDA 2020).

Methane (CH4) from livestock, especially burping cattle (known as enteric fermentation) and manure accounted for nearly half of all US methane emissions (The White House 2021, p. 40). Nitrous oxide (N2O) from chemical fertilizers and manure generated more than 82% of all US nitrous oxide emissions (Jordan 2021; US EPA 2022, pp. 5–4). In sum, nitrous oxide and methane emissions from chemical fertilizers, manure, and livestock have accounted for nearly all of the increase in GHG emissions from US agriculture since 1990 (US EPA 2022, p. 5-3).

US agricultural emissions of methane and nitrous oxide pose a more immediate challenge to climate mitigation than carbon dioxide releases (see Table 1). Methane has 28 to 75 times more heat-trapping capacity than carbon dioxide; and nitrous oxide is nearly 300 times more potent a greenhouse gas than carbon dioxide (Abernethy and Jackson 2022, p. 1; US EPA 2022, p. ES-3). Globally, methane releases have accounted for about half of the 1.0 C temperature increase since pre-industrial times (The White House 2021, p. 3). At United Nations Conference of the Parties 26 in 2021, more than 100 nations signed the Global Methane Pledge to reduce methane emissions by 30% by 2030 through practices such as better fertilizer and manure management (BBC News 2021). In the short run, reducing methane and nitrous oxide emissions will produce the highest returns on investment in US agriculture for climate mitigation.

Table 1 shows how the sources of greenhouse gases from US agriculture have changed between 1990 and 2020. It is important to note that production agriculture is not a major source of CO2, and the annual amount of CO2 from agriculture has increased by less than 10% over 30 years. But these figures do not include the amount of CO2 released in the conversion of farmland to other uses, the operation of agricultural machinery, or the processing and transporting of food.

Table 1 Sources of greenhouse gases from US agriculture, 1990–2020 (millions of metric tons of CO_2 equivalent). *Source*: US EPA. 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020, p. 5–3

Gas/source	1990	2020
CO_2	7.1	7.7
Urea fertilization	2.4	5.3
Liming	4.7	2.4
CH_4	218.2	250.9
Enteric fermentation	164.7	175.2
Manure management	37.1	59.6
Rice cultivation	16.0	15.7
Field burning of agricultural residues	0.4	0.4
N_2O	330.1	336.1
Agricultural soil management	315.9	316.2
Manure management	14.0	19.7
Field burning of agricultural residues	0.2	0.2
Total	555.3	594.7

Totals may not sum due to independent rounding. These figures do not include energy use in producing crops and livestock or changes in agricultural land use

The data on methane and nitrous oxide emissions are far more alarming. Together, methane and nitrous oxide emissions generated 587 million metric tons of CO2 equivalent in 2020. It is important to note that over the 30-year period, the US added more than 82 million people—248.7 million to 331.4 million (US Census Bureau 2021). This increased demand for food led to a greater use of manure and fertilizer for crop production along with more livestock, in particular chickens and hogs. Farmers applied commercial fertilizer (derived largely from natural gas, a source of methane) to 226.7 million acres in 1992 and 253.8 million acres in 2017 (USDA 1994, 2019). The number of cattle—a leading source of enteric methane—slipped from 96.1 million in 1992 to 93.6 million in 2017; but the number of chickens (layers and broilers) soared from 1.3 billion to 2 billion, and the hog population jumped from 57.6 million to 72.4 million (USDA 1994, 2019). Greater numbers of livestock mean more manure to manage and more methane and nitrous oxide emissions. Shifting consumer diets away from meat and toward plants would clearly help to reduce methane and nitrous oxide emissions.

If the US is to reach its goal of net zero GHG emissions by 2050, agricultural production practices will need to become more climate-smart along with changes in crops and livestock raised and alterations in consumer tastes and preferences (Philpott 2020, p. 188; Pollan 2006a; Popkin 2020a, p. 1; The White House 2021, p. 16). Rewarding farmers for conservation practices and for retaining their land in agriculture can aid in the transition to more climate-smart agriculture (Sharma et al. 2022; USDA 2022a).

3 The rise of nature-based solutions in agriculture as a focus of research

Interest in NBS in agriculture emerged in the 1990s. Since then, NBS have attracted greater attention because of the recognized need to reduce GHG emissions to keep the average global temperature increase well below 2.0 Celsius from pre-industrial levels (IPCC 2018; UN FAO 2021; UNFCCC 2015). NBS in agricultural production is now referred to as regenerative, carbon smart, or "climate smart" agriculture (McNunn et al. 2020, p. 2; Newton et al. 2020; Popkin 2020a, p. 1; Sharma et al. 2022; UN FAO 2021, p. vii). The goals of NBS in agriculture are to: (1) increase agricultural productivity and incomes in ways that are sustainable, (2) adapt and build resilience to climate change; and (3) reduce greenhouse gas emissions (McNunn et al. 2020; Sharma et al. 2022; UN FAO 2021). The Food and Agriculture Organization of the United Nations has taken a broader view of climate-smart agriculture (CSA) based on five principles: "(1) expanding the evidence base for CSA, (2) supporting enabling policy frameworks, (3) strengthening national and local institutions, (4) enhancing funding and financing options, and (5) implementing CSA practices at field level" (UN FAO 2021, p. vii). In particular, farmers must increase food production with sustainable practices to meet the Sustainable Development Goals of the United Nations (FAO 2021, p. 1). It is important to emphasize that climate-smart agriculture is not meant just for developed countries. Already there are many examples of climate-smart practices being implemented in developing countries, but primarily on small farms (UNCCD 2022, pp. 103–109; UN FAO 2021).

The literature on NBS has featured two strategies: (1) improving land management to increase carbon storage and sequestration and reduce erosion (Gullickson 2021; Jordan 2021; Mendes et al. 2020; Newton et al. 2020; Popkin 2020a; Simmons 2016); and (2) protecting agricultural land from conversion to residential and commercial development (California Strategic Growth Council 2021; Sallet 2020).

Although NBS alone cannot fully offset total GHG emissions or even all GHG emissions from agriculture, NBS can make important contributions (Griscom et al. 2017, p. 11645; IPCC 2007, p. 14; McNunn et al. 2020, p. 1). According to the National Academies of Science, US farmers could sequester between 240 and 305 million tons of carbon equivalent per year or 4–5% of US GHG emissions (National Academies 2019, pp. 107–8). This would offset about 40–50% of US GHG emissions from agriculture unless the land is plowed or mismanaged.

This NBS estimate for US agriculture appears somewhat high compared to two global estimates: (1) NBS could "provide over one-third of the cost-effective climate mitigation needed between [2017] and 2030 to stabilize warming to below 2 °C" (Griscom et al. 2017, p. 11645); and (2) On a global scale, soil has the potential to sequester an estimated 570 million metric tons of carbon each year out of total annual GHG emissions of 50 billion metric tons (Dunn 2021, p. 10). But even these global NBS estimates appear optimistic given that, historically, agricultural practices across the world have released a total of 200 billion tons of carbon dioxide from soils (Jordan 2021).

Researchers have warned that "[a]griculture is extremely vulnerable to climate change," which can limit mitigation options (Nelson et al. 2009, p. vii). Higher temperatures and changes in precipitation patterns can reduce crop and livestock yields. Heat waves, which are projected to increase under climate change, could directly threaten livestock (Gowda et al. 2018, p. 392). Prolonged droughts can lower grain yields for feed supplies and decrease the amount of quality forage available to livestock (Jagermyer et al. 2021, p. 881). Floods from intense rain events hurt crop yields and threaten to harm livestock. Warmer winters and earlier springs could allow some parasites and pathogens to survive and spread more readily, creating disease outbreaks among livestock (Gowda et al. 2018, p. 406). Crop and livestock damage from drought-induced wildfires, the spread of weeds and invasive species from higher temperatures, and a decline in pollinators also threaten agricultural output (VT Climate Report 2021, p. 109).

Researchers caution that NBS have a limited time frame for implementation as a warming planet threatens to make carbon sequestration less efficient (IPCC 2021; Jagermyer et al. 2021, p. 881). The NBS literature emphasizes the need for widespread implementation of NBS now and over the next few decades (IPCC 2021; Keestra et al. 2018; Mendes et al. 2020).

The gaps in the NBS literature are: (1) the lack of strategies to reduce methane and nitrous oxide at the farm level; and (2) the absence of a holistic analysis of the opportunities to reduce farm GHGs. Individual articles have focused on carbon retention and sequestration to improve soil health, yet manure management and the use of chemical fertilizers generate much more in GHGs than traditional plowing and lack of cover crops (McNunn et al. 2020, pp. 8, 9; US EPA 2022, p. 5-3) (see Table 1). Other researchers discuss technologies to increase food output (Kolbert 2021; Weber and Ratti 2021); carbon offset credits from agriculture (Dunn 2021; Gullickson 2021; Mittenberger et al. 2021); needed changes to federal farm policies to support NBS in agriculture (Philpott 2020); changes to the location of agricultural production in response to climate change (ibid.); and agricultural land preservation as a way to mitigate and adapt to climate change (California Strategic Growth Council 2021; Sallet 2020).

The following five sections present a review and analysis of the NBS literature to provide a holistic evaluation of how and how much NBS in US agriculture can reduce GHGs. The goal is to go beyond the dominant focus on the restoration of soil carbon to include the adoption of climate friendly crops and livestock, the sale of carbon credits, and the preservation of agricultural land. In addition, an evaluation of the literature will suggest how federal farm programs can financially support long-term management of farmland to lower GHG emissions and increase resilience in the face of climate change.

3.1 What foods do US farmers produce and how could US consumer diets become more climate-friendly?

Federal farm crop subsidies and crop insurance greatly influence what farmers produce (Schechinger 2021; Sharma et al. 2022, p. 13). The two leading crops grown in the US are corn and soybeans. Corn subsidies totaled an estimated \$116.6 billion between 1995 and 2020 and soybean subsidies were estimated at \$44.9 billion (EWG 2021a, b). Not surprisingly, the acreage planted in corn rose from 75.4 million acres in 1995 to 90.8 million acres in 2017, and soybeans jumped from 56.3 million acres to 90.1 million acres (USDA 2019). The large majority of corn and soybeans become animal feed for the production of meat, dairy products, and eggs. Moreover, crop subsidies are heavily skewed in favor of large producers. From 1995 to 2019, the top 10% of recipients received 78% of federal farm subsidies (Schechinger 2021). To support the transition to the use of NBS in agriculture, current federal subsidies will need to be reformed and directed toward: (1) support for climate smart farming practices, crops, and livestock (Sharma et al. 2022); (2) the production of fruits and vegetables—foods that nutritionists advise Americans to eat more of—which do not receive direct federal support, but in some cases do receive federally subsidized water for irrigation (Bentley 2017; Philpott 2020, p. 7); and (3) wider availability of financial support for small and medium-size farms (Sharma et al. 2022).

The production of drought-resistant and low-GHG crops and livestock will also depend on a change in the eating habits of consumers. Such a shift in diets will pose challenges given the correlation between the consumption of meat with the growth of incomes in developing countries and only a slight decline in meat consumption in high income countries (Komarek et al. 2021, p. 2; Schroder et al. 1996, p. 15). US consumers mostly follow a heavy meat-oriented diet (USDA 2021c) (see Table 2). Sales of cattle and calves underscore beef output and consumption, as do the sale of corn and soybeans, the main livestock feeds. Dairy products are also prominent in American diets. In 2018, 65.2 pounds of chicken and 54.6 pounds of beef per person were available for Americans to eat. Chicken availability per person has more than doubled since 1970 while beef has fallen by about one-third and pork has remained relatively steady at about 45 pounds per person (USDA 2021) (see Fig. 1). In sum, more than half of all US farmgate sales involve meat production, a major source of GHG emissions from agriculture.

The social or demand side of food is especially important. Author Michael Pollan has advised: “Eat food, not

Table 2 Leading crops and livestock sales in the US, 2020. *Source*: USDA 2021c. Farm income and wealth statistics: Cash receipts by state

Crop or livestock sold	Value in \$ billions	% of Total agricultural output
Cattle and calves	\$63.1	17.7
Corn	\$46.7	13.1
Dairy products	\$40.5	11.4
Soybeans	\$36.7	10.3
Miscellaneous crops \$21.7	\$21.7	6.1
Broilers (chickens)	\$21.7	6.1
Hogs	\$19.2	5.4
Wheat	\$8.8	2.5
Chicken eggs	\$8.7	2.4
Hay	\$7.3	2.1
Total	\$274.4	74.1

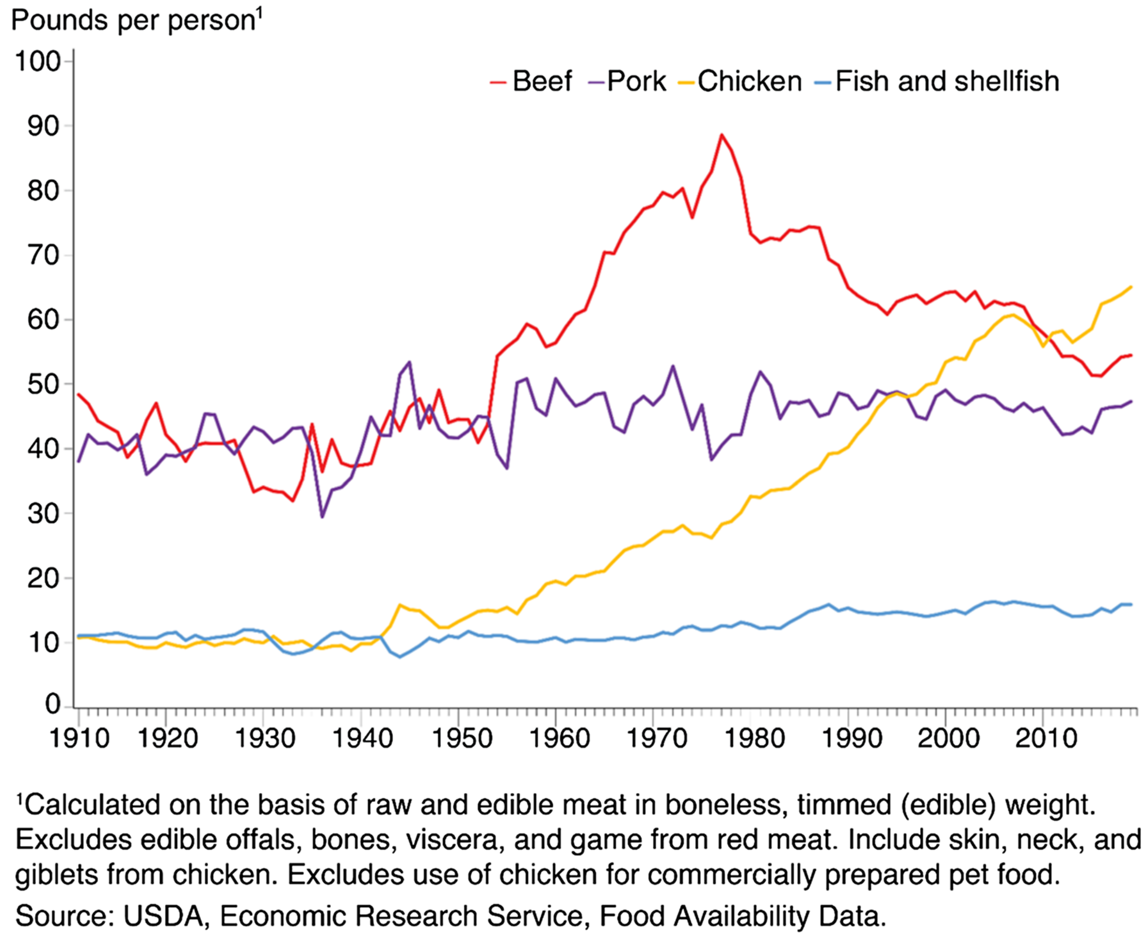

Fig. 1 U.S. per capita availability of beef, pork, chicken and fish/shellfish—1910–2018. https://www.ers.usda.gov/webdocs/charts/58311/food-availability_fig02-2-.png?v=167.7

too much, mostly plants" (Pollan 2009, p. xv). This recommendation, if widely embraced by consumers, would lead to a significant decline in the production of meat and feed grains in favor of fruits and vegetables and plant-based sources of protein and even plant-based "fake meat." The benefits in GHG reductions would be enormous (see Tables 1, 2), not only from less livestock but also from less livestock feed and a lower need for agricultural land. For instance, beef production creates an estimated 31 times more CO2 emissions per calorie than tofu (The Economist 2022). Globally about 80% of agricultural land is devoted to grazing livestock and animal feed; and if everyone on earth ate a vegan diet, only one-quarter of the agricultural land would be needed (ibid.).

How to encourage such a change? More research and development of delicious, inexpensive, nutritious, yet profitable plant-based food is essential; and perhaps a tax on meat, especially in developed countries, similar to a carbon tax would encourage consumers to shift their diets away from meat.

3.2 Changing how farmers grow crops and raise livestock

Farmers have choices in how to grow crops and raise livestock, which have different outcomes for carbon dioxide, methane, and nitrous oxide emissions. The two main options are: (1) the traditional agricultural practices featuring tilling or plowing the soil, a heavy use of chemical fertilizers, an avoidance of cover crops, a lack of crop diversification, and Concentrated Animal Feeding Operations (CAFOs) (Sharma et al. 2022, p. 9); and (2) regenerative and climate-smart agriculture which involves the "use of cover crops, the integration of livestock, and reducing or eliminating tillage… to improve soil health, to sequester carbon, and to increase biodiversity" (Newton et al. 2020, p. 1) (see Fig. 2).

Tilling the soil accelerates soil erosion, which contributes to poor soil health through the leaching of nutrients and in turn leads to more erosion. Tilling also adds to greenhouse gas emissions because disturbing the soil releases stored carbon in the form of carbon dioxide (McNunn et al. 2020;

Fig. 2 Winter cover crop on corn field holds carbon in the soil and minimizes soil erosion in Lancaster County, Pennsylvania, USA (Photo by author)

Roesch-McNally et al. 2017). A lack of cover crops leaves the land vulnerable to soil erosion from wind and rain and releases carbon (Clark 2015). Planting a continual single crop, such as corn, or a corn-soybean rotation reduces soil nutrients and creates a greater reliance on chemical fertilizers derived from natural gas (methane) (Philpott 2020; Roesch-McNally et al. 2017). Finally, CAFOs produce huge amounts of manure that add to methane and nitrous oxide emissions (Sharma et al. 2022, p. 9).

Among regenerative practices, no-till or reduced tillage can improve carbon storage and sequestration and soil health by either not disturbing the soil or minimal intrusion (McNunn et al. 2020; Roesch-McNally et al. 2017). No-till or reduced tillage requires less tractor use than in plowing and thus decreases fossil fuel consumption.

Cover crops hold the soil after harvest and keep the soil warm over the winter. Cover crops are also known as "green manure;" they are not harvested but instead are mixed into the soil in the spring to increase organic matter, fix nutrients into the soil, improve soil health, and fertilize the ensuing cash crops, such as corn or soybeans. Cover crops—rye, clover, and vetch, among others—can curb erosion and reduce the need for chemical fertilizers (McNunn et al. 2020).

The timing and carefully targeted amounts of fertilizer and manure applications can also reduce emissions of methane and nitrous oxide (Roesch-McNally et al. 2017). Diversified crop rotations that involve more than two crops can raise soil productivity because some crops, such as alfalfa and soybeans, can fix nutrients such as nitrogen in the soil. This way diversified crop rotations can decrease the need for manure and reduce or eliminate chemical fertilizer applications (ibid.).

Other conservation practices include grassed waterways and forested riparian buffer strips to intercept eroded soil and keep it from entering waterways; trees soak up flood waters to protect farm fields as well as sequester carbon (Gowda et al. 2018, p. 393; Sharma et al. 2022, p. 24). Many farms have woods and sustainably managed stands can add to carbon sequestration while generating income from timber harvests in a process known as agroforestry, though this is more common in the developing world (American University 2020; UNCCD 2022, p. 25).

An increasingly common practice, especially on farms in developed countries, is the application of precision agriculture, in which farmers use real-time data to manage the use of water, manure, fertilizers, feed, and labor (UNCCD 2022, p. 27). A variety of technologies, including geographic information systems, remote sensing, and drones, provide data on soil, livestock, and weather conditions. These technologies enable farmers to save money and raise crops and livestock in more climate-friendly ways.

In sum, the use of manure, compost, crop residues, a diversity of crops, no-till or minimum tillage, extended crop rotation, and cover crops can increase soil organic matter. This healthier, more productive soil has a greater ability to hold water, is more drought and flood resilient, and raises the amount of carbon retained and captured in the soil (Ontl and Schulte 2012; Roesch-McNally et al. 2017). These soil conservation practices reduce tractor use and fossil fuel consumption and decrease the application of chemical fertilizers which are methane- and nitrous oxide-intensive.

In 1992, US farmers applied commercial fertilizers to 226.7 million acres, rising to 253.8 million acres in 2017 (USDA 1994, 2019). That year farmers also practiced no-till on 104.5 million acres and reduced tillage on 97.7 million acres but planted cover crops on only15.4 million acres (USDA 2019). Given that farmers raised 90.8 million acres of corn in 2017, it is apparent that considerably greater use of cover crops is needed. After corn is harvested, the large majority of fields are left bare, vulnerable to erosion from wind, rain, and melting snow. This also results in a loss of soil carbon. Cover crops would help to hold soil, reduce erosion, and retain carbon (Clark 2015).

Farmers can change the livestock they raise, such as from dairy to chickens. But it may be stretch to expect farmers in the Midwest to move away from growing grain and soybeans to fruits and vegetables. Improved feeds, such as those containing seaweed or biochar, that reduce enteric methane emissions are becoming available for livestock (Vermont Climate Council 2021, p. 122). Also, better matching of feed to individual animals can help reduce manure; excess feed simply results in more manure (USDA 2021b).

To better manage manure and reduce methane and nitrous oxide emissions, farmers could store manure in anaerobic lagoons and then capture the methane to use in anaerobic digesters (US EPA 2021a). As of 2021, the US had only 317 anaerobic digesters, mostly on dairy farms. Yet, digesters reduced GHG emissions by an estimated 5.95 million metric tons in 2020 (ibid.). Many more digesters are needed to reduce methane emissions from livestock manure, especially on Concentrated Animal Feeding Operations (CAFOs). A CAFO is defined as having more than 1000 animal units (an animal unit is defined as an animal equivalent of 1000 pounds live weight and equates to 1000 head of beef cattle, 700 dairy cows, 2500 swine weighing more than 55 pounds, 125 thousand broiler chickens, or 82 thousand laying hens or pullets) confined on site for more than 45 days during the year (US EPA 2021b). As of 2020, there were 21,465 CAFOs in the US (ibid.).

Another obstacle to regenerative agriculture may be that about 40% of US farmland is rented, and often on a year-to-year basis (USDA 2020). Farmers who rent land have less of an incentive to invest in the productivity of the land because they may not be able to recoup their investment in soil improvements if they are farming the land for only a few years. So, farmland renters may be less willing to invest in regenerative agricultural practices.

Climate change has raised concerns about food security because, under business-as-usual practices, crop yields appear to be headed toward a decline (Gray 2021). But can farmers produce enough food to feed a growing global population while implementing regenerative agriculture? To enhance NBS scientific research, genetic engineering may be needed to create more resilient and productive crops and higher yielding livestock (Kolbert 2021). Already, over 90% of US corn and soybeans are genetically modified (USDA 2018). One possible breakthrough would be crops that self-fertilize, which would reduce the need for chemical fertilizers and thus lower methane and nitrous oxide emissions (Weber and Ratti 2021, p. 52). The Land Institute in Salina, Kansas has long been working to develop a perennial polyculture of deep-rooted grain plants that do not need to be planted each year and require less fertilizers (The Land Institute 2022).

Financing the adoption of climate-friendly agricultural practices is critical. A major challenge is that regenerative agriculture takes longer to see a return on investment than simply relying on chemical fertilizers (Philpott 2020). In most cases, small farmers have led the way in the adoption of regenerative agriculture; this is especially the case internationally (UN FAO 2021, p. vii). In the US, farmers have incorporated soil conservation practices and avoidance of pesticides to grow certified organic products which command a higher price than conventionally grown crops and livestock (Philpott 2020, pp. 148–58; Pollan 2006b, pp. 123–133). But now, large organic farms with more than $500,000 sales a year account for over 80% of organic food sales (USDA 2020b, p. 2).

Industrial organic farms can be expected to have somewhat higher emissions than a small organic farms because of the greater use of machinery powered by fossil fuels. Small organic farms would likely be more labor intensive. An organic dairy, however, would tend to have higher emissions than a conventional dairy if the organic dairy relies mainly on grazing as opposed to feed grains. Grass creates more methane in cattle than feed grains (A Well Fed World 2021).

Organic crops are grown and processed without the use of chemical fertilizers or pesticides; other certified organic standards are set by the US Department of Agriculture (USDA no date a). It takes three years for a traditional farm to transition to a certified organic farm. In 2019, there were 16,585 organic farms covering 5.5 million acres with $9.9 billion in sales (ibid.). This was less than 1% of all US farms and acres, but more than 2% of farm commodity sales.

NBS ideally would incorporate the standards of organic production that minimize the use of fertilizers derived from natural gas and require crop rotation, conservation tillage, and cover crops to build soil health. These organic standards, if put in practice, would lead to the reduction in methane, nitrous oxide, and carbon emissions and thus can be seen as part of the NBS approach.

Farmers can make investments themselves with financing from the farm credit system or commercial banks. Federal policies and funding programs can influence conservation practices that farmers employ in growing crops and raising livestock. For example, the Environmental Quality Incentives Program (EQIP) is a voluntary program that provides technical and financial assistance for farmers to adopt climate-smart conservation practices such as building soil health, improving nitrogen management, improving livestock waste management systems, and enhancing grazing and pasture management (NRCS 2021a). EQIP was funded at $1.8 billion in 2020 (NRCS 2021b). In February of 2022, the US Department of Agriculture created the Partnerships for Climate-Smart Commodities program, initially funded at $1 billion, to help finance projects that the production and marketing of commodities grown with climate-smart methods (USDA 2022a). But clearly more federal funding is needed to enable farmers to adopt more climate friendly practices (Sharma et al. 2022, pp. 21, 23).

3.3 Changing where food is grown in the US?

Climate change will exert a strong influence on the location of America's agriculture and food production. In his book, *Perilous Bounty*, author Tom Philpott features America's two major food producing regions: California, the source of a majority of the nation's fruits and nuts, and about a third of its vegetables, and the Corn Belt of the Midwest where corn and soybeans dominate (Philpott 2020, p. 6). Drought, intensified by climate change, has plagued California for more than ten years. Many farmers irrigate their crops. The decline in rainfall and surface water has compelled farmers to draw heavily on groundwater that is not being readily replenished or even to abandon water-thirsty crops such as almonds land (ibid.) In the Corn Belt, farmers have lost about half of the topsoil to wind and water erosion in part because of not planting cover crops after the corn harvest, leaving the soil exposed to the elements (ibid.) In short, these farming practices are unsustainable especially in the face of hotter and drier conditions in California and the greater frequency of floods that wash away soil in the Midwest.

Storing food and transporting it over hundreds, if not thousands, of miles (known as "food miles") consumes a large amount of fossil fuels. The amount of CO2 produced depends on the transportation mode and distance— air freight is the most carbon intensive, cargo ship the least, with truck transport in between (Alimentarium 2021). One option to reduce food miles and minimize food disruptions from climate change is to develop regional food production and distribution systems (Philpott 2020, p. 176). For example, the six states of New England imported about 90% of their food in 2010. A group of policy specialists drafted a plan to move New England to supply 50% of its food by 2060 (Food Solutions New England 2014). For New Englanders, a regional food system could mean the end to the 3,000-mile Caesar salad imported from California. Although New England agriculture would produce more GHGs from greater food production, this would likely be more than offset by the reduction in GHGs from less imported food. Moreover, a motivation for a regional food system is the ability of consumers to access locally grown fresh produce (Jordan 2021). While California growers struggle with a prolonged and punishing drought, dispersed fruit and vegetable production seems a wise alternative. In fact, dispersion has been a long-standing trend. In 1994, the US had 1755 local farmers markets where growers could sell directly to consumers. By 2019, the number of farmers markets had more than quadrupled to 8140 (USDA 2020c). Community-supported agriculture (CSA) operations and farm-to-school programs also involve direct sales to consumers and have been increasing in popularity (Philpott 2020, p. 177). The US Department of Agriculture reported that growers who sell directly to consumers stay in business longer (USDA 2017).

3.4 Carbon offset markets

Carbon offset credits are created by landowners who agree to adopt climate-smart practices in return for a payment from a carbon emitter (Kim and Daniels 2019). Carbon offset credits have existed for a few decades, although most credits have come from forests rather than farmland (Author 1). Two types of credit markets exist: (1) a compliance market; and (2) a voluntary market. Carbon credits in a compliance market are part of a cap-and-trade program to reduce GHGs. For example, in the California cap-and-trade program, created in 2012, the California Air and Resource Board (CARB) sets a fixed amount of allowable carbon emissions for targeted sectors and then sells emission allowances to a variety of emitters in the private sector. CARB permits emitters to meet up to 8% of their allowed emissions through the purchase of certified carbon credits. Most of these credits have been sold by forest owners who will improve their forestry practices to increase the sequestration of carbon (ibid.). Critically, the amount of allowable carbon emissions and offset credits allowed decline over time in order to drive down overall emissions and achieve long-term GHG reduction targets (ibid.).

In the voluntary carbon credit market, companies and institutions may purchase carbon credits to meet corporate carbon neutrality goals or to burnish their green image; this latter practice has led to charges of "greenwashing," in which the purchase of offsets is used to mask a lack of internal progress on emissions reductions (Dunn 2021). Also, the voluntary carbon credit market is unregulated, and the quality of the carbon credits has varied widely in the rigor of monitoring and verifying carbon sequestration over time (Miltenberger et al. 2021, p. 1). Adding agriculture carbon offset credits into the compliance market of cap-and-trade programs seems preferable to the variable standards of the voluntary market (Popkin 2020b).

So far, farmers have participated in the voluntary carbon market where they can generate carbon credits based on one credit equals the reduction in one metric ton of carbon; and farmers can sell the credits in return for raising crops or livestock in ways that sequester carbon and reduce emissions of carbon dioxide, nitrous oxide, and methane (Gullickson 2021). Farmers must prove they are sequestering more carbon or preventing additional carbon from entering the atmosphere through improved farming practices compared to their business-as-usual management. This additionality of carbon sequestered must be verified through sound science and careful record keeping; but monitoring and verifying carbon sequestration in the soil can be difficult and expensive. Farmers must demonstrate that they are employing the promised farming practices and that they have not developed land for commercial and residential uses (ibid.).

Agricultural carbon offset credits have become increasingly popular (Popkin 2020a). This has helped to address a basic problem in the voluntary market: finding willing buyers for landowners' carbon offset credits. Several credit purchasers are major agribusiness companies who see buying credits as a way to reward growers for good conservation practices. For example, the German company Bayer pays farmers up to $9 per acre based on practices the grower has implemented or plans to implement (Gullickson 2021). Corteva Agriscience offers between $6 and $30 per acre, depending on the amount of carbon sequestered (ibid.). The sale of carbon credits can more than pay for a farmer's investment in soil health. Importantly, farmers who sell carbon offset credits can continue to produce crops and livestock. But a risk is that the long-term ability of soils to retain carbon may be reduced as the atmosphere warms (Davidson et al. 2000; Popkin 2020a).

Ironically, farmers who have already adopted sound soil management practices stand to gain little from carbon markets that pay farmers for improving their management practices. Similarly, federal farm programs that subsidize traditional agriculture leave little incentive for farmers to adopt regenerative, climate-smart agriculture practices (Philpott 2020, p. 158).

A major problem with voluntary carbon credits for agriculture is that thus far the prices of credits have been too low to stimulate widespread participation. Carbon credit aggregator Indigo Ag currently offers a minimum of $20 per ton of sequestered carbon, which can rise to more than $30 per ton once a farmer adopts climate-friendly practices and demonstrates verified sequestration levels (Indigo Ag 2022). By comparison, the price for carbon allowances in California's GHG cap-and-trade program reached more than $31 a ton in late May of 2022 (Carbon Credits.com 2022). Yet, all carbon prices are expected to rise over the next decade. Higher carbon offset credit prices not only better reflect the true cost of carbon, but also farmers would receive more income for the carbon they are storing over time. In short, higher carbon offset credit prices payouts would increase the adoption of healthy soil practices in farming operations. Proven and measurable carbon storage and sequestration are essential for efficient and effective carbon markets.

3.5 The preservation of agricultural land to prevent conversion to other uses and retain agricultural soils

The statistics on GHG emissions from US agriculture do not include the carbon loss from the conversion of farmland to non-farm uses (US EPA 2022, p. ES-5). Residential and commercial development disturbs the soil and trap soil under buildings and pavement, causing a significant loss of stored carbon and a reduction in future carbon sequestration. For example, between 2001 and 2016, 11 million acres of agricultural land were converted to other uses (AFT 2021a).

Intense competition for land exists in US metro areas where farmland typically commands higher prices as sites for homes, offices, and stores than for growing crops and livestock (Author 2). The preservation of farmland has emerged as a popular option for farmers who wish to receive compensation for not selling their land for non-farm development. Since the early 1980s, the US has "preserved" 6.5 million acres of agricultural land through the purchase and donation of development rights (Sallet 2020).

In the United States, a landowner owns a bundle of rights to the property. These include the right to sell, lease, use, and develop the property. Each right in the bundle can be severed and sold or given away. A landowner can sell or donate the right to develop the property to a government agency or a qualified private non-profit land trust. The landowner and the government agency or land trust sign a deed of conservation easement which is then recorded in the county land records. The conservation easement spells out both permitted and non-permitted uses on the property. Generally, an agricultural conservation easement restricts the land to agricultural and open space uses *in perpetuity* (Daniels and Keene 2018, p. 71).

The funding for farmland preservation has come from local, state, and federal governments as well as private companies, foundations, and individuals. These sources have provided more than $8 billion to preserve US agricultural land (AFT 2013, 2021b; NRCS 2021a, b). Still, the United States continues to lose farmland to development. American Farmland Trust has called for reducing the rate of farmland loss from 2000 acres per day in 2020 to 500 acres a day by 2040, in part by doubling the amount of preserved farmland (AFT 2021c).

The California Sustainable Agricultural Lands Conservation program and the Vermont Land Trust present novel ways to assure the availability of farmland. In 2015, the State of California created the Sustainable Agricultural Lands Conservation (SALC) program, which uses revenue from the state's greenhouse gas cap-and-trade program to purchase development rights to agricultural land from willing sellers. Since its inception, SALC has invested $232.9 million to preserve more than 117,000 acres (California Strategic Growth Council 2021). This result can be seen as successful, given the cost of permanent preservation at under $2000 an acre is far less than the cost of purchasing the farmland (Daniels and Keene 2018). A major strategy is using farmland preservation to promote compact development and infill development to minimize automobile-dependent sprawl and thus limit GHG emissions (ibid.).

A typical agricultural conservation easement does not place an obligation on the landowner to actively farm the land. One way to avoid the possibility of a landowner letting farmland revert to nature is to include an additional easement known as an affirmative agricultural easement which requires that the land be actively farmed. Regenerative agriculture as a nature-based solution involves active farming, and active farming contributes to food production and the local agricultural economy. Thus, for nature-based solutions in agriculture to succeed in the long run, certainty in the availability of farmland for food production and good stewardship must become linked priorities.

The preservation of farmland does not ensure that the land will be affordable for future generations. This has emerged as a problem in metro areas and in rural areas with second home buyers. The Vermont Land Trust has been involved in the preservation of more than 200,000 acres of agricultural land in the State of Vermont (Vermont Land Trust 2021). Since 2003, the Vermont Land Trust has included a clause in their deed of easement known as the Option to Purchase at Agricultural Value (OPAV). The OPAV allows the sale of the preserved farmland only to certain farmers or family members and limits the sale price to the agricultural value of the land, as opposed to its higher fair market value. Also, under the OPAV clause, the Vermont Land Trust has the right to purchase a preserved farm at a predetermined agricultural value or to assign that right to a qualified entity such as another land trust (Land for Good 2013, p. 3). For example, the Vermont Land Trust exercised the OPAV option and purchased a preserved farm at its agricultural value in 2012 (ibid., p. 4).

4 Discussion

There is some consensus among researchers that regenerative, climate-friendly agricultural practices could significantly reduce GHG emissions (McNunn et al. 2020, p. 1; National Academies 2019, pp. 107–8; Roesch-McNally et al. 2017; Sharma et al. 2022, p. 7).

NBS happen one property at a time. But a variety of NBS are needed to mitigate greenhouse gases, including: (1) ensuring that land management will store and sequester carbon; (2) making changes to climate-friendly crops and livestock; (3) ensuring that the land can only be developed for agricultural uses; and (4) maintaining the affordability of farmland for farming. The NBS literature needs to connect the importance of these efforts and outcomes.

One risk, however, is that conservation practices and other nature-based solutions rely heavily on voluntary efforts by farmers, including the adoption of no-till and cover crops to build soil health, the sale of carbon credits to monetize the carbon sequestration from improving soil health, and the sale of development rights to avoid farmland conversion.

Another challenge to NBS is that federal farm policies and funding still favor traditional farming practices with a reliance on nitrogen-based chemical fertilizers and the production of a narrow number of crops, led by corn and soybeans, which are tied to a meat-intensive diet. Livestock continue to be a major source of GHGs through enteric methane and manure, and nitrous oxide from chemical fertilizer and manure is the leading source of nitrous oxide in the US. Methane and nitrous oxide from agriculture are much greater threats to climate mitigation in the short run than carbon emissions. Federal farm policies need to change to provide financial incentives for farmers to adopt practices, crops, and livestock that will reduce methane and nitrous oxide emissions.

Many farmers have adopted no-till practices but cover crops have not yet been widely popular. Farmers have shifted meat production away from beef to chicken over the past 30 years; even so, manure management continues to be a significant source of greenhouse gas emissions.

Consumer diets with a greater consumption of fruits, vegetables, and plant-based protein would help to lower GHG emissions. The local and regional production of fruits and vegetables would reduce reliance on California agriculture which continues to suffer from prolonged drought.

Also, one underappreciated problem is the fact that an estimated 30–40% of the food grown in the US is wasted and is dumped in landfills where it contributes to the generation of methane (USDA n.d.). Better labeling of food, such as clearer use by dates, would help and required recycling of food waste (as is done in San Francisco) through composting for soil amendments would keep food waste out of landfills.

The sale of carbon credits by farmers holds some promise as a source of funding to reward farmers for improving their soil conservation practices. Accurate measurement of carbon sequestration in soils on individual farms is critical to verifying that farmers' practices are actually increasing carbon sequestration, which is essential for efficient and effective carbon markets.

Farmland preservation has proven popular among farmers. The sale of development rights can avoid the conversion of farmland to non-farm uses and the loss of soil carbon. Dedicated funding sources are essential. Also, an OPAV clause in a deed of conservation easement can help to keep farmland affordable for future generations. For nature-based solutions in agriculture to succeed in the long run, certainty in the availability of farmland for food production and good stewardship must become linked priorities.

5 Conclusions and recommendations for nature-based solutions in US agriculture

US agriculture contributes 10% of the nation's total GHG emissions. Nature-based solutions in the form of regenerative, climate-smart soil conservation practices could reduce net carbon emissions from agriculture by as much as 50%. The literature on NBS has focused on increasing soil carbon but has generally overlooked the urgency and uncertainty in how to lower methane and nitrous oxide emissions, which are far more potent GHGs.

The amount and pace of mitigating GHG emissions from agriculture depends on the decisions of hundreds of thousands of farmers and changes in federal farm programs to give financial support to farmers who curb carbon, methane, and nitrous oxide emissions. Here, the US experience in transitioning the traditional industrial agricultural production model to a regenerative, climate-smart model holds relevance to farming in other countries. The economics of farming and ranching will be critical. Can farmers and ranchers adopt more climate-friendly crops, livestock, and carbon saving practices and still earn a decent living?

A holistic view of the individual "wedges" that could reduce GHGs is essential to lay out several options and opportunities. Changing consumer tastes will be important, especially in moving away from a meat-heavy diet supported by the abundant production of feed grains. Increasing the of use NBS will also depend on new technologies such as more productive and climate-resilient crops and livestock through biotechnology, as well as federal funding for proven practices, such as methane digesters for CAFO operations, no-till, cover crops, and improved manure management. Farmland could be an important source of carbon offset credits. To generate the credits, farmers have to agree to adopt practices that improve soil health. The voluntary carbon market will have to become more regulated and standardized to be effective and both the compliance and voluntary markets must have prices that are attractive to farmers to participate in the sale of carbon credits. Farmland preservation programs and the OPAV clause can help to maintain affordable agricultural land in the face of rising land values.

Finally, America's agricultural industry is a matter of national and international security and helping to feed a growing world population will be a challenge. The adoption of NBS portends greater food security through a greater ability of agricultural operators to withstand and adapt to climate change, while reducing GHG emissions. A national goal should be to make NBS in agriculture the standard, supported by farmers, consumers, agribusinesses, and federal conservation and subsidy programs. That would send a clear message to the world.

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Thomas L. Daniels is the Crossways Professor of City and Regional Planning at the University of Pennsylvania where teaches courses on Land Use Planning, Climate Change, and Environmental Planning. He is the author of *The Environmental Planning Handbook, 2nd ed.* and several articles on climate change.