Good Food Institute

Highland ECONOMICS

Transforming land use

Alternative proteins for U.S. climate and biodiversity success

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About The Good Food Institute

The Good Food Institute is a nonprofit think tank working to make the global food system better for the planet, people, and animals. Alongside scientists, businesses, and policymakers, GFI's teams focus on making plant-based and cultivated meat delicious, affordable, and accessible. Powered by philanthropy, GFI is an international network of organizations advancing alternative proteins as an essential solution needed to meet the world's climate, global health, food security, and biodiversity goals. All of GFI's open-access insights and data are made possible by gifts and grants from our global community of donors. If you are interested in learning more about giving to GFI, please contact philanthropy@gfi.org.

About Highland Economics

Highland Economics is a small, woman-owned firm specializing in the economics of natural resources and the environment, business planning, and feasibility assessment, and the socioeconomic impact of industries, policies, or management actions. We are a team of five economists, based in Oregon and Montana. We work with nonprofits, agricultural interests, tribes, water districts, private companies, and local, state, and federal agencies on a wide range of land, air, water, recreation, agriculture, and habitat issues. This study was led by principal and senior economist Barbara Wyse, who has nearly 20 years of experience analyzing resource management issues related to agriculture, land use, water resources, habitat, energy, and ecosystem services. We aim to provide rigorous, even-handed analysis that uses economic insights to transform complex data into clear and actionable information.

Executive summary

Introduction

Our nation has ambitious land conservation targets and climate goals that require reconnecting and restoring broad swaths of the American landscape. We can make significant progress in achieving these conservation goals by diversifying American protein sources to include land-efficient alternative proteins, specifically, plant-based, fermentation-derived, and cultivated proteins, while reducing the proportion of protein derived from land-intensive, animal-based foods.

Incorporating alternative proteins into the American food supply significantly reduces U.S. land requirements for food production and would enable large-scale restoration of U.S. habitats with significant climate and biodiversity opportunities.

A shift in land use would position the United States to reach its environmental and climate goals while continuing to be a global leader in agriculture and land stewardship.

Scope

This report quantifies the biodiversity and carbon sequestration opportunities of restoring U.S. croplands following a 50 percent shift from animal protein toward alternative proteins. Accounting for the land use efficiency of alternative proteins versus conventional animal protein, this report estimates the feed crop and forage cropland acreage available for restoration. Using two different strategies to prioritize land for restoration in each crop type, the analysis quantifies the biodiversity opportunity and the carbon sequestration opportunity of restoring cropland to the historical ecosystem that existed prior to Euro-American settlement. The analysis focuses exclusively on U.S. cropland demand to meet current (2023) U.S. protein consumption. As such, this report does not include the land restoration benefits associated with a) rangeland used for grazing livestock,[1] b) cropland used for biofuels or export of animal feed or products, c) other resource uses such as water demand, or d) other environmental impacts of animal production systems such as direct greenhouse gas emissions. Therefore, the results presented herein are conservative estimates of the carbon sequestration and biodiversity benefits of increased land use efficiency resulting from alternative protein adoption.

[1] Restoration benefits reported in this paper are based on a change in the vegetation-based ecosystem type. Rangelands are lands on which the native vegetation is predominantly grasses or other plants suitable for grazing livestock, so restoration of rangeland would not necessarily change the vegetation-based ecosystem type or quality, unless it is overgrazed. Changes in ecosystem quality (and the associated biodiversity and carbon benefits) resulting from reduced grazing or removal of livestock from rangeland will vary substantially based on grazing management practices, for which data are limited. As such, rangelands are not included in this analysis.

Key findings

Same amount of protein, less cropland: A 50 percent shift toward alternative proteins requires 47.3 million fewer acres of cropland (13.4 million acres of feed crop and 33.9 million acres of forage) to produce the same amount of protein. Restoring 47.3 million acres is equivalent to restoring an area approximately the size of South Dakota.

Large-scale restoration of threatened ecosystems: Under a biodiversity strategy that prioritizes restoring threatened ecosystems, a shift toward alternative proteins would enable restoration of acreage in 139, or 64 percent, of the 216 U.S. ecosystems that are currently threatened.

Carbon sink optimization through forests and riparian areas/wetlands: Under a carbon strategy that prioritizes the restoration of ecosystems with the highest sequestration potential, a shift toward alternative proteins would enable sequestration of 177.8 million metric tons of carbon dioxide equivalent (CO_2e) every year, a value larger than the combined CO_2 emissions of all U.S. domestic flights (FAA 2021). This would result in a 22 percent increase in the average net national carbon sink related to all land use, land use change, and forestry.

Restoration opportunities vary by region: The highest number of acres prioritized for restoration occurs in the Midwest and the South. These regions account for 33 to 48 percent of the restored acreage in both strategies.

Actions to enable an alternative protein solution

To reach climate and biodiversity goals, we must improve current agricultural land use efficiency, but a transformation of this scale will not occur passively. This report demonstrates that alternative proteins can enable nature-based solutions by vastly improving the land-use efficiency of American protein sources. By developing better-tasting alternative protein products at a scale that can meaningfully diversify the U.S. protein supply, we can reduce land pressure from agricultural activities and enable ecosystem restoration, carbon sequestration, and more.

We provide the following recommended actions to nongovernmental organizations (NGOs) and governments:

Actions for NGOs:

1. Advocate for governmental support for alternative protein research and development (R&D) and commercialization to advance climate and nature goals.
2. Evaluate the socioeconomic impacts associated with alternative protein adoption, including on local economies and workers, and advocate for policies that offer additive revenue streams for U.S. farmers.
3. Expand and optimize land use efficiency benefits across border geographies and diverse prioritization strategies.

Actions for governments:

1. Increase public funding into alternative protein R&D to advance the sensory experience, cost-effectiveness, nutritional benefits, and production capabilities of alternative proteins.
2. Promote commercialization and biomanufacturing scale-up to produce alternative proteins more efficiently and sustainably, while equitably supporting new workforce opportunities and regional diversity.
3. Adopt public policies that support U.S. farmers and bolster new markets for domestically produced alternative protein crops.

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Introduction

The United States is a long-standing global leader in natural area conservation, recognizing that natural areas promote human health and well-being and provide valuable ecosystem services. In 2021, the U.S. National Climate Task Force envisioned a strategy for Conserving and Restoring America the Beautiful (DOI 2024) by conserving at least 30 percent of our lands and waters by 2030, with emphasis on habitat restoration to protect at-risk wildlife and create jobs.[2] As the first U.S. national goal for the stewardship of nature, this is an ambitious target, requiring ecological restoration of lands across America. The benefits of this transformation can be maximized through careful analysis of restoration opportunities.

Numerous conservation organizations have identified land management, protection, and restoration of natural areas in the United States—and globally—as critical pathways to preserve biodiversity and address climate change (Table 1). Land conversion and other stressors have put pressure on species to survive in new areas and conditions, causing significant biodiversity loss in important ecosystems. For example, the Food and Land Use Coalition (FOLU 2019) identifies the conversion of global natural habitats into food and land use systems as the greatest contributor to the ongoing “sixth extinction” of biodiversity. Conservation and restoration of U.S. lands are vital to protect our natural biodiversity and ecosystems. In addition, myriads of other benefits flow from natural areas, including clean water, flood control, recreation opportunities, and commercial and subsistence hunting and fishing (See Socioeconomic Considerations).

Moreover, enhancing the carbon sinks of American ecosystems is an essential strategy to meet the U.S. Nationally Determined Contribution to the Paris Agreement global warming limitation of below 2°C above pre-industrial levels (DOS 2021). Our economy-wide target is to reduce U.S. net greenhouse gas emissions by 50 to 52 percent below 2005 levels in 2030 and reach net zero in 2050. In their Ambitious Climate Mitigation Pathways for U.S. Agriculture and Forestry model, the Environmental Defense Fund (EDF 2022) demonstrates that even alongside other mitigation strategies, such as improved nitrogen management and reduction of methane emissions from livestock enteric fermentation, land conservation and restoration strategies are necessary to meet EDF’s modeled 2030 agricultural emissions targets.

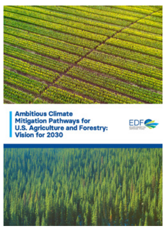
[2] Other leaders at COP26 also committed to sustainable land use, and to the conservation, protection, sustainable management, and restoration of forests and other terrestrial ecosystems in 2021 with 145 countries pledging sustainable land use transition as of May 2024.

Table 1. Environmental and food systems organizations' calls for more efficient agricultural land use and restoration.[3]

Food System Economics Commission (FSEC 2024)

***The Economics of the Food System Transformation* —** FSEC identifies five operational goals for a health-enhancing, environmentally sustainable global food transformation, including: "stress the protection and restoration of land" and "environmentally sustainable production throughout the food system." With deliberate planning, this transformation can offer enormous economic benefits.[4]

Environmental Defense Fund (EDF 2022)



Ambitious Climate Mitigation Pathways for U.S. Agriculture and Forestry: Vision for 2030 *(U.S.-specific)* **—** EDF illustrates that land-use change and afforestation/reforestation are necessary strategies for the United States to achieve climate goals outlined in the U.S. Nationally Determined Contribution under the Paris Climate Agreement. The report recognizes that the potential for greenhouse gas emission reduction and removal varies geographically, so maximizing the success of climate mitigation initiatives requires tailoring them to meet local environments and needs.

The Nature Conservancy (TNC 2021)

***Foodscapes: Toward Food System Transition* —** TNC demonstrates that "nature-based solutions" within our global food production systems are necessary to address climate change and conserve biodiversity. Further, intentionally mapping and analyzing agricultural lands to maximize transition impacts can provide achievable, localized opportunities. The report includes protecting and restoring natural ecosystems as a "nature-based solution."

World Resources Institute (WRI 2019)

***Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050* —** WRI analyzes the gaps in food production, agricultural land use, and greenhouse gas mitigation between 2010 data and projected 2050 goals. It explores five solution classes, including "increasing food production without expanding agricultural land" and "protecting and restoring forests, savannas, and peatlands." One of the seven key themes that emerged from the analysis is that reforestation and peatland restoration should be targeted and can only succeed by reducing agricultural resource demands.[5]

Food and Land Use Coalition (FOLU 2019)

***Growing Better: Ten Critical Transitions to Transform Food and Land Use* —** FOLU recognizes "scaling productive and regenerative agriculture" and "protecting and restoring nature" as two of the 10 critical transitions necessary to create food and land use systems that enable environmental sustainability, food security, and healthy diets for a global population of over nine billion by 2050. The report generates a "better futures" scenario in which 1.2 billion hectares of land currently used for agriculture could be restored and recommends spatially planning restoration efforts to maximize the climate and ecosystem service benefits.[6]

[3] All reports are global analyses unless otherwise specified.

[4] Another of the five goals is "consumption of healthy diets by all" and calculates that this change in diet accounts for 70 percent of the economic benefits of their food systems transformation scenario. A key insight from their scenario is that the consumption of animal-sourced food must decrease drastically in high- and middle-income regions, including the United States.

[5] Another one of seven themes identified in the 2019 WRI report to close these "gaps" is to moderate ruminant meat consumption, recommending a 30 percent relative reduction in global ruminant meat consumption from 2010 to 2050.

[6] The 2019 FOLU report also names "investing in diversified sources of protein" as one of 10 critical transitions to transform food and land use, recognizing the importance of reducing the global demand for ruminant meats, and identifying alternative proteins as a key technology to achieve this. Diversifying protein supply was estimated to generate 240 billion USD globally, with the plant-based meat industry contributing 140 billion USD.

Modifying agricultural systems and enhancing food production efficiency represent a significant opportunity for natural area restoration, for two reasons: 1) agriculture dominates land use across the United States and the globe, and 2) production of sufficient high-quality, nourishing food to feed our population can feasibly require substantially less land.

Over 60 percent of land in the contiguous United States is agricultural land: 21 percent is cropland and 42 percent is used for grazing livestock (including rangeland/grass pasture and grazed forested land) (Figure 1). The remaining land use categories are ungrazed forest (22 percent), developed uses (seven percent, including urban areas, transportation facilities, industrial and military land), and undeveloped/natural areas (nine percent).

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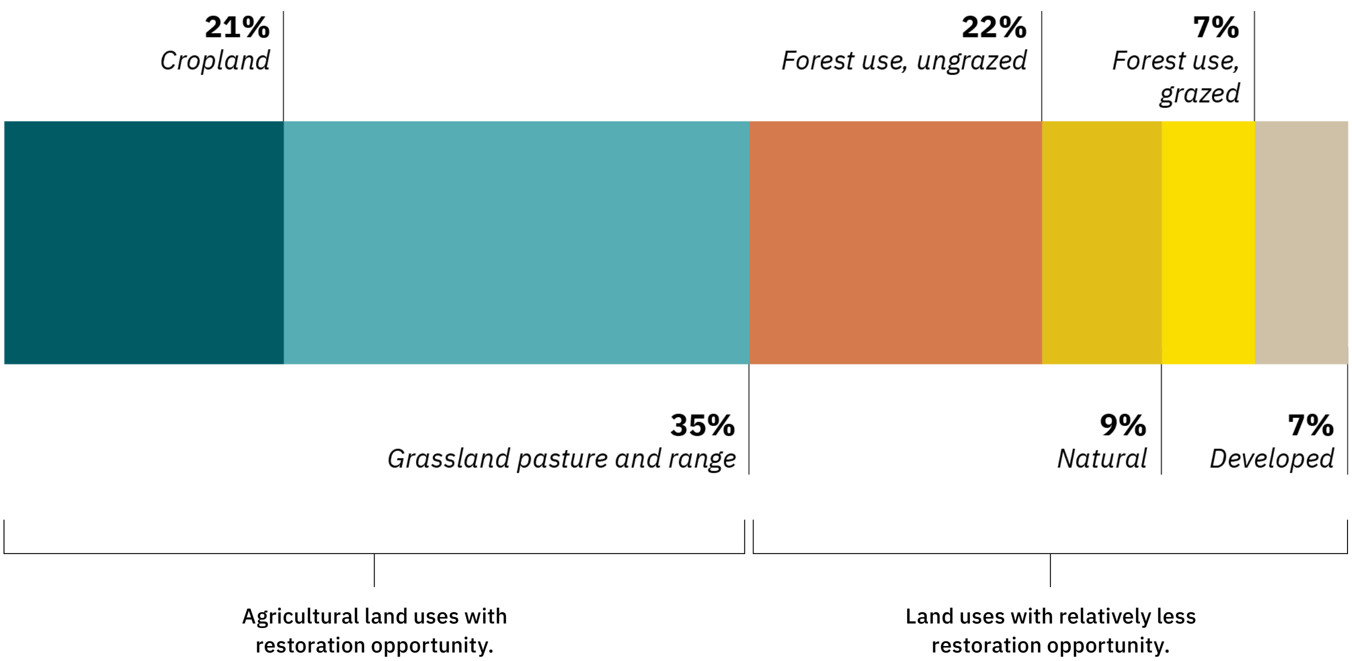


Figure 1: Land uses in the contiguous United States (% of acreage). Reference: Bigelow and Borchers 2017

Within cropland, 57 percent is in crops primarily used for animal feed (soy, grain corn, oats, barley, sorghum), 22 percent is in food and fiber crops, and 21 percent is in forage crops, including 17 percent in hay crops (alfalfa hay, other hay, and haylage) and four percent in cropland pasture (Figure 2). Altogether, 78 percent of cropland in the United States is in crops primarily supporting animal production. Combining cropland with grassland pasture and rangeland, approximately 90 percent of these agricultural lands and over one-half of the total land in the contiguous United States is used to support animal agriculture.

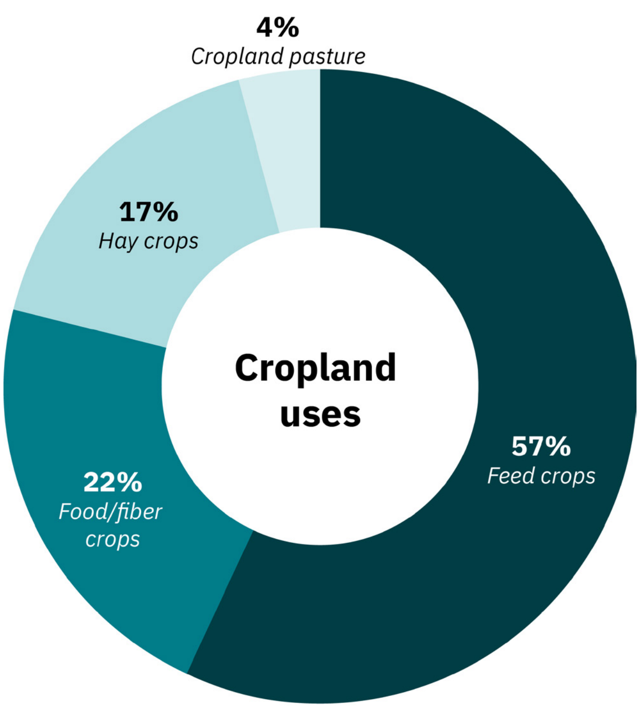


Figure 2. U.S. cropland uses (% of acreage). Feed crops: soy, corn, oats, barley, and sorghum, a portion of which is for human consumption. Food crops: crops grown primarily for human consumption. Reference: NASS 2017, 2022a.

While areas of non-agricultural land use (Figure 1) can be modified to increase carbon sequestration, biodiversity, and other ecosystem services, these provide less opportunity to restore natural areas at scale (either because the land is already predominantly natural area/forested or because restoration of developed land would be socially and economically disruptive).

Consequently, agricultural land (Figure 1) represents a key opportunity to restore natural areas in the United States at the scale needed to meet climate and biodiversity goals. More specifically, restoring a sizable portion of agricultural lands currently used to grow feed crops and forage crops for livestock is achievable given the significant amount of agricultural land dedicated to livestock and the opportunity to reduce our reliance on them, facilitated by shifting toward more land-efficient protein sources.

As noted by the World Resources Institute (2019), increased efficiency of natural resource use is the "single most important step toward meeting food production and environmental goals," and a big part of this is a shift away from animal-based foods. Replacing a portion of conventional animal-based protein in American protein sources with more land-use efficient protein sources, such as alternative proteins (see Introduction to Alternative Proteins), would significantly increase efficiency by reducing the acreage required to produce food for the American population. Alternative proteins, on average, require just under 20 square meters of cropland to produce one kilogram of protein, while animal-based proteins require an estimated 34 to 160 square meters of cropland and grassland pasture, depending on the animal protein (Eshel 2014; Poore and Nemecek 2018). In other words, per kilogram of protein, alternative proteins require 50 to 90 percent less land than animal proteins (Figure 3).

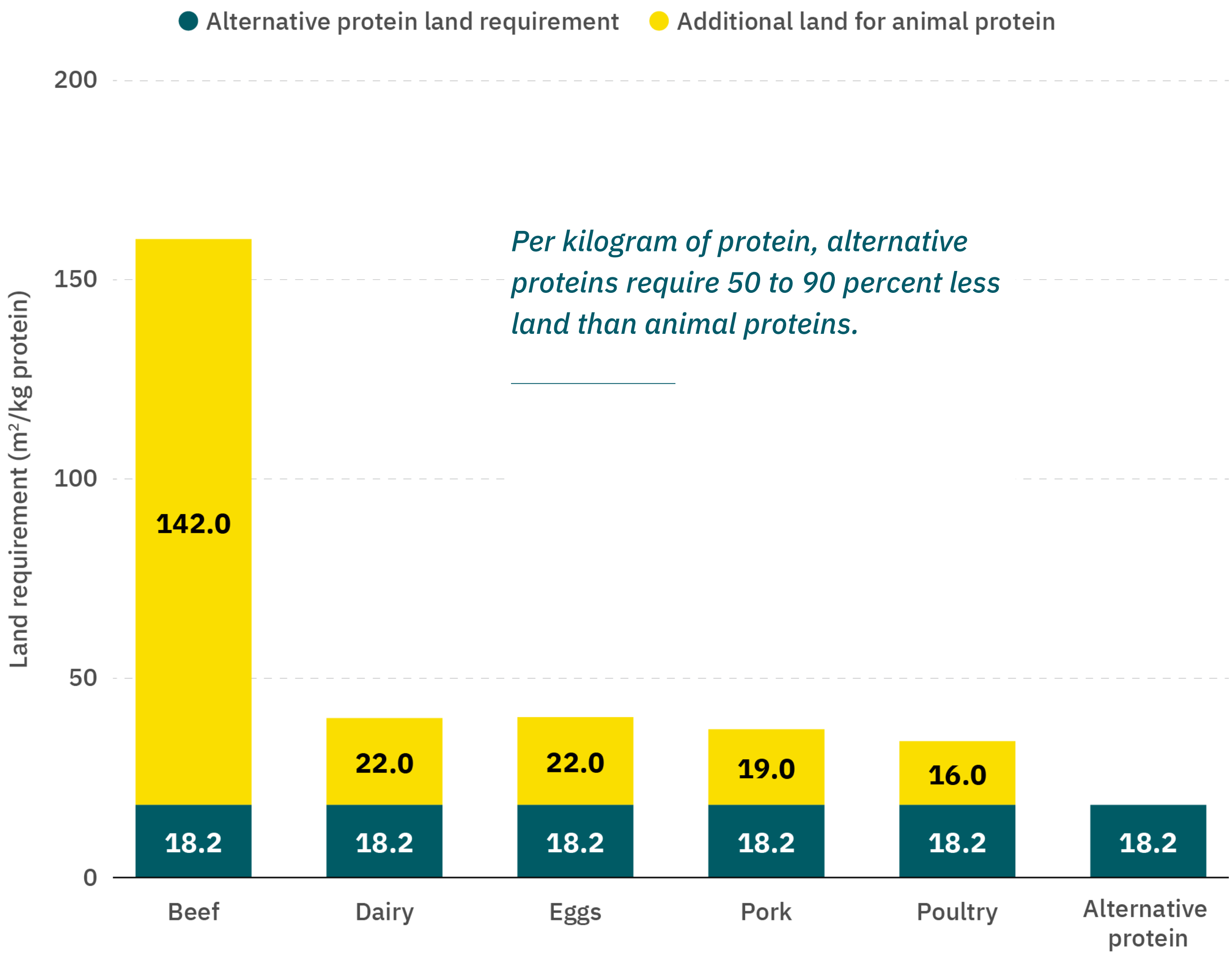


Figure 3. Land required per kilogram of protein production (m^2/kg protein). Note: The cropland required to produce alternative proteins was calculated as an average of cropland use to produce cultivated meat (Sinke et al. 2022), biomass fermentation-derived meat (Kazer et al. 2021), soy-based meat with precision fermentation ingredient (Khan et al. 2019), and pea-based meat (Heller and Keoleian 2018). The additional land requirements for animal proteins is based on Sinke et al. 2022.

The potential climate and biodiversity benefits of reduced reliance on animal protein are recognized by many research-based conservation organizations (Table 1). For example, The World Resources Institute notes: “Closing the land and GHG mitigation gaps requires that, by 2050, the 20 percent of the world’s population who would otherwise be high ruminant-meat consumers reduce their average consumption by 40 percent relative to their consumption in 2010” (World Resources Institute 2019). Alternative proteins can play an important role in meeting consumer taste preferences while reducing demand for conventional meat and, consequently, reducing demand for land.

In this report, we specifically examine the biodiversity and climate change benefits of improved land use efficiency associated with a 50 percent shift toward alternative proteins. The analysis shows that diversifying American protein sources with alternative proteins significantly reduces U.S. land requirements for food production. This reduction could enable large-scale restoration of U.S. habitats with substantial climate and biodiversity benefits and facilitate a tractable path for the United States to reach its environmental and climate goals while continuing to be a global leader in agriculture and land stewardship.

Socioeconomic considerations

This paper focuses on the environmental potential of agricultural land restoration. While not addressed in this paper, in addition to the environmental benefits, large-scale land restoration will have social and economic effects, both positive and adverse. Positive effects of natural area restoration can include reduced flooding and associated damages to cropland and infrastructure (particularly from restoration of riparian and wetland areas); enhanced aesthetics and recreation opportunities that improve community quality of life and spur economic development by attracting new residents and tourism; and improved water quality and water availability (particularly in basins where irrigation of feed crops and forage crops is the primary use of water) for other economic uses. To maximize socioeconomic benefits and minimize adverse effects, national, regional, and local strategies, policies, and planning are needed to enhance the benefits of restoration and minimize or address socioeconomic disruption. These may include: identifying marginal or flood-prone lands for restoration; interspersing restored lands to increase pollinator habitat and provide pest control in predominantly agricultural areas; developing restoration-based economies and financial payments for ecosystem services such as carbon sequestration[7] or habitat provisioning to compensate landowners for restoration; and carefully distributing restored lands across states and regions to minimize land use change in any one area.

[7] The average per acre annual carbon sequestration for acres prioritized for restoration under the carbon strategy is 3.76 metric tons per acre, as described below. At a carbon payment to landowners of $10 to $25 per metric ton, this would provide revenue of approximately $38 to $94 per acre per year.

Introduction to alternative proteins

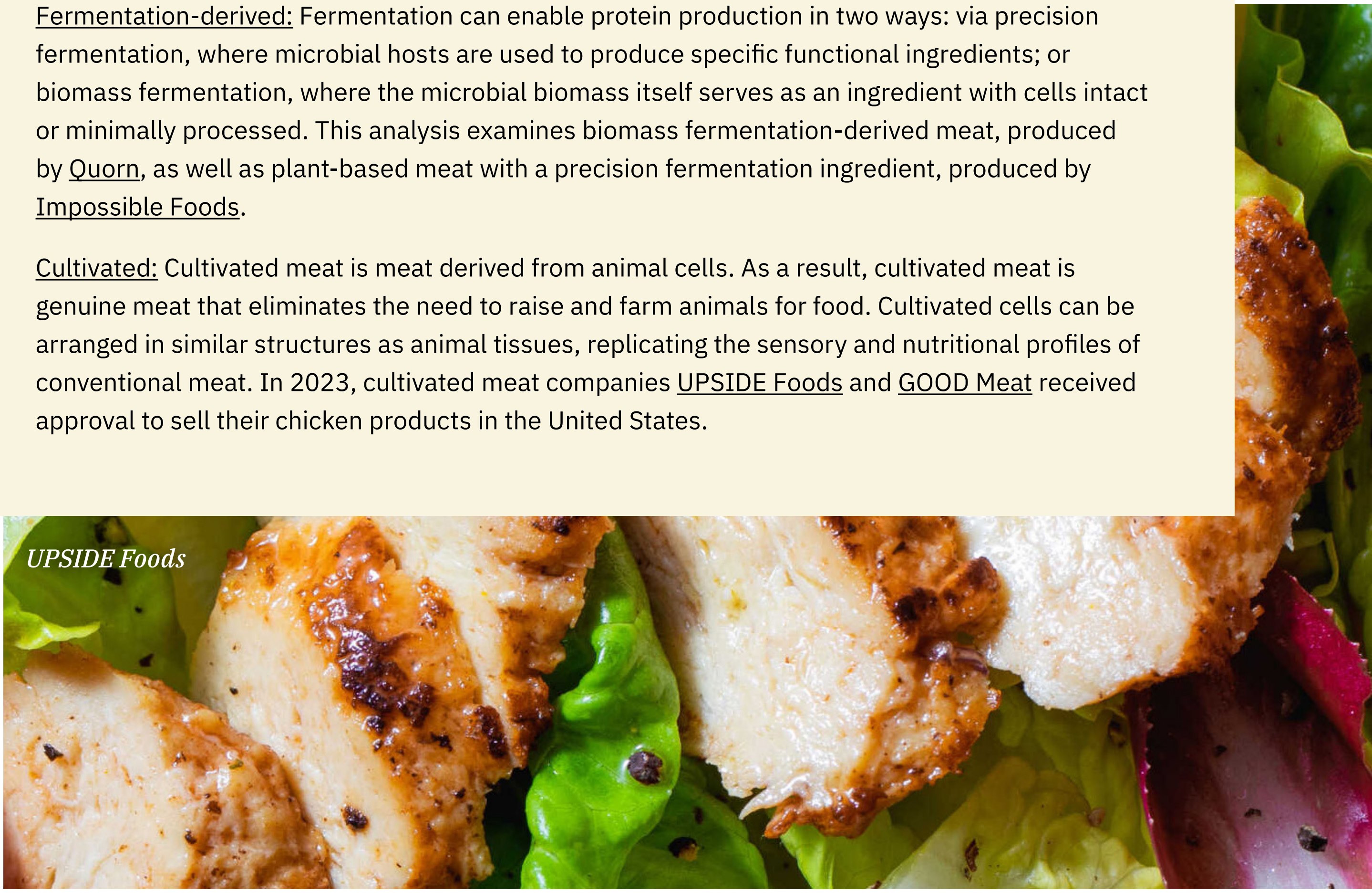
While traditional plant-based foods, such as legumes, tempeh, and tofu, provide consumers with sustainable protein choices, these products have been on the market for decades with minimal household adoption in the United States. Alternative proteins are protein-rich foods with the sensory experience of animal meat, eggs, and dairy, providing more sustainable protein choices that interest consumers. Importantly, alternative proteins use a fraction of the land and water required by conventional meat and generate fewer greenhouse gases and ecosystem pollutants. The Paris Agreement's 1.5° C warming limitation goal cannot be met unless conventional meat consumption declines. It follows that alternative proteins are a key strategy to diversify our protein supply, so we can mitigate the environmental impact of our food system and ultimately feed more people with fewer resources.

Here, we define alternative proteins as foods made from one of the following technologies:

Plant-based: Plant proteins are intentionally texturized and formulated to emulate the experience and nutrition of animal meat. Typically, soy, pea, and wheat are used as protein sources, while other crops like canola, coconut, and potato are used to create other ingredients. These are the most common commercially available alternative meats, such as those produced by Beyond Meat.

Fermentation-derived: Fermentation can enable protein production in two ways: via precision fermentation, where microbial hosts are used to produce specific functional ingredients; or biomass fermentation, where the microbial biomass itself serves as an ingredient with cells intact or minimally processed. This analysis examines biomass fermentation-derived meat, produced by Quorn, as well as plant-based meat with a precision fermentation ingredient, produced by Impossible Foods.

Cultivated: Cultivated meat is meat derived from animal cells. As a result, cultivated meat is genuine meat that eliminates the need to raise and farm animals for food. Cultivated cells can be arranged in similar structures as animal tissues, replicating the sensory and nutritional profiles of conventional meat. In 2023, cultivated meat companies UPSIDE Foods and GOOD Meat received approval to sell their chicken products in the United States.



UPSIDE Foods

Analysis scope and approach

Glossary

Term	Definition
Feed crop	Crops that are grown primarily for livestock feed. In the United States these crops include soy, grain corn, barley, sorghum, and oats. These are the crops analyzed in the feed crop category in this report.
Forage crop	Crops that are grown exclusively for animal feed and include pasture, alfalfa hay, other hay, haylage, and silage. Only forage crops grown on cropland are included in this analysis.
Cropland pasture	A subset of forage crops, and includes crops grazed by livestock that are not harvested prior to grazing (such as grass hay) as well as cropland grazed by livestock that could have been used to cultivate and harvest crops without additional improvements (NASS 2022b).
Haylage	A product of grass hay, and similar to silage, is a high-moisture animal feed preserved using fermentation. The U.S. Census differentiates grass hay acreage harvested for hay versus for haylage.
Grassland pasture	Characterized by introduced vegetation planted to provide preferred forage for grazing livestock. Pasture is managed through such practices as tillage, fertilization, mowing, weed control, and irrigation (NRCS 2024).
Rangeland	Lands on which the native vegetation is predominantly grasses or other plants suitable for grazing livestock. Rangelands include natural grassland, savannas, many wetlands, some deserts, tundra, and certain forb and shrub communities. Rangeland is distinguished from pasture based on the predominant vegetation type (native versus introduced for pasture) and management level (low management level versus intensively managed for pasture) (EPA 2024).
Alternative proteins	Protein-rich foods that provide the sensory experience of animal meat, dairy, and eggs and can be plant-based, fermentation-derived, or cultivated (meat derived from animal cells).
Threatened ecosystems	Ecosystems that are critically endangered, endangered, or vulnerable.
Historical ecosystem	Ecosystem modeled as dominant in a given location prior to Euro-American settlement, taking into account the "current biophysical environment and an approximation of the historical disturbance regime" (Landfire 2024).
Carbon dioxide equivalent (CO_2e)	A carbon dioxide equivalent is a unit used to express the climate change effects of all greenhouse gases in units of carbon dioxide.

Scope

This analysis quantifies the biodiversity and carbon sequestration opportunities of U.S. cropland restoration enabled by increased land use efficiency from a shift toward alternative proteins. As such, the focus of this analysis is on U.S. cropland used to grow animal feed (i.e., soy, grain corn, barley, oats, sorghum) and forage (i.e., alfalfa, other hay, haylage, and cropland used for pasture) for domestic animal meat consumption. The feed crop and forage cropland acreage associated with domestic animal protein consumption was derived as described here and in Figure 4.

The U.S. Department of Agriculture (NASS 2017; 2022a) reports that approximately 253.4 million acres of cropland are dedicated to the production of feed crops (soy, grain corn, barley, oats, sorghum) and forage (alfalfa, other hay, haylage, and cropland used for pasture) (Figure 4). Of this land, 16.7 million acres of feed crops are used for direct human food consumption and another 35 million acres are used for biofuels. Approximately 60.6 million acres produce feed crops and forage that are exported, primarily for animal feed. In addition to the export of feed crops, some domestic livestock products are also exported, particularly poultry and pork, but also some dairy and eggs.[8] These exported animal proteins are produced almost exclusively with feed crops, which we estimate requires 10 million acres.

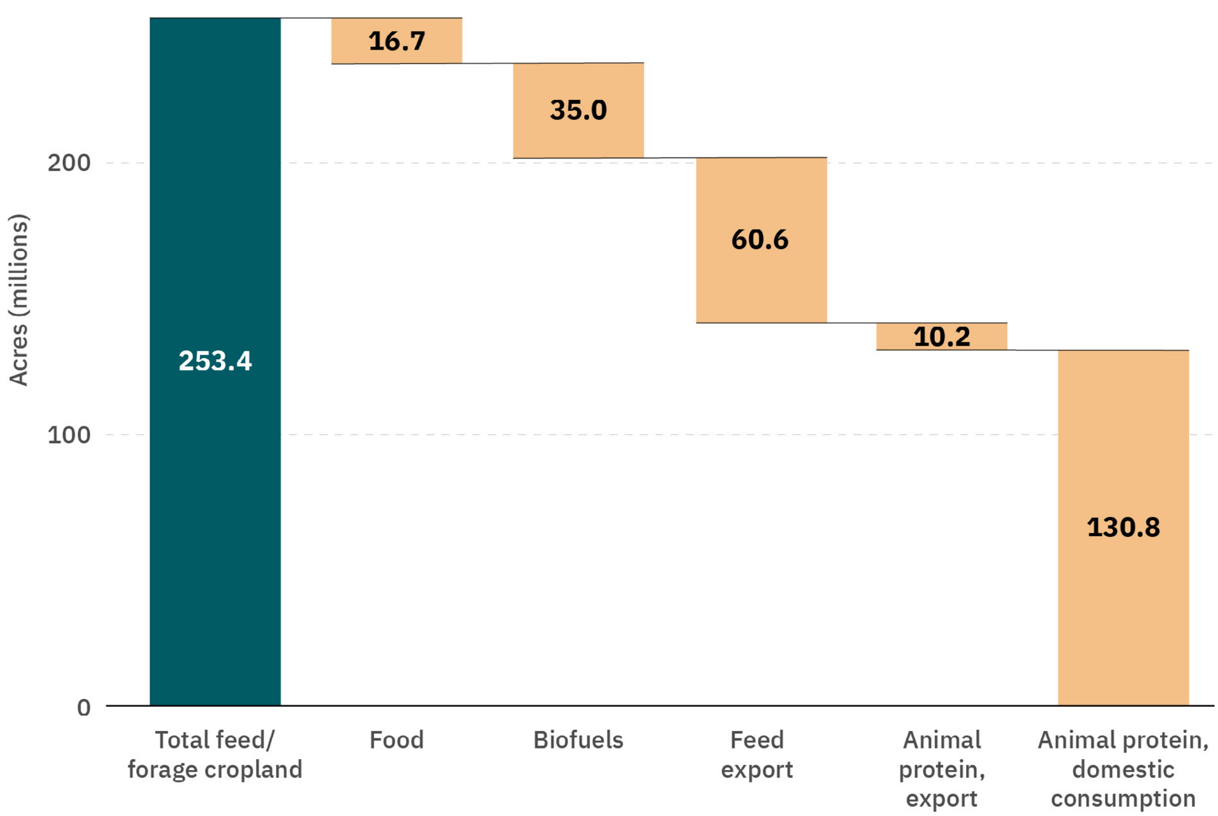


Figure 4. Calculation of feed crop and forage cropland acres for domestic animal protein consumption (million acres).

[8] Beef is also exported, but exports and imports of beef are roughly balanced, while the United States is a net exporter of poultry, pork, eggs, and dairy.

The remaining 131 million acres of U.S. feed crop and forage cropland are used to support the production of animal protein for domestic consumption (Figure 4).

As highlighted in Figure 1, a large percentage of U.S. land used to support animal agriculture is grassland pasture and rangeland. However, our analysis conservatively focuses on the cropland used to grow animal feed and forage for domestic animal protein consumption and *does not include any land use efficiency benefits of a shift to alternative proteins related to grazed lands such as rangeland or non-cropland pasture.* We focus exclusively on cropland because restoration of monoculture agriculture to natural areas is a clear shift in vegetation, whereas removing grazing from rangeland is a change in management but is not necessarily a shift in the vegetation-based ecosystem type (which is the primary driver for carbon sequestration and biodiversity opportunities as estimated in this report).[9]

We focus on the primary feed crops of soy, corn, barley, oats, and sorghum. Wheat is also used in animal feed, but we do not analyze the shifts in wheat acreage that may result due to the relatively small proportion (approximately five percent) of U.S. wheat production used in domestic animal feed.[10]

Please see the Simplifications & Assumptions Table for a more detailed discussion of the potential limitations of these and other exclusions, assumptions, and simplifications.

[9] Additional reasons we did not include rangelands in this analysis are: 1) There is a substantial body of literature on the restoration potential in grazed rangelands, but there is not consensus in the literature on the degree to which restoration requires removal of livestock versus modified livestock management, 2) While improved rangeland management can provide carbon and biodiversity opportunities, the level of benefits depends greatly on current management, which varies substantially across different rangeland areas and for which data are limited, 3) there is limited data available quantifying the change in carbon and biodiversity that would result from removing grazing from rangelands.

[10] Due to the large acreage of land cultivated for wheat in the United States, five percent translates to approximately 1.9 million acres of U.S. wheat used in animal feed.

Approach

This analysis consists of three main components, as described below and in Figure 5.

1 *Quantify the land efficiency benefit*

- Calculate the total U.S. cropland required to produce the domestic animal protein supply in 2023.
- Estimate 50% of the protein demand based on the 2023 U.S. annual animal protein demand per person and U.S. population.
- Account for the increase in cropland for alternative protein production to meet 50% of the protein demand.
- Calculate the reduction in cropland acreage required to meet U.S. protein demand with a 50% shift toward alternative proteins.

Two prioritization scenarios

2 *Biodiversity prioritization*

- Map the historic ecosystems of current U.S. feed and forage croplands.
- Quantify the amount of acreage of each ecosystem type that could be restored by prioritizing the land efficiency opportunity to restoring currently threatened ecosystems.

3 *Carbon sequestration prioritization*

- Map the historic ecosystems of current U.S. feed and forage croplands.
- Calculate the average annual carbon sequestration rate of each ecosystem.
- Quantify the total carbon sequestration rate by prioritizing the land efficiency opportunity to restoring ecosystems with the highest carbon sequestration rates.

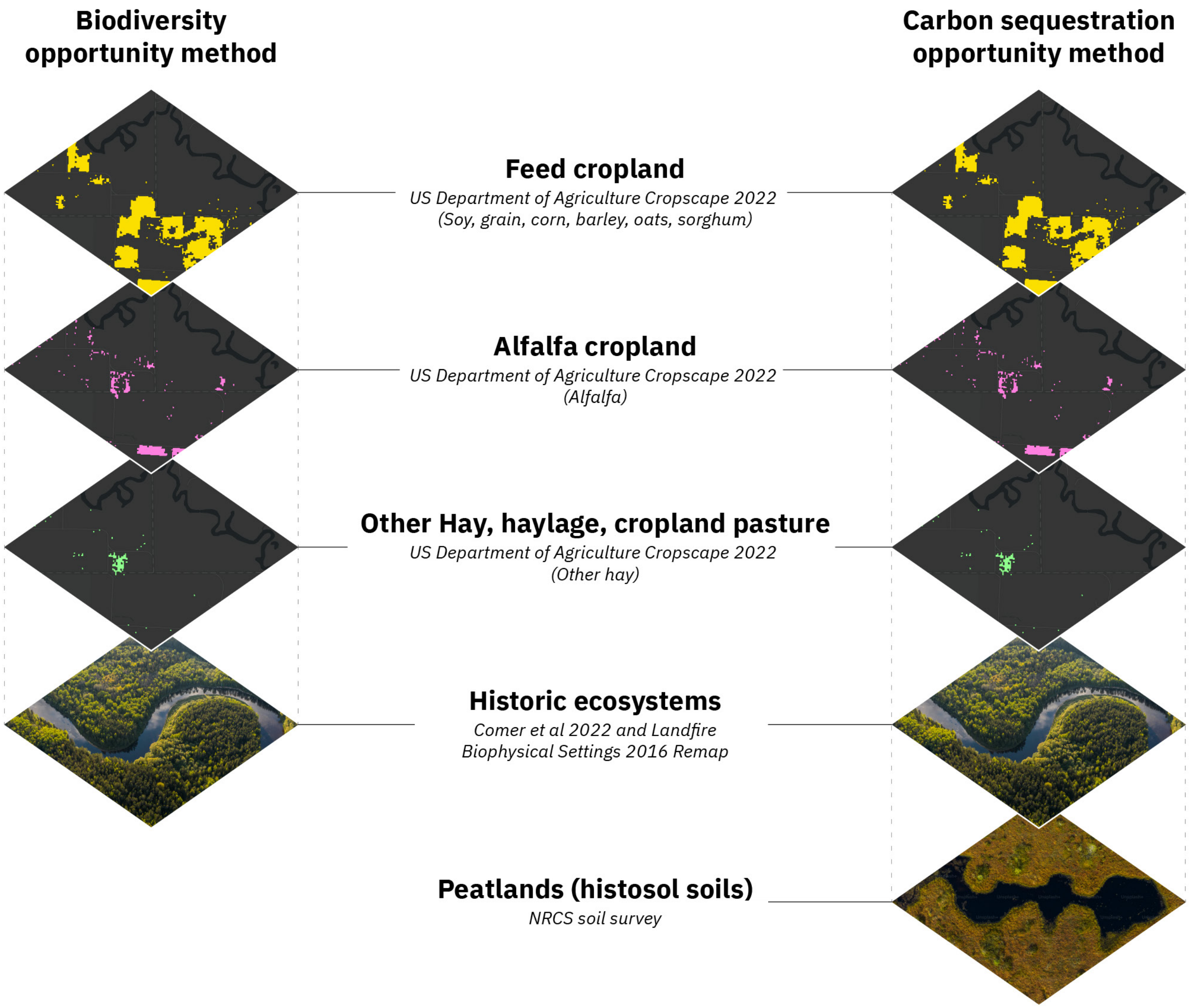


Figure 5. GIS data layers and overlays used for the two prioritization scenarios: the biodiversity opportunity and the carbon sequestration opportunity.

Land use efficiency benefit of alternative proteins

We estimate that 47.3 million acres of cropland would no longer be needed to produce food for the population if Americans were to substitute alternative proteins for 50 percent of their animal protein consumption, a shift in animal protein consumption similar to that called for by the World Resources Institute (2016).

This reduction is based on 1) the 2023 crop acreage used to produce feed and forage for livestock raised and consumed in the United States and 2) the cropland required to meet 50 percent of the U.S. protein demand with alternative proteins, as described below.

In 2023, approximately 131 million acres of U.S. feed crop and forage cropland, including 63 million acres of feed crops and 68 million acres of forage cropland, were used to support the production of animal protein for domestic consumption (Figure 4). This represents 40 percent of the 324.1 million acres of cropland (of all types of crops) cultivated nationally.[11]

47.3 million fewer acres of cropland would be needed to produce food for the American population with 50 percent of protein sources from alternative proteins.

Current per capita consumption of animal proteins in the United States is approximately 24 kilograms annually (Food and Agricultural Organization (FAO), 2024).[12] This translates to 8 billion kilograms of animal protein consumed annually by 335.6 million Americans. A 50 percent substitution for alternative proteins would result in 4 billion kilograms of reduced animal protein demand and an increased demand of 4 billion kilograms of protein from alternative proteins.[13]

With a 50 percent shift toward alternative proteins, this analysis assumes that approximately 50 percent of the current cropland required to produce domestically consumed animal protein, or 34 million acres of forage and 31.5 million acres of feed crops, would no longer be needed to produce animal proteins for U.S. consumers. To produce 4 billion kilograms of protein from alternative proteins, approximately 18 million acres of feed cropland (expected to be similar crop types to feed crops, including soy and grains) are needed.[14] Therefore, we estimate that approximately 47.3 million fewer acres of cropland would be needed to produce food for the American population with 50 percent of protein sources from alternative proteins (Figure 6). Specifically, we estimate 13.4 million fewer feed crop acres and 33.9 million fewer forage crop acres would be required.

[11] According to the U.S. Census of Agriculture, in 2017, there were 301.3 million harvested cropland acres and 13.0 million acres of cropland used for pasture; in 2022 there were 320.0 million acres of harvested cropland and 13.8 million acres of cropland used for pasture. On average, in the two Census years there were 324.1 million acres of cropland harvested or used for pasture; we take an average of the last two Census years since acreage fluctuates in these crop categories and an average provides a better estimate of acreage in any given year. The 131 million acres producing livestock feed for domestic animal protein consumption represents 40 percent of this total acreage.

[12] This is based on the average of the FAO "business as usual scenario" data for the United States for 2020 and 2025. This annual consumption estimate is similar to data from the U.S. Department of Agriculture on animal protein consumption in the United States.

[13] This is the weight of the protein consumed; the total weight of animal products required is over five times this weight as protein by weight is typically 10 to 20 percent of total animal product weight.

[14] This is based on 18.22 square meters of cropland required per kilogram of protein in alternative proteins, as shown in Figure 3, which is equivalent to 0.045 acres per kilogram. Multiplying the land required per kilogram by four billion kilograms of protein results in 18 million acres of cropland.

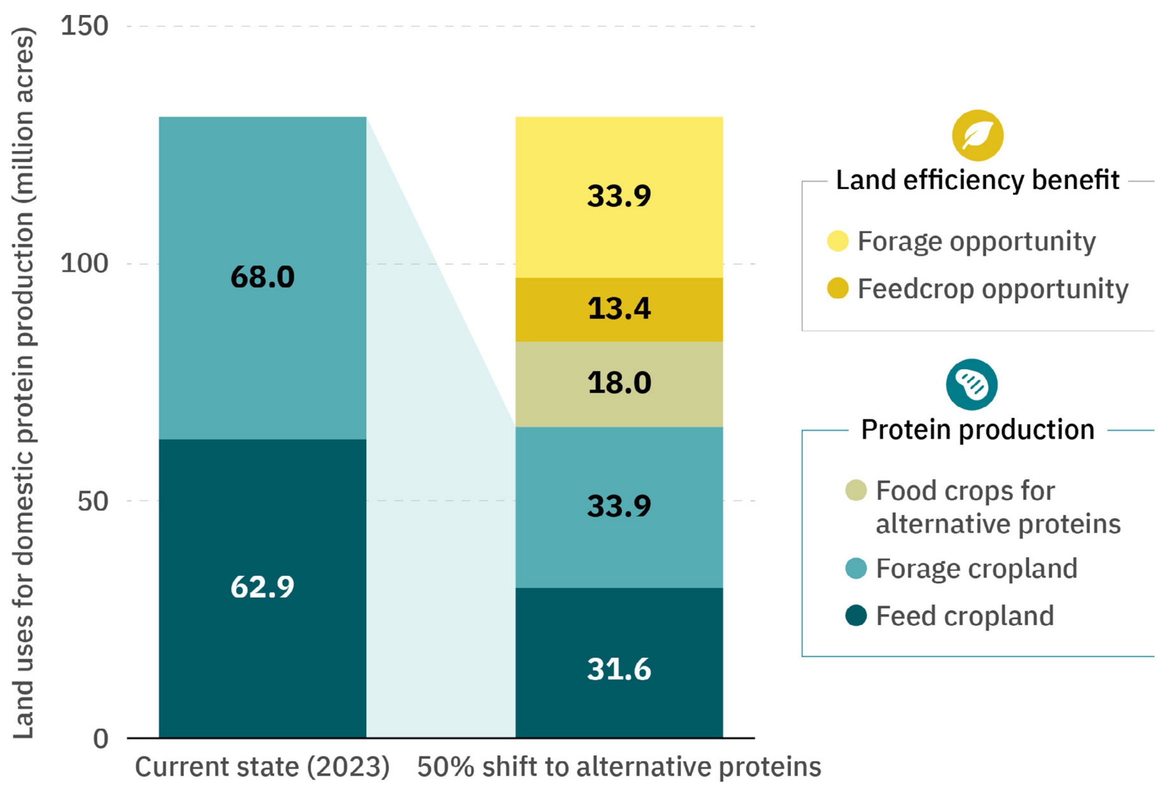


Figure 6. Land use shift of feed crop and forage cropland and land use efficiency benefit with a 50 percent shift toward alternative proteins (million acres).

With a 50 percent shift toward alternative proteins, 47.3 million acres of U.S. cropland currently used for domestic animal protein consumption could be transitioned to other land uses. There are many opportunities associated with this increased land use efficiency, including increasing the export of food to help reduce the projected conversion of natural areas to agricultural land uses in the tropics and elsewhere. This analysis focuses on the potential environmental benefits of restoring these 47.3 million acres to natural areas within the United States to evaluate the role of alternative protein land use efficiency in achieving U.S. climate and biodiversity goals.

The 47.3 million acres to be restored is far less than the approximately 257 million feed crop and forage cropland acreage in the United States.[15] Further, depending on the location of the feed crop and forage cropland, the restored natural areas could be wetland, forest, grassland, shrubland, or other ecosystem types. Which of these lands to restore requires prioritization. Ecosystem restoration could be prioritized using many strategies to achieve different environmental goals.

[15] The 47.3 million acres available for restoration is also much less than the approximately 95 million U.S. cropland acres used to produce feed crops exported for foreign livestock production or used for ethanol.

This analysis explores two prioritization strategies:

1. **Biodiversity opportunity:** Prioritize biodiversity benefit by focusing on restoring cropland areas where the historical ecosystem[16] is currently threatened.

2. **Carbon sequestration opportunity:** Prioritize the climate regulation benefit by focusing on restoring areas where the historical ecosystem has the highest annual carbon sequestration rates.

In either strategy, both biodiversity and carbon sequestration would be greatly enhanced. We model each type of benefit separately for clarity and due to challenges in linking the datasets used in each priority strategy. We first explore the potential benefits of prioritizing biodiversity, and then we explore the potential benefits of prioritizing carbon sequestration.

[16] Historical ecosystems are the native plant communities that are modeled to have been dominant in the landscape prior to Euro-American settlement (and conversion of lands to agriculture) based on the current biophysical environment and the historical disturbance regime. The historical, potential ecosystem in every location in the entire United States has been modeled and mapped by Landfire, a shared program between the Wildland Fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior.

Alternative protein biodiversity opportunity

A recent analysis of ecosystems at risk in North America found that 45 percent or 216 of the 485 terrestrial ecosystems in the United States are threatened (defined as critically endangered, endangered, or vulnerable) (Comer et al. 2022).[17,18] To assess the biodiversity benefits of restoring the 47.3 million acres of cropland used for domestic animal protein consumption, we prioritized restoring feed crop and forage cropland acreage where the historical ecosystem is classified as currently threatened.[19] Using maps of historical ecosystems, we identified those that were present before land conversion to feed crop and forage cropland (and that could exist in the future on these lands with restoration). We then prioritized restoring the cropland areas that were converted from currently threatened ecosystems. Using this biodiversity prioritization strategy, we found that 40.4 million acres, or 85 percent of the available acreage, could be restored to 139 different ecosystems classified as threatened.[20] In other words, of the 216 at-risk terrestrial ecosystems in the United States, 64 percent would benefit from the restoration enabled by a 50 percent shift toward alternative proteins in American protein sources.

A 50 percent shift toward alternative proteins enables restoration of acreage in 64 percent of currently threatened U.S. ecosystems.

Across all crop types, 60 percent of the 47.3 million acres could be restored to ecosystems that are currently critically endangered or endangered and 25 percent in vulnerable ecosystems (Figure 7). The vegetation types of all potentially restored ecosystems (threatened and not threatened) are: 49 percent is forest (23.1 million acres), 39 percent is grassland/shrubland (18.4 million acres), and 12 percent is wetlands/riparian areas (5.8 million acres) (Figure 7).

17 Highland Economics analysis of Supplemental Appendix 3 from this paper. The text of the paper notes that 33 percent of the 655 terrestrial ecosystem types found in North America are threatened. Using the data in the Supplemental Appendix 3 of the paper, and narrowing the analysis to the 485 terrestrial ecosystems identified as native to the United States, 216 are classified as threatened.

18 This 2022 assessment of at-risk status of ecosystems is based on the International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE), which is an emerging global standard for ecosystem risk assessment that integrates data and knowledge to document the relative risk status of ecosystem types.

19 See Methodology for details.

20 Only threatened ecosystems with at least 100 restorable acres are included in this count.

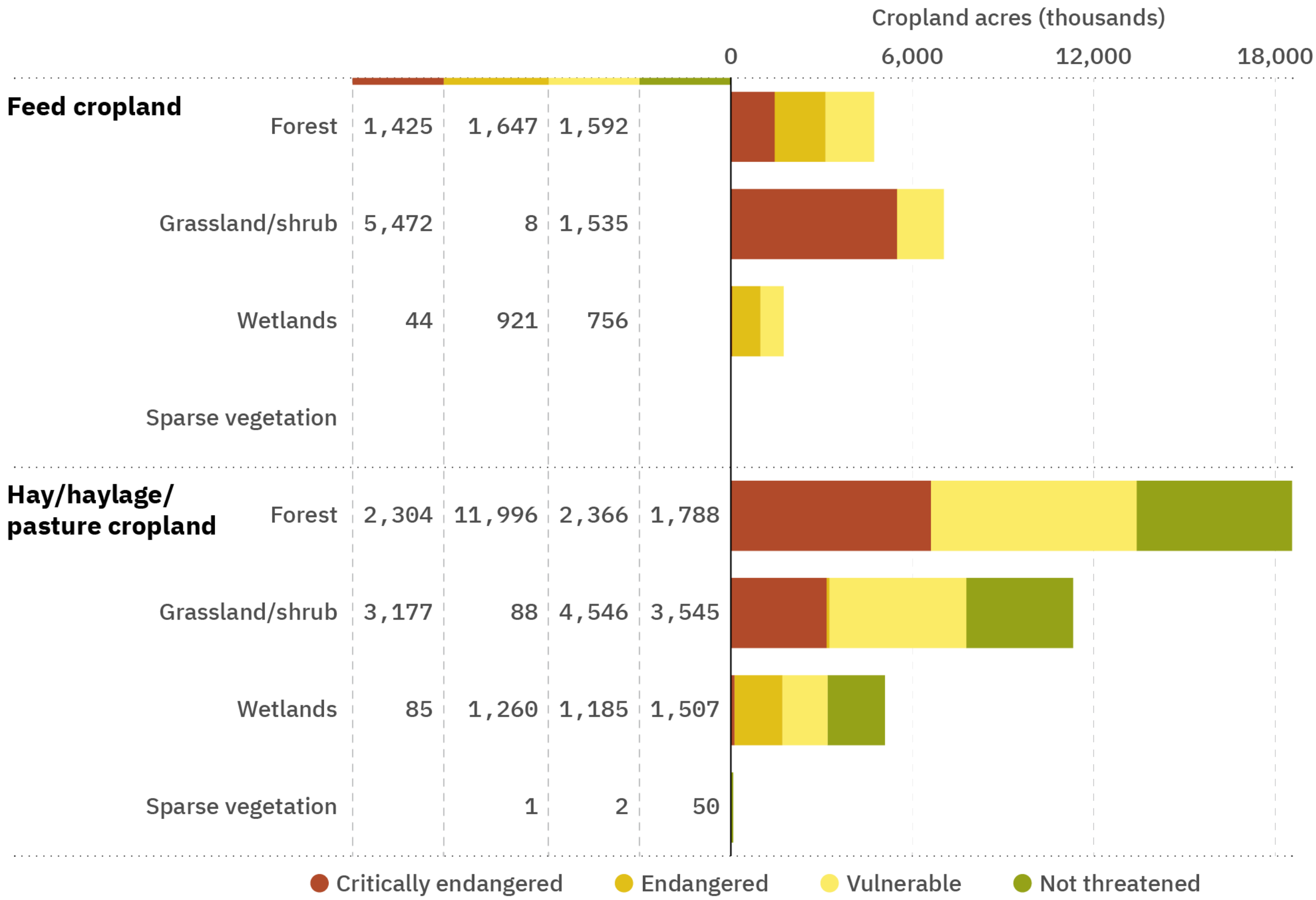


Figure 7: Modeled 47.3 million cropland acres restored, by vegetation type and threatened status.[21]

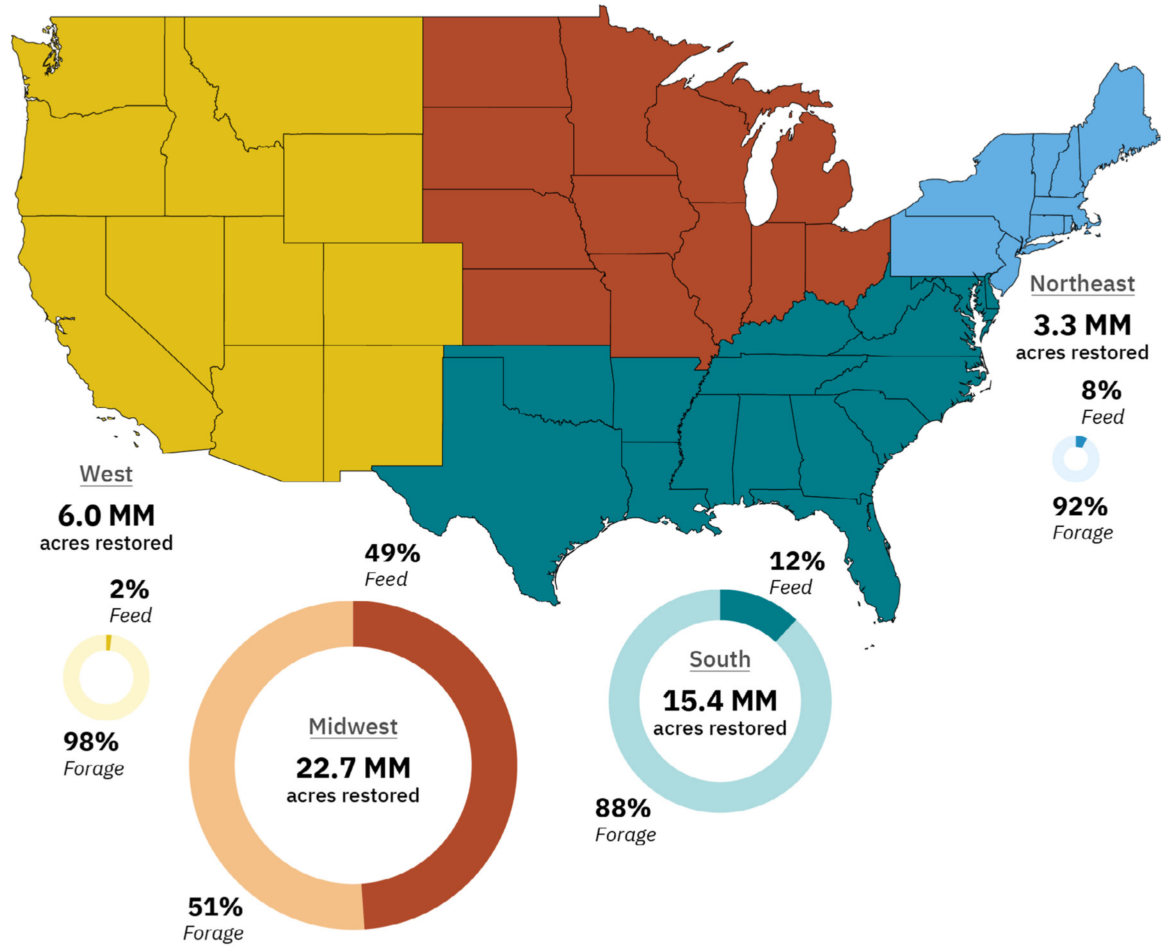
Regional variability in the biodiversity opportunity

The biodiversity opportunity enabled by a 50 percent shift toward alternative proteins varies significantly by region due to the distribution of feed crop and forage cropland, overlap with historical ecosystems, and the current threatened status of ecosystems. The South and the Midwest have the greatest number of acres prioritized for restoration in this analysis (Figure 8) because these regions are home to a significant percentage of the U.S. feed crop and forage cropland and have a high number of currently threatened ecosystems (Figure 9). Due to the dominance of feed crop acreage in the Midwest, this region has the greatest feed crop restoration opportunity (11.2 million of 13.4 million acres). These acres could be restored to currently threatened ecosystems, including grassland/shrubland, forests, and wetlands (Figure 9). While the Midwest has the greatest number of acres prioritized for restoration in this analysis, the South has the greatest number of threatened ecosystems that would benefit. For additional details and assessment of regional opportunities, refer to the Regional Opportunities section.

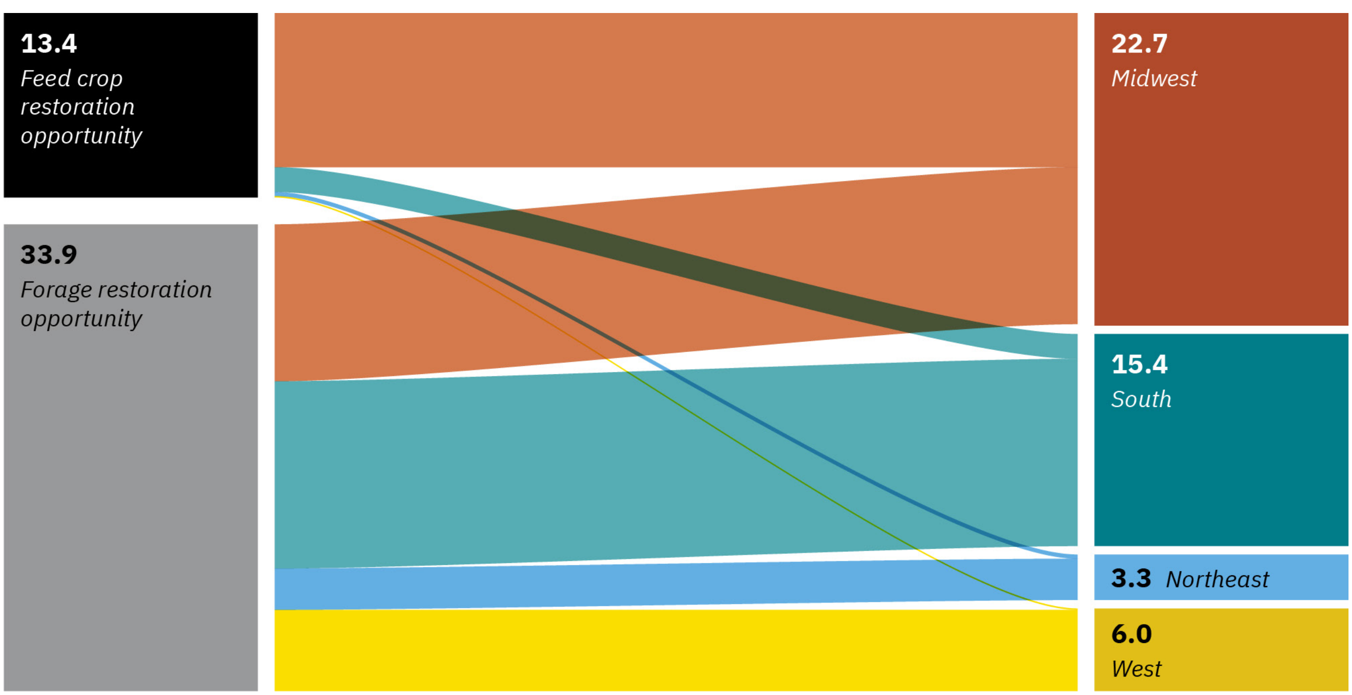
[21] Highland Economics analysis using GIS crop data from Cropscape 2022, GIS historical ecosystem data from NatureServe, and Red List of Ecosystems status from Comer et al. 2022.

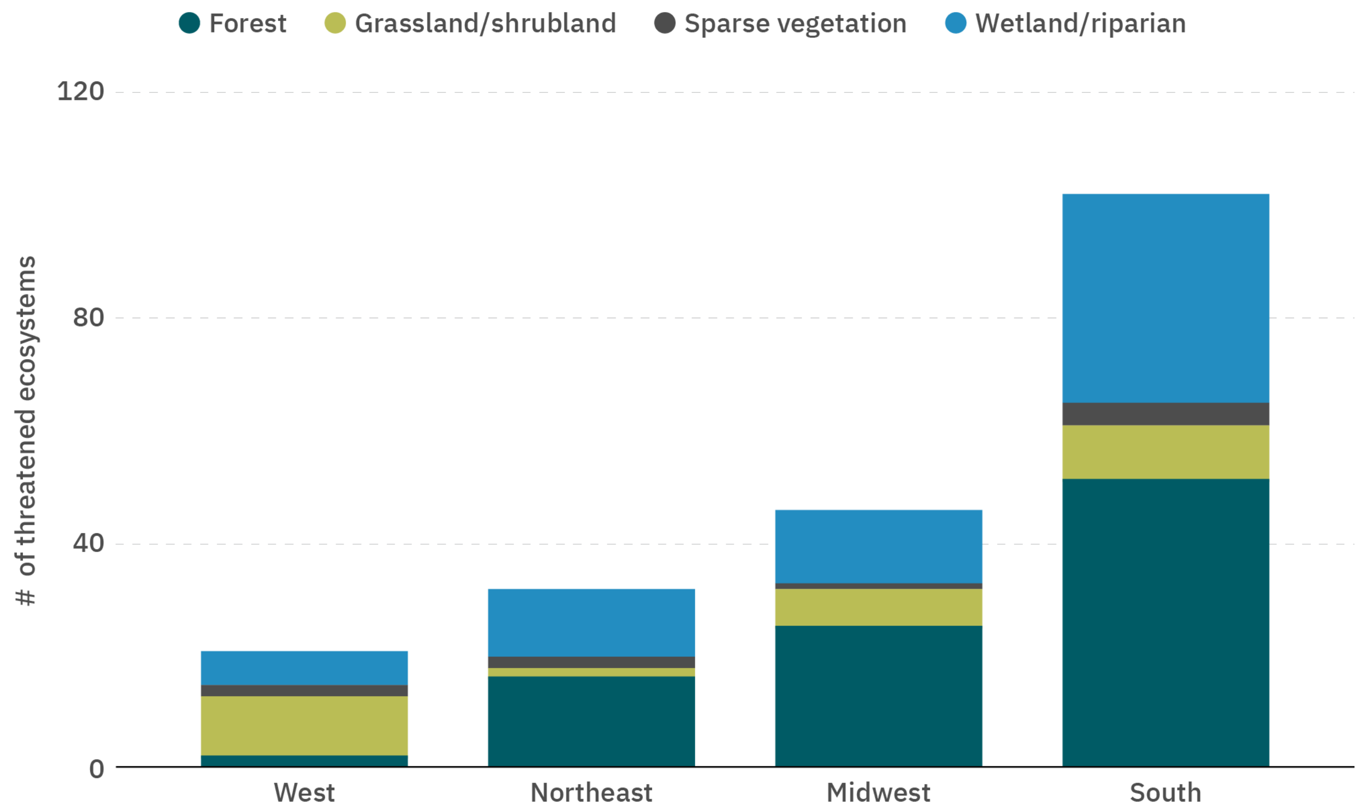
Figure 8. a. *Map:* geographic regions classified by the Bureau of Labor Statistics used to summarize regional results in this analysis. *Pie charts:* total acres and share by region of feed crop and forage cropland prioritized for restoration under the biodiversity strategy. b. Allocation of feed crop and forage cropland restoration opportunity by region under the biodiversity strategy (million acres).

a.



b.





	West	Northeast	Midwest	South
Wetland/riparian	6	12	13	37
Sparse vegetation	2	2	1	4
Grassland/shrubland	11	2	7	10
Forest	2	16	25	51

Figure 9. Number of threatened ecosystems restorable in current feed crop and forage cropland by region and ecosystem vegetation type.

Whether by conserving the most threatened habitats or prioritizing the conservation of wetland/riparian areas (Wetland/Riparian opportunity),[22] the U.S. National Climate Task Force has established a national goal of conserving 30 percent of U.S. lands and waters by 2030. To reach this goal, we estimate that approximately 358 million more acres of natural area need to be conserved or restored.[23] Restoring 47.3 million acres represents approximately 13 percent of this target. A 50 percent shift toward alternative proteins would help achieve the national 30X30 conservation target.

[22] The U.S. federal government has a policy of "no net loss" of wetlands, the only ecosystem type to have this federal protection, due to the importance of wetlands in providing numerous public benefits (water quality, flood regulation, habitat, carbon sequestration, aesthetics, etc.). Restoration of wetlands may thus be another promising biodiversity restoration prioritization method.

[23] Based on a target total of approximately 678 million acres and an estimated 320 million acres already conserved according to the Protected Areas Database from the U.S. Geological Survey.

Wetland/Riparian opportunity

If wetland/riparian ecosystem restoration is prioritized (instead of prioritizing restoration of the most threatened ecosystems), a shift to 50 percent alternative proteins could enable 24.9 million acres of wetland/riparian restoration nationwide. Assuming proportionate distribution of this acreage by state based on current hay, pasture/haylage, and feed crop acreage, three-quarters (75 percent) would occur in the Midwest and South. In eight states in the Mississippi River Basin, more than one million acres of wetland/riparian areas could be restored: Arkansas, Iowa, Louisiana, Mississippi, Missouri, Montana, Nebraska, and Texas (Figure 10).

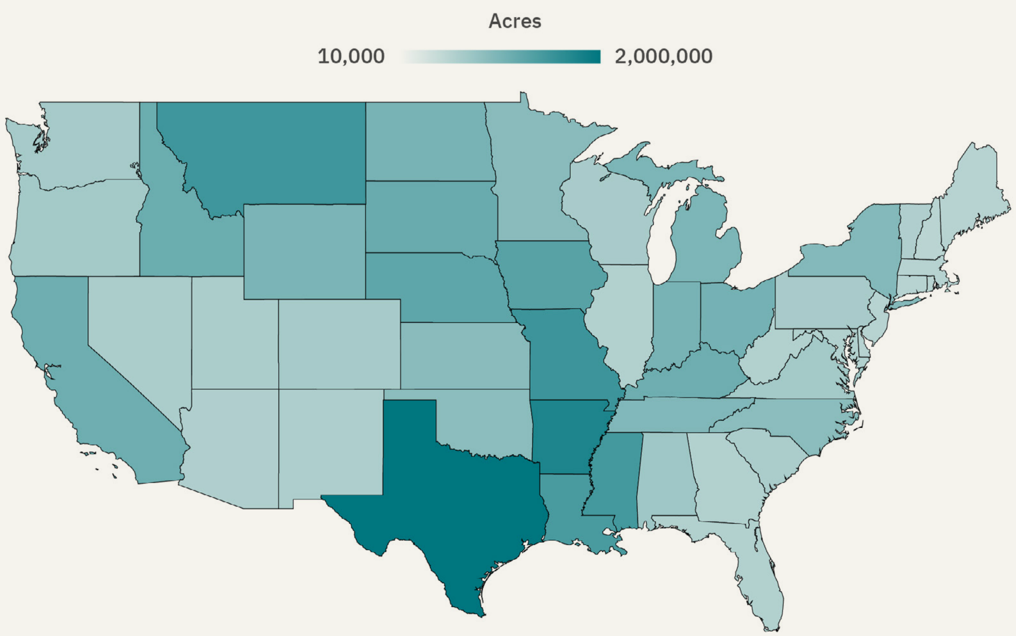


Figure 10. Wetland/riparian allocation of cropland restoration opportunity (acres).

Alternative protein carbon sequestration opportunity

A second strategy for prioritizing the restoration of the 47.3 million acres is to maximize carbon sequestration potential. In this strategy, we estimate the metric tons of carbon that could be sequestered annually by restoring 47.3 million acres of current feed crop and forage croplands to their historical forest, wetland, grassland/shrubland, or peatland ecosystem. We identify the annual carbon sequestration rates for each historical ecosystem and then, within each crop type, prioritize restoration areas based on the ecosystems that provide the highest annual carbon sequestration.

We estimate that a 50 percent shift toward alternative proteins enables a potential annual carbon sequestration opportunity of 177.8 million metric tons of carbon dioxide equivalent (CO_2e) from land use efficiency and restoration. This would generate a 22 percent increase in the net national carbon sink related to all land use, land use change, and forestry (referred to as the LULUCF sector in U.S. national greenhouse gas accounting).[24] This sequestration opportunity is greater than the CO_2 emissions of all U.S. domestic flights per year (FAA 2021).

Restored natural areas on croplands made available from a 50 percent shift to alternative proteins could sequester 177.8 million metric tons of CO_2e annually, greater than the CO_2 emissions of all U.S. domestic flights per year.

Sequestration rates are analyzed for each ecosystem type, and are aggregated in Figure 11 to summarize per-acre carbon sequestration rates by vegetation type (i.e., forest, riparian/wetland, grassland/shrubland) for the 47.3 million acres of lands prioritized for restoration. Within each vegetation type, the average sequestration rate differs by region based on the composition of vegetation and the associated sequestration rate. As shown in Figure 11, in all regions of the United States, forest and riparian/wetland areas provide the highest potential sequestration per acre. These lands are therefore prioritized for restoration, with 94 percent of modeled restored croplands in these two vegetation types.

Within the forest and riparian vegetation types, there can be significant variation in per-acre sequestration rates based on the tree type. For example, in the South, sequestration rates in forest ecosystems that overlay feed and forage cropland range from 1.92 metric tons to 4.42 metric tons of CO_2e sequestration per acre per year. Even for the same tree type there can be significant variation within a region. For example, the Douglas fir tree type can have an average annual sequestration rate of approximately 0.6 metric tons CO_2e in the Rocky Mountains and nearly 8.5 metric tons CO_2e in the western Pacific Northwest. Additionally, while the average sequestration rate of the riparian/wetland vegetation type is lower than forest vegetation type in most regions, some riparian/vegetation ecosystems have higher sequestration rates than some forest ecosystems. Across all acres prioritized for restoration, the average annual sequestration rate is 3.76 metric tons CO_2e.

[24] This is based on an average annual LULUCF Carbon Stock Change in the period 2019 to 2021 of 817.6 million metric tons, as published in the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks from 1990 to 2021.

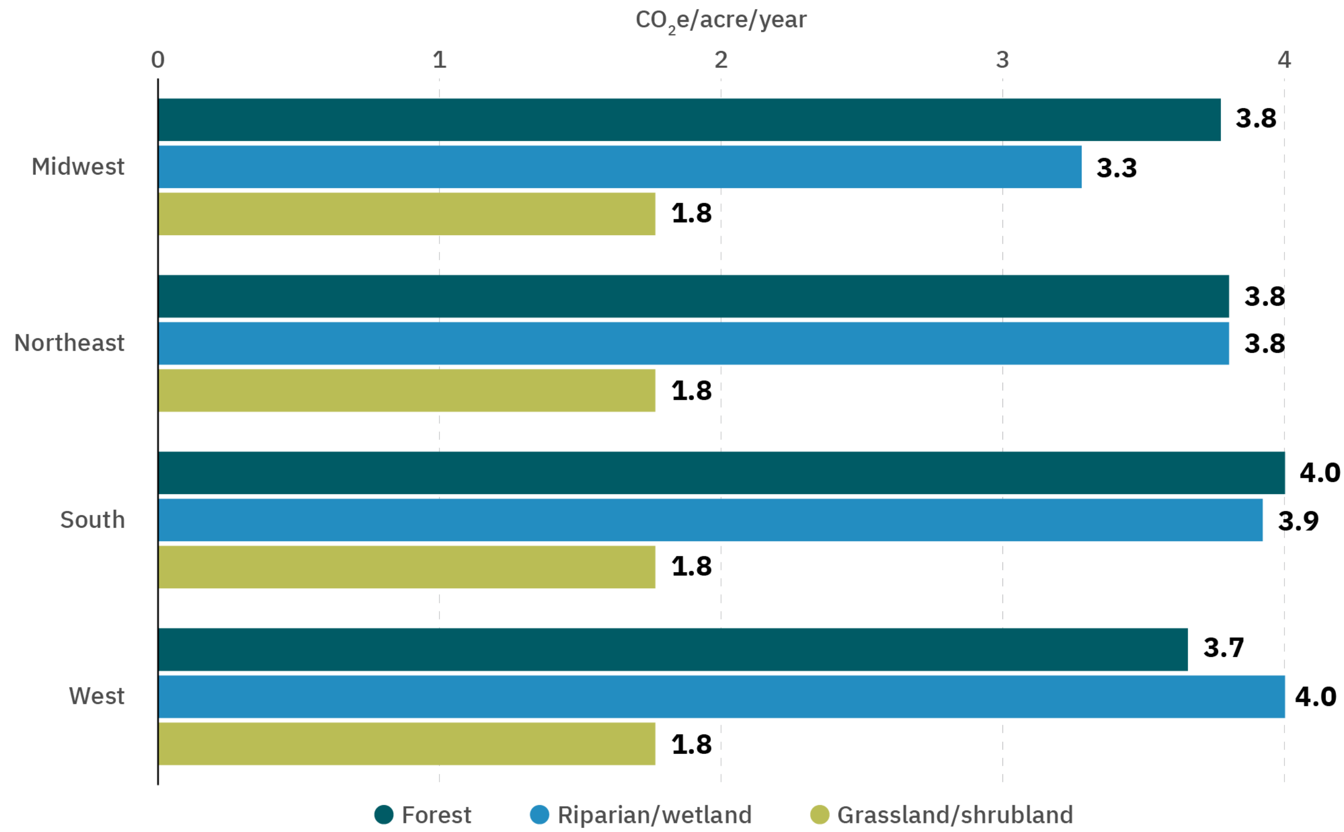


Figure 11. Annual average sequestration rate of acres prioritized for restoration by vegetation type and region, in metric tons CO_2e per acre per year (estimated average annual rate over 30 years after restoration). Reference: Hoover et al. 2021.

Figure 12 presents the total metric tons of CO_2e that could be sequestered annually in the United States with the restoration of 47.3 million acres of land currently used to grow animal feed, summarized by crop type, region, and vegetation type. The analysis sorts and prioritizes acreage for restoration based on expected sequestration rate in historical ecosystems, with lands with the highest sequestration rates selected first for restoration in each crop type.[25]

As highlighted in Figure 12 and consistent with the data in Figure 11, forests are the predominant vegetation type in restored ecosystems, followed by riparian/wetland vegetation.[26] The exception is in the West where there are more acres of historical wetland/riparian areas available for restoration than forest areas. Restoration of 13.4 million acres of feed cropland to forests and riparian/wetland areas provides 31 percent of the modeled sequestration opportunity (55.8 million metric tons CO_2e annually), while alfalfa and other hay combine for 47 percent of the sequestration opportunity (25.6 million metric tons and 58.3 million metric tons CO_2e annually, respectively) and restoration of cropland used for pasture/haylage accounts for the remaining 21 percent (38.1 million metric tons CO_2e annually).

[25] This process continues until the modeled restoration acreage in each crop type equals the acreage in that crop type made available from the transition to alternative proteins. In each crop type, there are more crop acres in each historical ecosystem type than are selected for restoration (i.e., in no crop type or region are all of the historical forest or riparian/wetland acres restored).

[26] More forest acres are restored than riparian/wetland acres both due to the higher sequestration rate in many forests (although some riparian ecosystems have higher sequestration rates than some forest ecosystems) and the fact that feed crop and forage crops generally overlap with more historical forest area than riparian wetland area (except in the West for all crops, and in the South for alfalfa hay and feed crops).

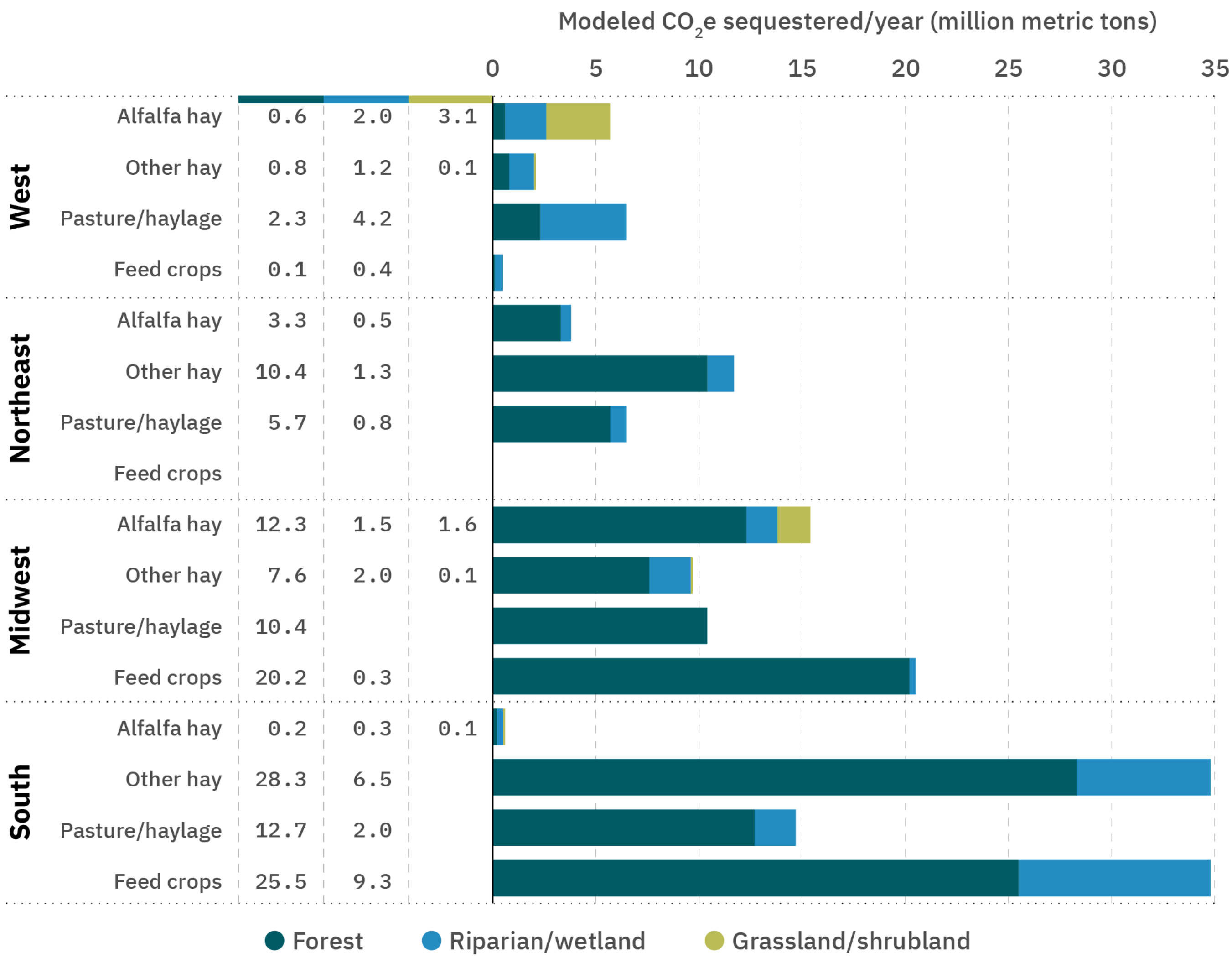


Figure 12: Total modeled metric tons CO_2e sequestration per year* by crop type, region, and vegetation type on modeled land restored due to a 50% alternative protein substitution. *Estimated average annual rate over 30 years after restoration.

Regional variability in carbon sequestration opportunity

As in the biodiversity strategy, the opportunity for cropland restoration for carbon sequestration varies by region and is concentrated where there is a significant amount of feed crop and forage cropland and historical ecosystems with high carbon sequestration potential, specifically forests and wetland/riparian habitats. Similar to the results from the biodiversity strategy, the South and the Midwest have the greatest number of acres prioritized for restoration in this analysis (Figure 13). While the total acreage restored in these two regions is similar in the two strategies, the acreage allocation shifts from the Midwest toward the South in the carbon sequestration strategy because the South has more feed crop acreage overlying historical forest ecosystems (Figure 13). The South has a particularly high carbon sequestration opportunity with 48 percent of the modeled carbon opportunity (85.0 million metric tons CO_2e annually, Figure 14). This is due to its high density of feed crop and forage cropland that could be restored to historical forest ecosystems. The Midwest follows the South with 31 percent of the modeled carbon opportunity (56.0 million metric tons CO_2e annually) (Figure 14). For additional details and assessment of regional opportunities, refer to the Regional Opportunities.

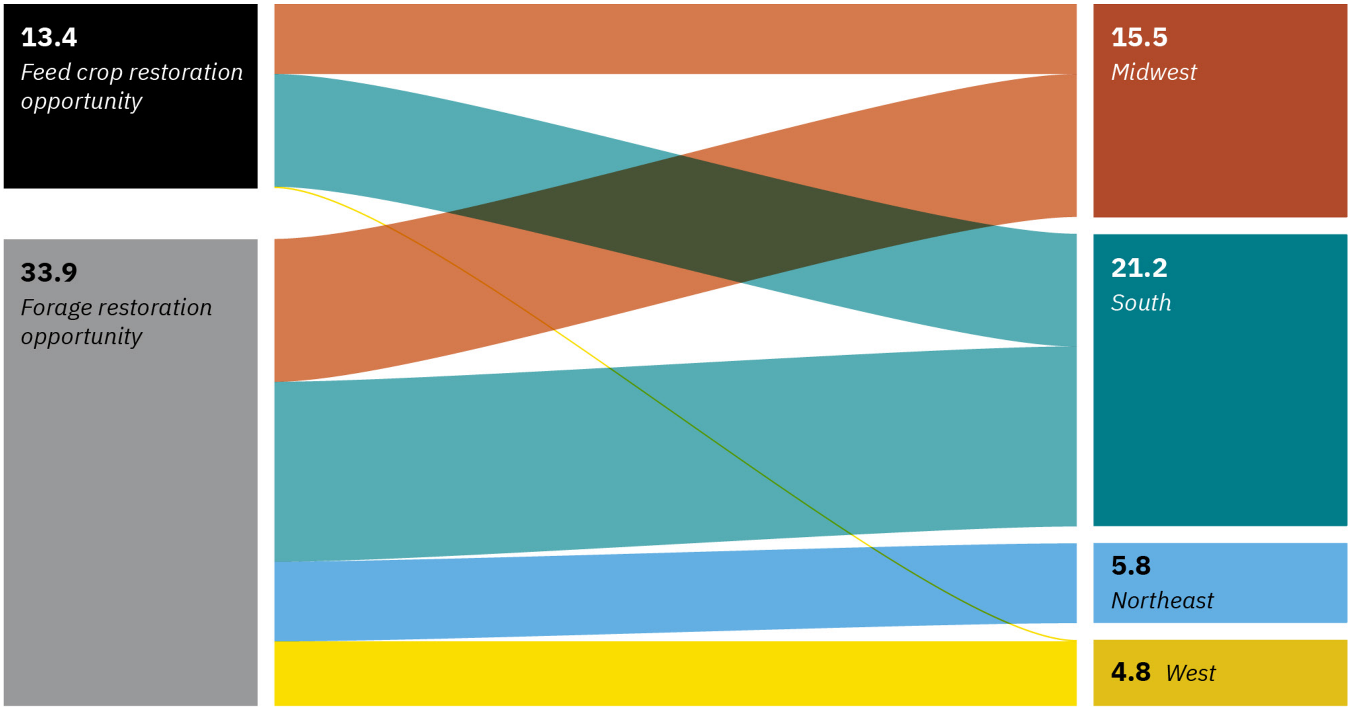


Figure 13. Allocation of feed crop and forage cropland for maximum carbon sequestration restoration opportunity by region (million acres).

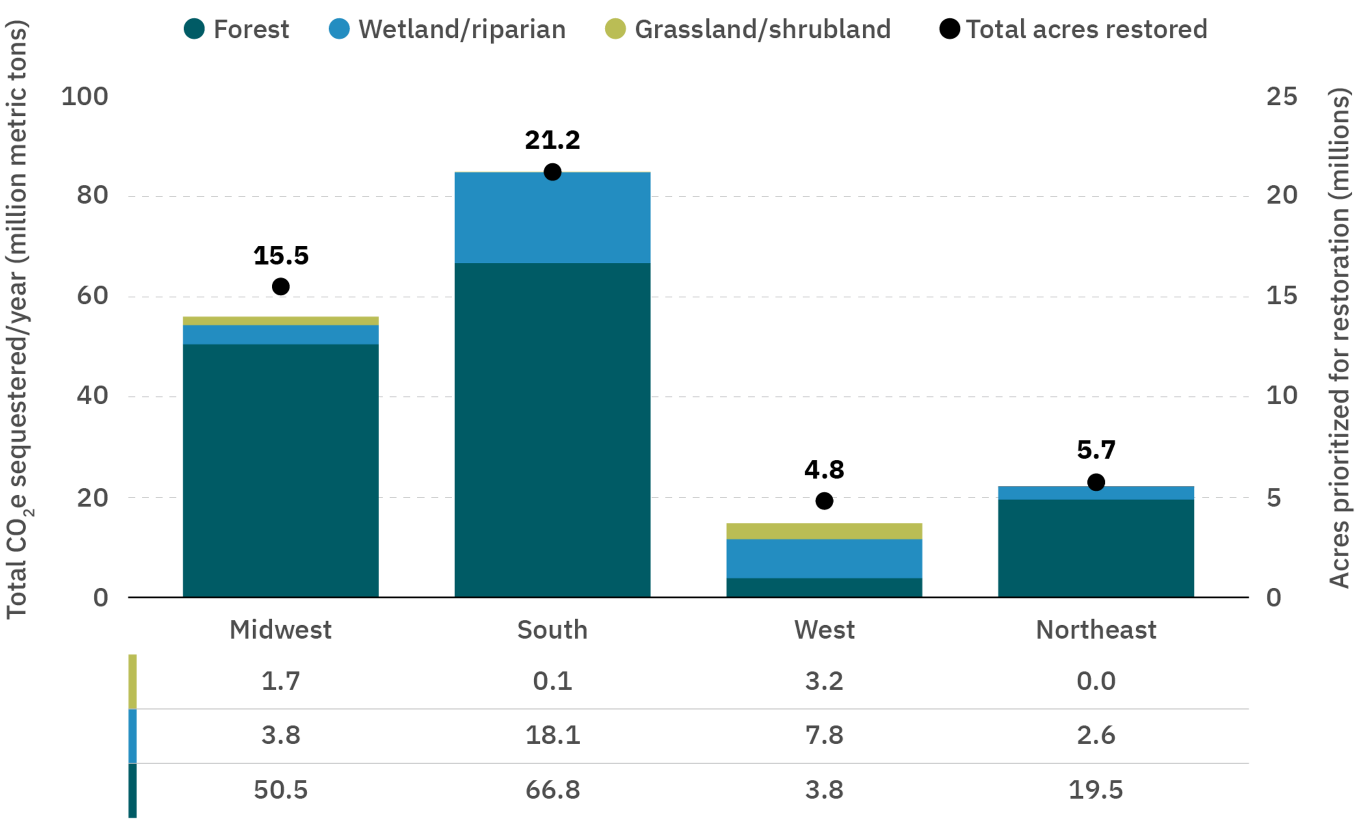


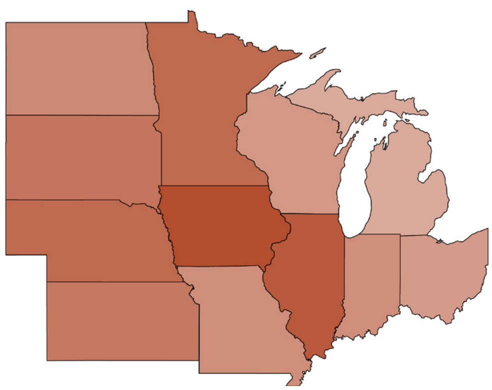
Figure 14: Total metric tons CO_2e sequestration per year* and acres prioritized for restoration due to a 50% alternative protein substitution. *Estimated average annual rate over 30 years after restoration.

Regional opportunities

This report demonstrates the importance of understanding regional variables to implement widespread land restoration benefits; historical ecosystems and current uses are just some of the many factors to consider. Here, we summarize opportunities in the Midwest, South, West, and Northeast of the United States to provide a focused understanding of the benefits available to each region.

Midwest

Hotspot of biodiversity and climate potential via mixed land use.



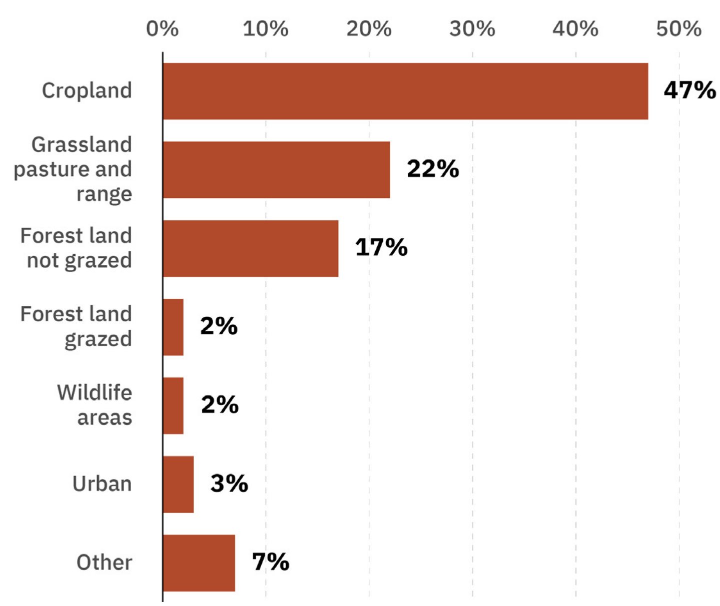
Current state

The conversion of a significant amount of land to agriculture and other uses, along with other stressors such as climate change, have reduced biodiversity in Midwestern prairies, wetlands, forests, and freshwater systems. One key concern for the Midwest is the decline in pollinator species, which affects ecosystem diversity and food production potential in the region.

Of land acres in the Midwest:
(NASS 2017; 2022a)

- Nearly one-half is cropland, largely for corn and soy feed crop production.
- 22% is grassland for rangeland and pasture, a source of additional restoration potential not examined in this analysis.
- Just 2% (11 million acres) are in rural parks or wildlife areas and 19% of land cover (93.5 million acres) is in forest uses.

The Midwest is home to the top 10 feed crop production states by acreage with ~ two-thirds of all U.S. feed crop acreage.

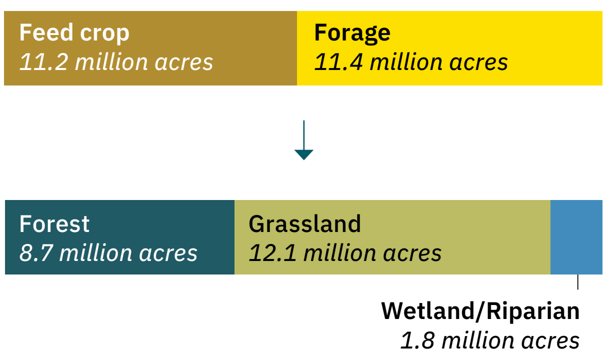


Diversifying American protein sources to include 50% alternative proteins

Biodiversity opportunity

46 threatened ecosystems restored using 10.0% of current cropland

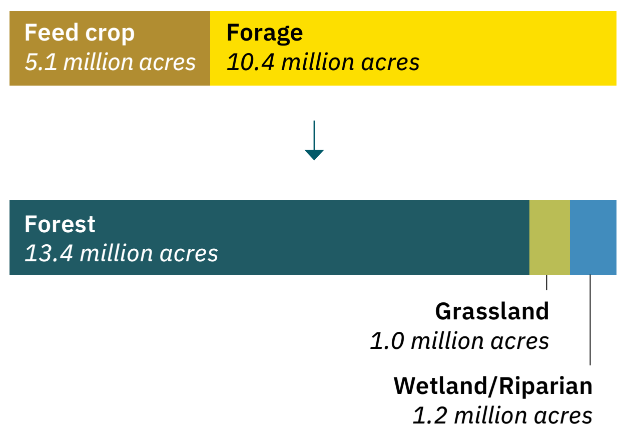
- The majority of acreage available for restoration was allocated to this region due to the high number of critically endangered ecosystems in this region and high concentration of feed and forage cropland.
- A relatively small (10%) shift in land use from feed crop and forage to grasslands and forests could provide a significant increase in ecosystem diversity and critical habitat.



Carbon sequestration opportunity

56 million metric tons of CO_2e annually using 6.9% of current cropland

- The Midwest ranked second to the South for its carbon sequestration potential.
- The majority of this sequestration is gained through restoration of forage and feed crop land to forests.
- Unlike the biodiversity strategy, grassland restoration was not prioritized under the this strategy due to its relatively low carbon sequestration potential.



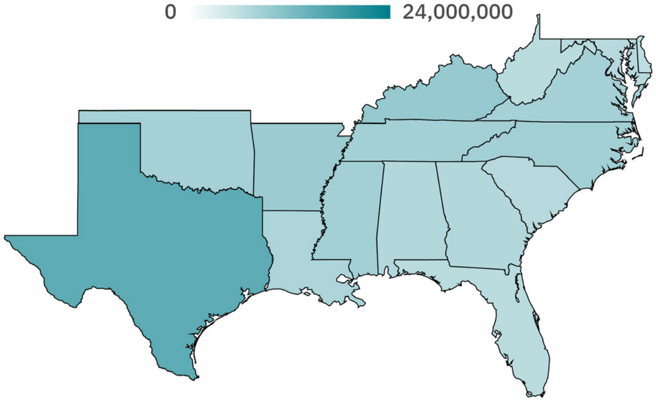
Wetland opportunity

8.6 million acres of wetland and riparian ecosystems restored if wetland restoration is prioritized

- The Midwest suffers from flooding and water quality issues; both of these challenges are expected to be exacerbated by climate change.
- Restoration of riparian/wetland ecosystems can be an effective approach to addressing both flooding and water quality.

South

Forested, biodiverse region with further reforestation potential.



Current state

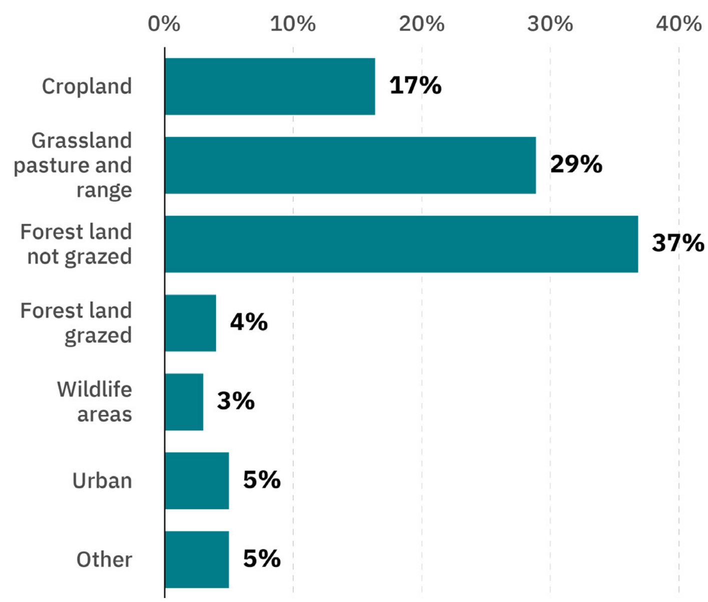
Biodiversity in the South is particularly high and is concentrated in several areas, including the Southern Appalachians, the Panhandle of Florida and Alabama, and the Everglades. More than 250 species in the southern United States are listed under the Endangered Species Act as being at risk of extinction.[27]

Of land acres in the South:

(NASS 2017; 2022a)

- 17% is cropland, 29% is grassland for rangeland and pasture, and 40% is forest.
- In Texas and Oklahoma, 63% and 45% is grassland for rangeland and pasture, respectively, a source of additional restoration potential not examined in this analysis.
- Just 3% of land, or 16.7 million acres, are in rural parks or wildlife areas.

Cropland uses are highest in Delaware, Tennessee, Kentucky, Maryland, and Arkansas, and lowest in West Virginia, South Carolina, Florida, and Alabama.



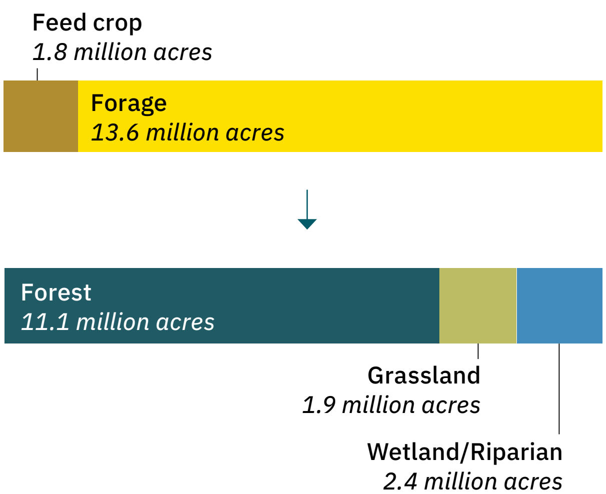
[27] Terah Boyd, 'Endangered Species Act changes 'step in the right direction' towards protecting Southern willife', Southern Environmental Law Center, 21 June 2023, https://www.southernenvironment.org/press-release/endangered-species-act-changes-step-in-the-right-direction-towards-protecting-southern-wildlife/.

Diversifying American protein sources to include 50% alternative proteins

Biodiversity opportunity

102 threatened ecosystems restored using 16.7% of current cropland

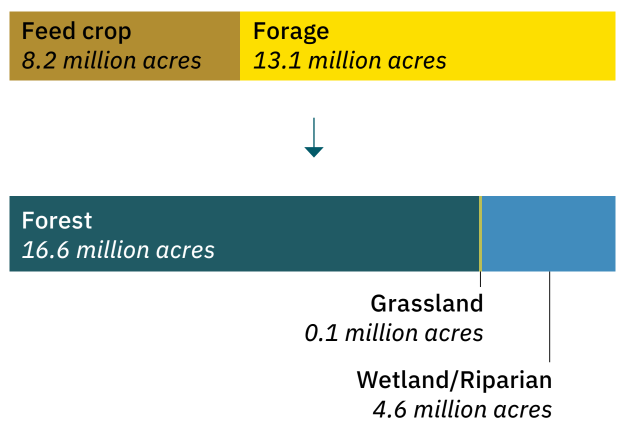
- Compared to the Midwest, the South contains fewer acres of feed cropland that could be restored to threatened ecosystems. So, feed crop acres were not as highly allocated for restoration under the biodiversity strategy.
- The South still had the greatest number of threatened ecosystems that would benefit from restoration, due to the native ecosystem diversity of this region.



Carbon sequestration opportunity

85 million metric tons of CO_2e annually using 23.1% of current cropland

- The South has the highest potential carbon sequestration of the regions analyzed in this study.
- The majority of this sequestration is gained through restoration of feed and forage crops to native forest and wetland habitat, which have high carbon sequestration per acre.



Wetland opportunity

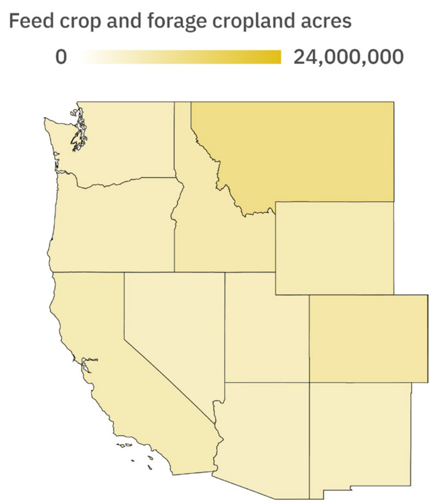
10.1 million acres of wetland and riparian ecosystems restored if wetland restoration is prioritized

- Restoration of wetland and riparian ecosystems would improve water quality in the Gulf of Mexico, biodiversity, and flood control.
- Wetland restoration projects from active agricultural lands have demonstrated success in the South.[28]

[28] Diane De Steven and Joel M. Gramling, 'Assessing Wetland Restoration Practices on Southern Agricultural Lands: The Wetlands Reserve Program in the Southeastern Coastal Plain', USDA Forest Service Southern Research Station, 14 November 2011, https://www.nrcs.usda.gov/publications/ceap-wetland-2012-WetlandsReserveProgramSoutheasternCoastalPlain-full.pdf

West

Natively biodiverse region ripe for grassland and wetland restoration.



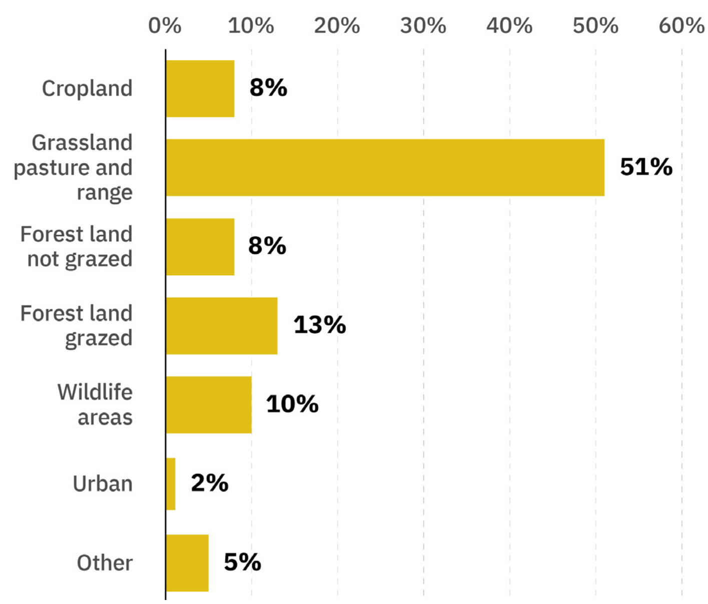
Current state

Biodiversity in the West is high, with California, Arizona, and New Mexico ranking as having the highest levels of State species diversity. In California, 292 species are listed under the Endangered Species Act as being at risk of extinction; 75 species in Arizona, 61 species in New Mexico, and 47 species in Oregon are also listed.[29] Nearly all crops in the Western United States are irrigated, so increased agriculture land efficiency would also reduce pressure in water constrained basins.

Of land acres in the West:

(NASS 2017; 2022a)

- 8% is cropland, most of which is used to cultivate forage crops.
- In the Mountain States, 60% is grassland for rangeland and pasture, a source of additional restoration potential not examined in this analysis. In the Pacific States, 28% is grassland for rangeland and pasture.
- 10% of land, or 72.9 million acres, is in rural parks or wildlife areas.



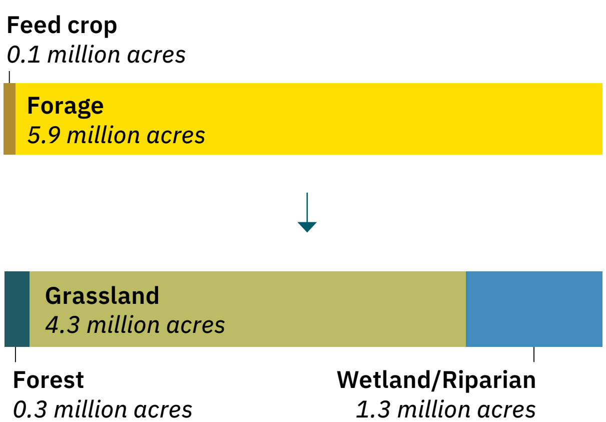
[29] 'Listed species with spatial current range believed to or known to occur in each state', U.S. Fish & Wildlife Service, accessed 5 July 2024, https://ecos.fws.gov/ecp/report/species-listings-by-state-totals?statusCategory=Listed.

Diversifying American protein sources to include 50% alternative proteins

Biodiversity opportunity

21 threatened ecosystems restored using 9.7% of current cropland

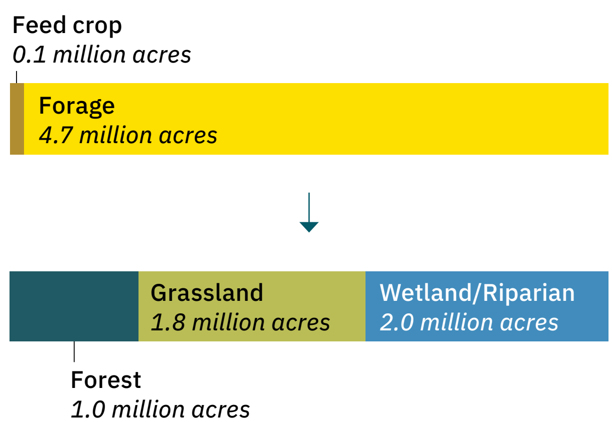
- Grassland/shrubland in the West is particularly well-suited for threatened ecosystem restoration.
- Ecosystem restoration aligns with California's and Nevada's State 30x30 goals to conserve and restore 30 percent of lands and coastal waters by 2030.[30,31]



Carbon sequestration opportunity

15 million tons of CO_2e annually using 7.8% of current cropland

- Sequestration can be roughly equally gained through restoration of forage crops to either forest, grassland, or wetland.
- Given the prominence of grassland use for rangeland and pasture in the West Mountain States, there are additional protein diversification benefits to consider outside this study's scope.



Wetland opportunity

5.1 million acres of wetland and riparian ecosystems restored if wetland restoration is prioritized

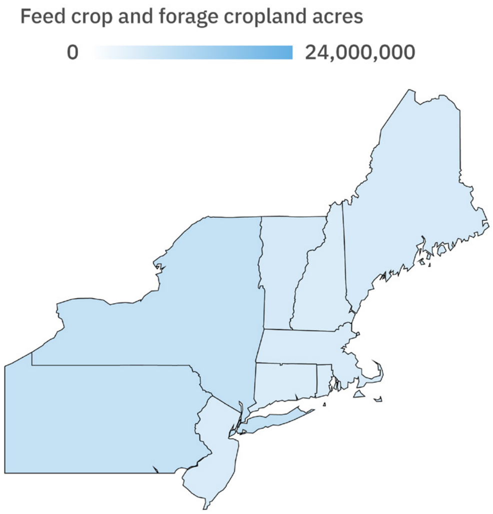
- A key benefit of all restoration strategies and reduced crop cultivation in the West would be water conservation.
- Reduced irrigation water usage would reduce groundwater aquifer drawdown, increase instream flows for fish and other aquatic species, and reduce the effects of drought on water supplies for other uses.

30 '30x30 California', California Natural Resources Agency, accessed 11 July 2024, www.californianature.ca.gov

31 'AJR3', Nevada State Legislature, 21 May 2021, https://www.leg.state.nv.us/App/NELIS/REL/81st2021/Bill/7487/Text

Northeast

Forested and urban landscape with strong climate potential.



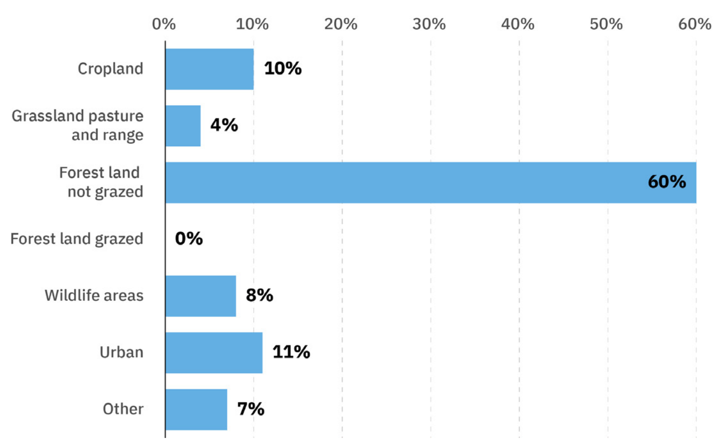
Current state

The Northeastern United States is the most urban region of the country and has relatively little agricultural land use. Smaller states (New Jersey, Massachusetts, Rhode Island, and Connecticut) are ~40% urban areas, which affects natural ecosystems and agriculture. Agriculture- and urban development- driven deforestation has reduced Northeast soil carbon stocks.[32]

Of land acres in the Northeast:

(NASS 2017; 2022a)

- 10% is cropland, with <5% as cropland in Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut and higher cropland demands in New York (13%) and Pennsylvania (14%).
- Forest land uses comprise 60% of land use in the Northeast, and urban areas account for 11%, the highest of any region in the nation.
- 8% of land, or 8.3 million acres, are in rural parks or wildlife areas.



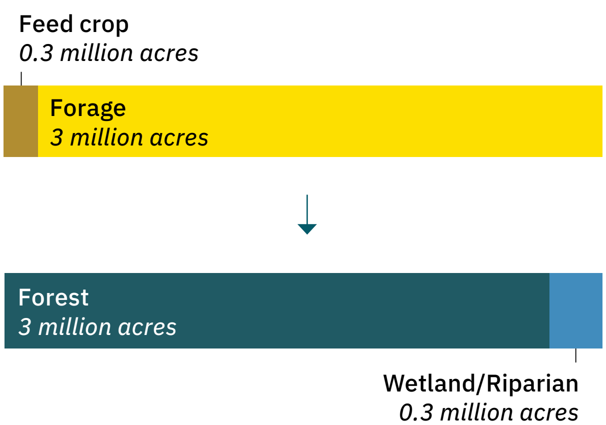
[32] Lucas E. Nave et al., 'Land use change and forest management effects on soil carbon stocks in the Northeast U.S.', Carbon Balance and Management ISSN: 1750-0680, Springer Nature, 6 February 2024, https://cbmjournal.biomedcentral.com/articles/10.1186/s13021-024-00251-7.

Diversifying American protein sources to include 50% alternative proteins

Biodiversity opportunity

32 threatened ecosystems restored using 31.7% of current cropland

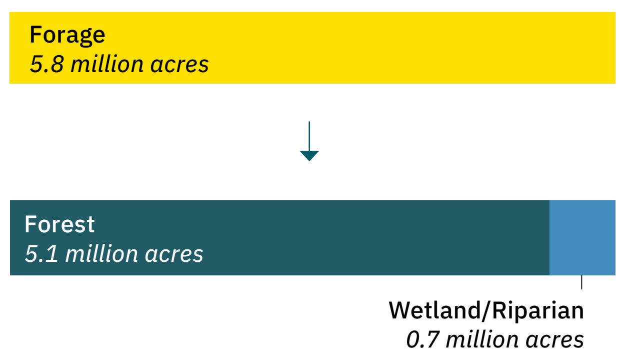
- Interactions with urban environments place additional stressors on wildlife species like bats, birds, turtles, fish, and other terrestrial and aquatic ecosystems.[33]
- Ecosystem restoration aligns with Maine's State Climate Action Plan to conserve 30 percent of lands and coastal waters by 2030.[34]



Carbon sequestration opportunity

22 million tons of CO_2e annually using 55.7% of current cropland

- The majority of this sequestration is gained through restoration of forage crops to forest, prioritized due to its high carbon sequestration potential.
- Reforestation would increase soil carbon stocks, aligning with regional goals such as The Securing Northeast Forest Carbon Program.[35]



Wetland opportunity

1.2 million acres of wetland and riparian ecosystems restored if wetland restoration is prioritized

- Restoring wetlands provides habitats for fish, turtles, and other wildlife—augmenting other biodiversity benefits.
- Wetland restoration in the Northeast is a priority for the National Resources Conservation Service, which provides options for landowners to restore wetlands.[36]

[33] 'Protecting Northeast Lands, Waters, and Wildlife,' Center for Biological Diversity, accessed 11 July 2024, www.biologicaldiversity.org/programs/public_lands/forests/protecting_northeast_lands_waters_and_wildlife/index.html.

[34] Jennifer Mitchell, 'Maine's New Climate Action Plan Calls For Lowered Emissions, Land Conservation, Job Creation', Maine Public, 13 November 2020, https://www.mainepublic.org/environment-and-outdoors/2020-11-13/maines-new-climate-action-plan-calls-for-lowered-emissions-land-conservation-job-creation.

[35] 'Securing Northeast Forest Carbon Program', accessed 5 July 2024, www.northeastforestcarbon.org.

[36] 'Working Lands for Northeast Turtles', accessed 23 July 2024, www.nrcs.usda.gov/sites/default/files/2022-10/Working_Lands_for_Northeast_Turtle_web.pdf

Conservation organization and policy mechanisms to realize these benefits

Alternative protein products that offer nutritional, taste, and price parity to animal-sourced foods can provide protein with lower resource use and environmental burden than their animal-based counterparts. This report demonstrates the immense biodiversity and climate mitigation benefits of diversifying American protein sources. Reducing land pressure also enables nature-based solutions such as land restoration and agroforestry. In addition to the land use efficiency benefits, alternative protein adoption will result in significant direct and indirect emission reductions (e.g., GHGs, pesticides, fertilizers). However, for alternative proteins to provide the advantages demonstrated in this analysis, they would need to comprise 50 percent of the U.S. domestic protein demand, or approximately 4 billion kg of protein per year. For context, *global* alternative meat consumption was approximately 1.0 million metric tons (MMT) in 2022 (at 20 percent protein content, this is an estimated 200 million kg of protein, equal to 2.5 percent of current U.S. domestic protein demand), with an estimated 2.2 MMT of plant-based meat production capacity. As a result, reaching large production volumes in the United States will require increased alternative protein demand, R&D, and manufacturing infrastructure.

A land use transformation of this scale will not occur passively but instead will require multistakeholder buy-in to develop better products and scale their production. Here, we urge the following actions from two key stakeholder groups, NGOs and governments. We also recognize the importance of other vital contributors to protein diversification and land restoration efforts, such as farmers, tribal groups, and the alternative protein industry, and invite them to explore how these actions fit in with their goals and missions.

Actions for nongovernmental organizations

NGOs play an important role in holistically analyzing critical societal issues, influencing governmental and corporate actions, and working with key stakeholders to implement solutions. Environment-focused NGOs (e.g., Table 1) can support alternative proteins as a significant and achievable part of the solution to the biodiversity and climate crises by recognizing that alternative proteins are enablers of nature-based solutions. GFI recommends the following actions for environment-focused NGOs:

1

Act as advocates for governmental support for alternative protein R&D and commercialization to advance climate and nature goals:

NGOs who work on biodiversity, conservation, and climate mitigation can influence governments to increase their support for alternative proteins. These groups are doing important work across their existing programs, including working with key stakeholders to conserve land and implement climate-smart farming practices, partnering with companies to achieve their sustainability goals, and calling for stronger conservation and climate policies. Alternative proteins provide another important avenue for NGOs to advance environmental and climate goals, as discussed in this report. NGOs can support the likelihood of alternative proteins making a significant contribution to nature and climate goals by being advocates for governments and philanthropies to fund 1) open-access alternative protein

R&D to help products reach taste and price parity to accelerate consumer adoption, and 2) incentives for companies who are producing alternative protein products (in the form of loan guarantees, tax incentives, and/or advance market commitments).

2

Evaluate the socioeconomics associated with alternative protein adoption and advocate for policies that benefit U.S. farmers:

This analysis is a starting point to understand how diversifying the U.S. protein supply will affect agriculture and natural ecosystems. A limitation of this study is that we do not address socioeconomic variables (see Socioeconomic considerations). We urge other NGOs who are more specialized in this area to explore the impacts on the workforce and economy, as well as the equity impacts, of a shift toward alternative proteins. Strong policies and governmental support will be crucial for farmers who decide to grow food crops and explore nature-based solutions on their land, instead of traditional feed crops and forage crops. We encourage NGOs to work alongside farmers on designing policies that provide economic, workforce development, and social benefits to the U.S. agricultural sector while also supporting land restoration and climate goals. By prioritizing critical stakeholders, like farmers and rural communities, alternative proteins can provide important economic and environmental benefits.

Alternative proteins are enablers of nature-based solutions.

3

Expand and optimize land use efficiency benefits across border geographies and diverse prioritization strategies:

Food system transformations can be daunting, especially when presented in a global context. By providing national- and regional-level insights, this analysis reveals achievable spatial unit opportunities for restoration but is still limited to the geographies and datasets targeted here. Climate, biodiversity, and other environmental benefits from alternative protein adoption should be analyzed and mapped for other regions, especially those particularly vulnerable to climate change and biodiversity loss. For example, Green Alliance's "A new land dividend: The opportunity of alternative proteins in Europe" 2024 report explores land opportunities that a shift toward alternative proteins could yield in ten European countries, emphasizing food security, nature recovery, and carbon storage benefits. Finally, when examining these benefits, NGOs should explore optimal locations for restoration and regenerative opportunities, such as agroecological farming.

Actions for governments

Governmental action is critical in agricultural and food systems as governments set policies and provide financial, operational, and market support to enact large-scale changes. The U.S. has already made great strides toward conservation goals since the release of the America the Beautiful initiative in 2021. However, to reach its ambitious 2030 and 2050 targets for climate change mitigation and land conservation and restoration, diversifying our protein supply is essential. More policy support will be necessary to create appealing alternative protein products, scale their production, and provide them at an affordable price to the public. We recommend the following actions for U.S. federal and state governments:

1

Increase public funding into alternative protein R&D to advance the sensory experience, cost-effectiveness, nutrition, and production capabilities of alternative proteins:

R&D is necessary to accelerate consumer adoption and achieve parity with conventional meat products on taste, price, and other parameters. R&D can also scale alternative protein production capabilities and drive alternative protein product innovation, reducing costs for both producers and consumers. Governments must play a leading role in accelerating basic research that fuels open-access scientific breakthroughs. Despite being home to many of the world's experts, the United States currently ranks behind several other countries in publicly funded R&D into alternative proteins. Specifically, domestic policymakers should properly consider alternative proteins for all relevant grant programs related to food, agriculture, biotechnology, decarbonization, and similar topic areas. Additionally, to address the cross-cutting nature of alternative protein R&D, policymakers should support the establishment of research centers of excellence focused on alternative protein innovation.

2

Promote commercialization and biomanufacturing scale-up to produce alternative proteins more efficiently and sustainably, while equitably supporting new workforce opportunities and regional diversity:

Policymakers should provide financial incentives to alternative protein companies and manufacturers to support product commercialization. As with other emerging industries, financial incentives are crucial to driving alternative protein commercialization—the process of bringing alternative protein products to market—and increasing the scale of the alternative protein sector. Policy measures to support commercialization include direct financial investments, grants, loan guarantees, tax incentives, and advance market commitments like offtake agreements. These tools can reduce risks for startups and facilitate scale-up for the entire industry. Alternative protein facilities can create economic opportunities for rural communities throughout the United States. This biomanufacturing will likely take place near feedstock crops, improving supply chain resilience while fostering regional economic growth and new job opportunities in all parts of the nation. For this reason, equitable policy-making will also invest in the growing bioworkforce by supporting training programs for students and professionals entering the alternative protein sector.

3

Adopt public policies that support U.S. farmers, bolster new markets for domestically produced alternative protein crops and feedstocks, and offer financial and technical assistance for any agricultural producer affected by changing market conditions:

Farmers who incorporate alternative protein crops into their existing operations can profit from new sources of income while ensuring a more sustainable and resilient future. Creating a supportive environment for alternative proteins can champion an entirely new sector in which agricultural side-streams can be made useful and profitable. Strong policies and governmental support for farmers who decide to grow crops for alternative proteins rather than more conventional feed and forage will be imperative, and corresponding policies should incorporate principles to bolster agriculture for nature-positive solutions like alternative proteins. In addition to providing fiscal support, building management tools for farmers and other public and private landowners will help reduce operational friction when transitioning to crops for alternative protein production and managing restored lands.

To achieve U.S. targets for land conservation and restoration, enhanced biodiversity, and reduced net greenhouse gas emissions, we must advocate for feasible, scalable practices, such as diversifying our protein supply.

The United States has historically led global food and agricultural transformations through research innovations, science-driven policies, and strong market forces. We now have the opportunity to build a secure and sustainable agricultural system by aligning fund and resource allocation with outcome-based frameworks—providing more resources to solutions with strong evidence of social and environmental benefits.

Alternative proteins are a key to sustainably diversify protein supplies, having consistently demonstrated improved resource use efficiency by using agricultural inputs directly, without cycling them through animals. This report examines the land use efficiency benefits of alternative proteins, demonstrating that by restoring only 2.5 percent of lands in the contiguous United States, we can help restore 64 percent of threatened ecosystems or enable a 22 percent increase in the net national carbon sink related to all land use, land use change, and forestry. With multistakeholder buy-in for alternative protein adoption, the United States can continue to lead global agricultural and land stewardship. However, to realize these benefits by 2030, we must act urgently to diversify our protein supply with plant-based, fermentation-derived, and cultivated proteins.

By restoring only 2.5 percent of lands in the contiguous United States, we can help restore 64 percent of threatened ecosystems or enable a 22 percent increase in the net national carbon sink related to all land use, land use change, and forestry.

Appendix

Simplifications & Assumptions

Table A1. Rationale and implications of analysis simplifications and assumptions.

Simplification or Analysis Boundary	Rationale and Implications
Cropland focus Only cropland is analyzed; no analysis of land use change and environmental benefits on rangeland or grassland pasture (except cropland used as pasture).	This analysis focuses on the benefits of land use efficiency defined by a change in the vegetation-based ecosystem type (i.e., from animal feed and forage crops to the historical ecosystem). Rangelands are ecosystems with native vegetation that is predominately grasses or other plants suitable for grazing, so restoration of rangeland would not necessarily result in a change in ecosystem type or quality, unless it is overgrazed. The changes in ecosystem quality (and associated biodiversity and carbon effects) resulting from reduced grazing or removal of livestock from rangeland will vary substantially based on current grazing management practices and other site-specific factors. Therefore, effects on rangeland and grassland pastures were excluded from this analysis and the results presented herein are likely conservative estimates of the carbon sequestration and biodiversity benefits of increased land use efficiency resulting from alternative protein adoption.
Primary feed crops focus The analysis only considers the primary feed crops in the U.S.: soy and the feed grains of grain corn, sorghum, barley, and oats.	Soy and the main feed grain crops of grain corn, sorghum, barley, and oats are the only feed crops analyzed. Other grain crops such as wheat are also fed to livestock; however, the proportion of these crops fed to livestock is low so a change in demand from domestic livestock producers is less likely to affect total acreage cultivated in the United States.
Focus on dietary protein instead of protein products	The focus of this analysis is a transition to a more land-use-efficient protein source. As such, the analysis estimates the alternative protein requirement to replace conventional protein on a per kilogram of protein basis, rather than a per product weight or per calorie basis. To the extent that consumers focus on protein intake, and not caloric intake or weight of food intake, this approach provides an accurate estimate of the alternative protein production and associated cropland requirement that would be required for a 50% transition.

Focus on current U.S. protein consumption Analysis does not account for growth in U.S. protein demand over time.	The analysis focuses on current (2023) protein consumption as the land-use efficiency benefits are based on current land-use patterns that produce protein to meet current demand levels (i.e., for consistency we match current protein demand with current land-use patterns). The U.S. population is projected to grow and slightly increase its animal protein intake (see Appendix A). Increased animal protein demand in the future would tend to increase the land-use efficiency benefits (in terms of number of acres) of a shift toward alternative proteins, indicating that our analysis may be conservative. We take this approach as projecting the future is uncertain, and it is feasible that increased future demand for feed and forage crops may be met through increased crop yields rather than increased acreage.
Focus on contiguous U.S. No data for Hawaii or Alaska included.	Very little livestock feed is produced in these two states, and the land area/land is very different than the contiguous United States.
All feed crop acreage may be used as animal feed	The specific location of feed crop acreage used for domestic livestock feed versus other uses (export, fuel, etc.) is not known or available since these are commodity crops produced and then not traced through to final use. We assume that a reduced demand for feed crops could result in any feed crop acreage being made available for restoration.
Acreage is proportional to final use	We assume that the proportion of feed crop acreage producing livestock feed is equal to the percent of feed crop production used for animal feed. In other words, we implicitly assume that the yield per acre of feed crops being produced for U.S. animal feed is the same as the yield for feed crops being produced for export, fuel, or other uses.
Alternative protein land use requirement similar across categories	The analysis assumes that the average cropland requirement across all alternative protein products consumed in the 50% scenario is an average of the land requirements for four alternative protein products, based on their life cycle analysis data—a cultivated meat meat, a biomass fermentation-derived meat, a soy-based meat with precision fermentation ingredient meat, and a pea-based meat.
No analysis of market effects of reduced U.S. feed/forage crop demand This analysis assumes that reduced demand for feed and forage crops makes land available for restoration.	Feed and forage crops are global commodities. This analysis does not consider how imports/exports or other market dynamics may change with decreased U.S. demand for feed crops. This analysis assumes that reduced U.S. demand for U.S. feed and forage crops is not offset by increased export or other uses of feed and forage production.

Average annual sequestration There is no analysis of annual variation in sequestration rate.	We use an average annual sequestration expected for the first 30 years of forest, grassland, or peatland restoration. In reality, sequestration rates vary annually depending on many factors including existing carbon stocks, climate, and vegetation age and growth rates. In afforested ecosystems annual sequestration rates are slow initially (when the trees are young), increase as the trees grow larger, and then slow again as trees mature. Carbon saturation may eventually occur where there is no net sequestration; the data indicate that this would likely be past the 30-year timespan analyzed in this paper.
Historical ecosystems for haylage/cropland pasture Assumed to be similar to the historical ecosystems for other hay croplands.	No data is available for spatial distribution of haylage or cropland used as pasture to overlap with modeled historical ecosystems. We use data from other hay as indicative of the historical ecosystems overlapped by haylage and cropland used as pasture, as haylage and cropland pasture are different uses of other hay cropland (haylage is grass hay that is made into silage while cropland used as pasture could also be harvested as grass hay).
Maximum potential sequestration Restoration feasible on croplands converted from high sequestration ecosystems.	The analysis prioritizes restoration of cropland areas where the historical ecosystem has the highest carbon sequestration potential per acre and assumes that these acres are available for restoration.
Maximum biodiversity enhancement Restoration feasible on croplands converted from currently threatened ecosystems.	The analysis prioritizes restoration of croplands where the historical ecosystem types are currently threatened and assumes that these acres are available for restoration.
Proportional allocation of biodiversity restoration We do not analyze the number of acres that need to be restored such that an ecosystem is no longer threatened.	In the biodiversity strategy we allocate restored acres across each threatened ecosystem proportionate to the number of acres that can be restored to each threatened ecosystem. For example, if 20% of restorable threatened acreage is in the Central Tallgrass Prairie ecosystem, then we allocate 20% of restored acres in that ecosystem.

Methodology

This analysis consists of four primary components:

1. Quantifying the land use efficiency benefit, specifically in terms of reduced feed crop and forage cropland acres required to meet U.S. protein demand, associated with a 50 percent substitution of conventional proteins with alternative proteins.
2. Mapping the historical ecosystems converted to U.S. feed crop and forage croplands to quantify the acreage in each ecosystem type that could be restored with increased land use efficiency.
3. Computing the net maximum carbon opportunity of restoring cropland acres potentially available with increased land use efficiency.
4. Evaluating the maximum biodiversity opportunity of restoring cropland potentially available with increased land use efficiency.

The methods and supporting data used in each of these components are provided below.

Quantifying the cropland use efficiency benefit

The reduction in cropland required for U.S. domestic protein production with a 50 percent shift to alternative proteins is estimated by taking the difference between 1) the cropland acreage used to produce feed and forage for livestock raised and consumed in the United States and 2) the cropland acreage required for alternative protein production to supply 50 percent of U.S. protein demand, as described below.

Cropland used in domestic animal protein consumption

This analysis is based on the current agricultural acreage used to grow feed crops and forage crops in the United States, based on the average of the 2017 and 2022 Census of Agriculture data. Feed crops analyzed are: soy, grain corn, barley, sorghum, and oats. Forage crops analyzed are: alfalfa hay, other hay, haylage, and cropland used as pasture.

Not all U.S. feed crop and forage cropland production is fed to domestic livestock; therefore, the analysis adjusts the feed crop and forage cropland acreage reported in the Census of Agriculture to account for other uses including export, fuel, food/beverage, seed, and industrial. The analysis estimates the average proportion of each crop used for domestic livestock feed based on the average from 2013 to 2022 as reported by U.S. Department of Agriculture Feed Grains Database on Supply and Disappearance by crop (Table A2, % domestic supply used for domestic animal feed). The analysis assumes the proportion of acreage used to produce animal feed is equivalent to the proportion of production used for animal feed (i.e., 38% of grain corn production is used for domestic animal feed, so the analysis assumes 38% of grain corn acreage produces domestic animal feed).

Table A2: Feed crop and forage cropland supporting domestic livestock production.[37]

Crop type	Census of Agriculture data			Cropland acreage producing domestic livestock feed	
	2022	*2017*	*2017/2022 average*	*% domestic supply used for domestic animal feed*	*2017/2022 average*
Corn, Grain	80,597,963	84,738,562	82,668,263	38%	31,400,000
Corn for silage or greenchop	5,978,417	6,109,414	6,043,916	100%	6,000,000
Soybeans for beans	84,599,236	90,149,480	87,374,358	38%	33,200,000
Oats	914,059	814,140	864,100	48%	400,000
Barley for grain	2,430,308	2,206,808	2,318,558	18%	400,000
Sorghum for grain	4,692,243	5,070,159	4,881,201	27%	1,300,000
Sorghum for green-chop or silage	427,981	335,647	381,814	100%	400,000
Subtotal, Feed crops	**179,640,207**	**189,424,210**	**184,532,209**	**40%**	**73,100,000**
All Alfalfa	16,791,249	17,869,949	17,330,599	98%	17,000,000
Other Hay	30,416,449	32,596,508	31,506,479	98%	30,900,000
Haylage* and Pasture	19,916,654	20,218,140	20,067,397	100%	20,100,000
Subtotal Forage	67,124,352	70,684,597	68,904,475	99%	67,900,000
Total, Feed crops and Forage	**246,764,559**	**260,108,807**	**253,436,683**	**56%**	**141,100,000**
Wheat (Not included in analysis)		37,211,994	38,811,620	5%	1,900,590

**Haylage is a product of grass hay, and similar to silage, is a high moisture animal feed preserved using fermentation.*

[37] Highland Economics analysis of US Census of Agriculture 2017, US Census of Agriculture 2022, US Department of Agriculture Feed Grains Database on Supply and Disappearance

The analysis further adjusts the cropland requirement to support domestic animal protein production by accounting for export of U.S. livestock and animal products, and the associated acreage that supports production of these exports. The analysis estimates the proportion of U.S. domestic meat and dairy production that is exported based on USDA data on total supply and disappearance for each type of animal protein (ERS 2024a; 2024b). This data was calculated as the average over five years (2018–2022)[38] of the percent of domestic production that is a net export, where net export = (Exports – Imports)/Domestic Production. Then, relying on estimated proportional use of animal feed by livestock type from Eshel et al. (2014), the analysis estimates the proportion of U.S. animal feed used to produce animal proteins for export. As shown in Table A3, an estimated 14 percent of feed crop that is fed to U.S. livestock supports U.S. livestock and animal products for export. In other words, 86 percent of U.S. feed crop used for livestock feed is required to meet U.S. animal protein demand.

Table A3: Estimated % of U.S. animal feed used to produce animal proteins for export. Source: Eshel et al. 2014.

Livestock product	% net export of U.S. production	% of feed crop use by U.S. livestock	% of U.S. animal feed used to produce animal proteins for export
Beef	0%	24%	0%
Poultry	15%	15%	4%
Eggs & Egg Products	3%	4%	5%
Pork	20%	23%	0%
Dairy (Skim solids basis)	19%	21%	4%
Total	**N/A**	**100%**	**14%**

[38] We use a five-year average here instead of a ten-year average to be conservative. The five-year average results in a lower estimate of cropland use for domestic protein production. Exports as a proportion of production were higher for the last five years than for the preceding five years for dairy and pork.

The analysis uses the data presented in Tables A2 and A3 to estimate the acreage of feed crop used to support production of animal products to meet U.S. dietary demand. Multiplying the feed crop acreage used for domestic livestock feed by 86 percent reduces the feed crop acreage required to produce domestic protein from 73.1 million acres to 62.9 million acres, as shown in Table A4.

Beef production accounts for nearly all forage consumption (pasture and hay) in the United States. Since there is little to no net export of beef from the United States, all pasture and forage used to produce domestic beef is expected to be used to meet domestic animal protein demand. Therefore, there is no adjustment made to the forage crop acreage to account for export of animal proteins. As shown in Table A4, the total U.S. cropland acreage estimated to support domestic livestock produced to meet domestic animal protein demand is approximately 131 million acres. Reducing this acreage to account for a 50 percent reduction in animal protein demand results in an estimated 65.4 million acres of reduced cropland demand.

Table A4: U.S. cropland acreage required to meet U.S. animal protein demand.

Crop type	U.S. cropland acreage producing domestic animal feed	% of U.S. animal feed used to produce livestock for domestic protein consumption	U.S. cropland acreage required to meet U.S. animal protein demand	Reduction in cropland with 50% reduction in animal protein demand
Feed Crops	73,100,000	86%	62,900,000	31,500,000
Forage	67,900,000	100%	67,900,000	33,900,000
Total, Feed Crops and Forage	141,100,000	NA	130,800,000	65,400,000

Note: Numbers may not sum due to rounding.

Cropland required to produce alternative proteins to meet 50 percent of the U.S. protein demand

Increased production of alternative proteins will require cropland acreage that will partially offset the reduction of acreage demand from reduced animal protein demand presented in Table A4. To quantify cropland acreage to produce 50 percent of the U.S. conventional animal protein demand with alternative proteins, the analysis estimates 1) 50 percent of U.S. annual conventional animal protein consumption in kilograms and 2) the cropland requirement to produce a kilogram of protein from alternative proteins based on life cycle assessment data.

As of 2023, Americans annually consume approximately 24 kilograms of animal protein per capita according to the United Nations Food and Agricultural Organization (FAO 2024).

Multiplying this by the population of the United States in 2023 of 335.6 million Americans results in a demand of approximately 8 billion kilograms of animal protein consumed annually. A 50 percent protein source shift to alternative proteins would thus result in an additional demand of 4 billion kilograms of protein from alternative proteins to replace animal proteins, as shown in Table A5. (This is the weight of protein, not the weight of animal or alternative protein products. Animal products and alternative protein products are approximately 10 to 20 percent protein by weight.)

This analysis uses population and animal protein demand as of 2023. Over time, U.S. animal protein demand is projected to grow, primarily due to population growth, but also due to slight growth in animal protein demand. By 2050, U.S. animal protein demand in a business-as-usual scenario will increase by 17 percent to 9.42 billion kilograms, based on U.S. Census population data and FAO projections for per capita animal protein consumption. This analysis uses 2023 animal protein demand since our estimate of cropland required for animal protein production is based on current land use patterns that are driven by current animal protein demand. However, given the growth projected in animal protein demand by 2050, the land use efficiency benefits of a 50 percent protein source diversification in 2023 are likely an underestimate of the cropland use benefits that would be experienced in the future.

Based on life cycle assessment data for a range of alternative proteins including plant-based, fermentation-derived, and cultivated products, we estimate that alternative proteins require, on average, 18.22 square meters of cropland to produce 1 kilogram of protein.[39] Using this ratio, to produce 4 billion kilograms of protein from alternative proteins would require approximately 18.1 million acres of land, as shown in Table A5. Netting out 18.1 million acres from the 65.4 million acres presented in Table A4 results in an overall land use efficiency benefit of 47.3 million U.S. cropland acres from the 50 percent shift to alternative proteins. The analysis assumes that all 18.1 million acres used to produce alternative proteins would be similar to the cropland currently used to produce feed crops. As such, the analysis subtracts the 18.1 million acres required for alternative protein production from feed crop acreage to estimate a net reduction in feed crop acreage of 13.4 million acres resulting from a shift to alternative proteins. The reduction in forage crop acreage remains at 33.9 million acres, as shown in Table A4.

Table A5: Cropland requirement to produce alternative proteins to replace 50% of U.S. animal protein consumption.[40]

	U.S. per capita animal protein demand (kilograms/year)	Kilograms of animal protein demand, U.S. (total/year)	50% reduction with protein diversification (kilograms of protein/year)	Cropland requirement for alternative protein production to replace 50% animal protein (acres)
Beef	4.7	1,589,300,000	794,600,000	3,600,000
Dairy	8.1	2,708,800,000	1,354,400,000	6,100,000
Poultry	6.8	2,294,800,000	1,147,400,000	5,200,000
Pork	2.7	908,200,000	454,100,000	2,000,000
Eggs	1.6	525,500,000	262,700,000	1,200,000
Total	23.9	8,026,600,000	4,013,300,000	18,100,000

39 The cropland required to produce alternative proteins was calculated as an average of cropland use to produce cultivated meat (Sinke et al. 2022), biomass fermentation-derived meat (Kazer et al. 2021), soy-based meat with precision fermentation ingredient (Khan et al. 2019), and pea-based meat (Heller and Keoleian 2018).

40 Highland Economics analysis of United Nations Food and Agricultural Organization (FAO) data on U.S. protein demand and U.S. Census Bureau data on population. The FAO data for U.S. protein consumption in 2020 and 2025 was averaged to estimate the protein demand in 2023.

Mapping U.S. feed and forage cropland to historical ecosystems

This analysis generates spatial data layers for U.S. feed crops, alfalfa, and other hay using the Cropscape 2022 Geographic Information Systems (GIS) data layer developed by the U.S. Department of Agriculture (NASS 2022c). The analysis combines soy, grain corn, barley, oats, and sorghum acreage into a feed crop spatial data layer. The analysis also uses Cropscape data to develop alfalfa and "other hay" spatial data layers.

The restoration benefits in this paper are estimated based on modeled, historical ecosystems that existed prior to conversion to cropland use. The historical ecosystem in every location in the United States has been modeled by Landfire and is available as a GIS data layer. Landfire is a "shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior, providing landscape scale geo-spatial products to support cross-boundary planning, management, and operations" (Landfire 2024). Specifically, the analysis uses data on historical, potential ecosystems as modeled in the Landfire Biophysical Settings (BPS) GIS layer. **BPS represents "the vegetation system that may have been dominant in the landscape prior to Euro-American settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime."** BPS vegetation types are based on NatureServe's ecological systems classification and represent natural plant communities. While both the biodiversity and carbon prioritization strategies estimate restoration benefits using the ecosystems predicted by BPS, different BPS-based spatial datasets were used for the two analyses (this was required for compatibility of the spatial datasets with the biodiversity and carbon data).

Cropscape data includes grassland/pasture acres, but this includes non-cropland acreage (328.4 million acres in the 2022 dataset). As spatial data on cropland used for pasture and for haylage is lacking, the analysis estimates the potential, historical ecosystem overlap for the 20.1 million acres of pasture and haylage based on the distribution of potential, historical ecosystems that overlap with the "other hay" GIS data layer. Other hay, haylage, and cropland used as pasture are often grown on the same cropland (i.e., one year cropland may be used as pasture and the next harvested for other hay or haylage). As such, within each state, we assume the distribution of ecosystem potential on pasture and haylage cropland to be similar to other hay cropland. The carbon analysis allocates the acreage of pasture and haylage cropland in each state (based on U.S. Census of Agriculture data) that could be restored to each historical, potential ecosystem based on the percentage of other hay acreage that is overlapped by each of these types of potential, historical ecosystems in that state.

Results are summarized into four geographic regions: West, South, Midwest, and Northeast as classified by the U.S. Bureau of Labor Statistics (BLS 2024). The states in each region are presented in Figure 8.

Carbon sequestration prioritization strategy

The analysis follows a similar approach and uses the same carbon data sources as a recent analysis of carbon sequestration potential from "U.S. Natural Climate Solutions for the United States" led by scientists at The Nature Conservancy (Fargione et al. 2018). Specifically, the analysis uses data on carbon sequestration by ecosystem type paired with data on the historical ecosystem type that overlaps with feed and forage crops as defined in the section above. The analysis estimates the maximum potential increase in annual average carbon sequestration from restoration of U.S. cropland made possible by diversifying American protein sources with alternative proteins.

To quantify the carbon sequestration potential of restoring historical, potential ecosystems on current cropland, we take the following steps:

1. **Quantify the acreage that overlaps each historical ecosystem type in each crop type (feed crop, alfalfa, other hay).** At the state level, the analysis overlays the feed crop, alfalfa, and other hay crop spatial layers with the Landfire BPS 2016 Remap data (Landfire 2016) on historical ecosystems. This identifies the amount of acreage of each historical ecosystem that overlaps each crop data layer. Across the contiguous U.S., 403 historical ecosystems overlap with the Cropscape data for feed crops and forage cropland.

2. **Quantify the acreage of restoration in peatland ecosystems.** This analysis overlays the feed crop, alfalfa, and other hay crop spatial layers with NRCS soil survey data for histosol soils to identify areas with peatland restoration potential. All areas with histosol soils were identified as peatland.

3. **Quantify the annual average carbon sequestration potential in each historical ecosystem type over the next 30 years.** The analysis uses different datasets to quantify the additional carbon in forest restoration, grassland/shrubland restoration, and peatland restoration types, as described below:

For forest ecosystems, the analysis matches each ecosystem with the "forest ecosystem" BPS "groupveg" classification[41] to one of the 53 U.S. Forest Service ecosystems (specific to tree type and ecoregion) for which carbon stock data for afforestation are available from a 2021 Forest Service analysis (Hoover et al. 2021). The analysis uses a crosswalk developed by The Nature Conservancy that matches the BPS ecosystem to the correct U.S. Forest Service tree type, and then for each tree type the analysis matches the tree type to the correct USFS region. For each tree type/region, the analysis takes the difference between the soil carbon stock and the non-soil total at Year 0 and at Year 30 and divides by 30 to derive an annual average sequestration estimate.[42] For conifers, to account for the albedo effect, the analysis follows Fargione et al. (2018) and reduces the above-ground carbon by 50 percent.

There are some BPS ecosystems classified as a forest ecosystem in the "groupveg" classification that lack a corresponding U.S. Forest Service ecosystem (e.g., the USFS does not provide carbon stock data for the Longleaf/Slash Pine tree type in the South Central region). For these forest ecosystems, the analysis applies the state average forest ecosystem carbon stock data (calculated based on the results from all other forest ecosystems in the state, weighted by the acreage of forest ecosystems in the state). These values vary from 0.27 to 5.73 metric tons of carbon per hectare per year, as shown in Table A6.

4. **Identify the cropland acreage to restore in each crop type.** Acreage in ecosystems with the highest annual carbon sequestration is restored up to the acreage restorable in each crop type.

5. **Estimate total annual carbon dioxide equivalent sequestration from restoration.** The analysis converts the values presented above into a carbon dioxide equivalent per acre, and then multiples annual carbon dioxide sequestered in each ecosystem type by the number of acres determined in Step 4.

[41] These include "groupveg" classifications of hardwood, conifer, hardwood-conifer, and riparian.

[42] Note that Fargione et al. (2018) did not include soil carbon. In this analysis we take the difference in soil carbon anticipated in Year 30 compared to soil carbon in Year 0, and divide by 30 to get annual average sequestration in the first 30 years.

Table A6: Average annual forest sequestration of carbon by region and tree type, metric ton or megagram (Mg)/Ha/Year. Source: Hoover et al. 2021.

Usfs region and tree type	0 To 30 years	Conifer, value adjusted for albedo effect[43]
Central States Elm/Ash/Cottonwood Group	2.60	N
Central States Oak/Hickory Group	2.69	N
Great Plains Elm/Ash/Cottonwood Group	2.14	N
Great Plains Oak/Hickory Group	1.30	N
Northeast Maple/Beech/Birch Group	2.62	N
Northeast Oak/Hickory Group	2.64	N
Northeast Spruce/Fir Group	1.03	Y
Northeast White/Red/Jack Pine Group	1.19	Y
Northern Lake States Aspen/Birch Group	2.11	N
Northern Lake States Elm/Ash/Cottonwood Group	2.51	N
Northern Lake States Maple/Beech/Birch Group	2.45	N
Northern Lake States Oak/Hickory Group	2.33	N
Northern Lake States Spruce/Fir Group	1.00	Y
Northern Lake States White/Red/Jack Pine Group	0.80	Y
Pacific Northwest Douglas-fir Group2	3.61	Y
Pacific Northwest Fir/Spruce/Mountain Hemlock Group[44]	0.64	Y
Pacific Northwest Lodgepole Pine Group	0.77	Y
Pacific Northwest Ponderosa Pine Group	0.62	Y
Pacific Northwest Alder/Maple Group	2.79	N
Pacific Northwest Hemlock/Sitka Spruce Group	5.73	Y
Pacific Southwest Fir/Spruce/Mountain Hemlock Group	0.79	Y
Pacific Southwest Ponderosa Pine Group	0.53	Y
Pacific Southwest Redwood Group PSW	1.99	N

[43] Above ground carbon storage is reduced by 50% to account for albedo effect.

[44] Data for this region and tree type was presented separately for the eastern portion of states in the Pacific Northwest and the western portion of states in the Pacific Northwest. We use the average of the data for the two regions as our analysis is conducted at the state level. Other Pacific Northwest tree types are generally only found in the eastern or the western portion of the state and the USFS only provided one set of data for these tree types.

Pacific Southwest Western Oak Group	1.96	Y
Rocky Mountain, North Douglas-fir Group	0.27	Y
Rocky Mountain, North Fir/Spruce/Mountain Hemlock Group	0.40	Y
Rocky Mountain, North Lodgepole Pine Group	0.68	Y
Rocky Mountain, North Ponderosa Pine Group	0.37	Y
Rocky Mountain, South Aspen/Birch Group	0.82	N
Rocky Mountain, South Douglas-fir Group	0.40	Y
Rocky Mountain, South Fir/Spruce/Mountain Hemlock Group	0.77	Y
Rocky Mountain, South Lodgepole Pine Group	0.51	Y
Rocky Mountain, South Ponderosa Pine Group	0.56	Y
South Central Elm/Ash/Cottonwood Group	2.09	N
South Central Loblolly/Shortleaf Pine Group	2.98	Y
South Central Oak/Gum/Cypress Group	2.48	N
South Central Oak/Hickory Group	2.93	N
South Central Oak/Pine Group	2.80	N
Southeast Loblolly/Shortleaf Pine Group	2.86	Y
Southeast Longleaf/Slash Pine Group	2.53	Y
Southeast Oak/Gum/Cypress Group	2.93	N
Southeast Oak/Hickory Group	2.69	N
Southeast Oak/Pine Group	2.48	N

For grassland/shrubland vegetation types, we apply an annual carbon sequestration rate of 1.19 Mg C per hectare per year, following Fargione et al. (2018). For peatland ecosystems (areas with histosol soils) (Fargione et al. 2018), the analysis uses an annual carbon sequestration rate, adjusted for methane emissions, that varies by region from 4.52 to 8.20 metric tons carbon dioxide equivalent annually (in carbon terms, this is equivalent to 0.95 metric tons to 2.24 Mg C per hectare per year), see Table A7. There were very few peatland soils in the analysis.

Table A7: Annual carbon dioxide equivalent sequestration values for peatlands by region, CO_2e/ha/year. Source: Fargione et al. 2018.

Type of peatland	States	Total flux Ce/Ha/Year	Total flux CO_2e/ha/year
Warm Temperate	AL, AZ, AK, CA, DE, GA, IL, IN, KS, KY, LA, MD, MS, MO, NJ, OK, TN, TX	2.24	8.20
Cool Temperate	CO, CT, ID, IA, ME, MA, MI, MN, MT, NE, NV, NH, NM, NY, ND, OH, OR, PA, RI, SD, UT, VT, WI, WY	0.95	3.47
Va, NC, SC	VA, NC, SC	1.49	5.46
Tropical Moist	FL	1.23	4.52

Biodiversity prioritization strategy

Under the biodiversity prioritization strategy, this paper prioritizes the restoration of cropland areas that could be restored to an ecosystem that is currently threatened. As in the carbon analysis, the restoration potential of cropland areas is based on the historical ecosystem that could exist where feed crops or forage are now grown. To identify at-risk ecosystems, the analysis relies on Comer et al. (2022) who classified the at-risk status of all terrestrial ecosystems in North America using the International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE) system. For each of the 655 vegetation-based NatureServe ecosystems in North America, Comer et al. categorized the ecosystem as collapsed, critically endangered, endangered, vulnerable, near threatened, least concern, data deficient, or not evaluated. Ecosystems that are critically endangered, endangered, or vulnerable were classified by Comer et al. as threatened ecosystems.

This analysis quantifies the extent to which areas that have been converted to feed crop and forage cropland could be restored to these currently threatened ecosystems. As noted by Comer et al. (2022), "One can see concentrations of [critically endangered] ecosystems where historical patterns of land conversion for cropland agriculture have been concentrated in recent centuries. Temperate grasslands and savannas, especially where relatively humid climates supported tallgrass prairies and oak savanna, or the California Central Valley, as well as fertile bottomlands like the lower Mississippi River valley, encompass many of these types. [Endangered] ecosystems historically extended over large expanses of converted or degraded forests, wetlands, and grasslands from the Atlantic Coastal Plain and adjacent Appalachian Mountains, the Midwest, Canadian Prairies, Southern California coast, and Central Valley of Mexico"

To evaluate the biodiversity benefits of restoring historical ecosystems where on feed and forage cropland, we take the following steps:

1. **Quantify the acreage of restoration in each historical ecosystem type in each crop type (feed crop, alfalfa, other hay).** The analysis overlaps the feed crop, alfalfa, and other hay crop spatial layers with geospatial data layers developed by Comer et al. (2022) of historical ecosystems (which are based on Landfire BPS 2016 Remap data).[45]

2. **Match threatened status to each historical ecosystem type.** Using the findings from Comer et al., each ecosystem type is classified as threatened (critically endangered, endangered, or vulnerable) or not threatened. The analysis overlays each crop data layer with GIS data on historical ecosystems developed by Comer et al. for their analysis of threatened and endangered ecosystems in North America.[46] That data is also based on Landfire 2016 BPS Remap data. For example, NatureServe Ecological systems are: "Western Great Plains Tallgrass Prairie" or "Western Great Plains Dry Bur Oak Forest and Woodland."

3. **Group ecosystems by region and summary vegetation type.** Data by state is summarized into regions, as presented in Figure 8.

4. **Quantify the acreage by threatened status and vegetation type that can be restored in each crop type and each region.** The analysis prioritizes the restoration of ecosystems that are currently threatened, up to the acreage that can be restored due to land use efficiencies of a 50 percent dietary shift to alternative proteins. For feed crops, the acreage of critically endangered ecosystems far exceeded the acreage that could be restored. To ensure that all threatened ecosystems would be restored, the analysis allocated the acreage of restored ecosystems proportionately across all threatened ecosystems (so if an ecosystem represented 5 percent of the acreage of all threatened ecosystems, then 5 percent of restored feed crop acreage would be in that ecosystem). For alfalfa hay and other hay, there were more acres available to restore than there were acres in threatened ecosystems. For these crop types (and for cropland pasture and haylage), we assumed restoration of all threatened acres, and then proportionately allocated the remaining restoration across all other ecosystem types based on the acreage that could be restored in the non-threatened ecosystems.

[45] The analysis uses the data from Comer et al. (2022) as the Landfire BPS data did not match exactly with their classifications (some categories were more aggregated in BPS and some were less aggregated). See https://transfer.natureserve.org/download/Longterm/Ecosystems_NA_RLE/Raster%20Maps/

[46] This 2022 assessment of at-risk status of ecosystems is based on the International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE), which is an emerging global standard for ecosystem risk assessment that integrates data and knowledge to document the relative risk status of ecosystem types (Comer et al. 2022).

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