Decarbonization of Nitrogen Fertilizers, from Production to Runoff: A Policy Memo

Luis Delgado[1,4], Mason Klemm[2,4], Matias Milia[3,4,6], Alyssa Rudelis[4], Emilie Sinkler[4,5]

[1]Pennsylvania State University, Department of Mechanical Engineering, University Park, PA
[2]Rice University, Department of Physics and Astronomy, Houston, TX
[3]University of Notre Dame, Department of Anthropology, Notre Dame, IN
[4]The National Academies of Sciences, Engineering, and Medicine, Christine Mirzayan Science & Technology Policy Fellowship 2024, Washington, DC
[5]University of Alaska Fairbanks, Department of Geosciences, Fairbanks, AK
[6]Open Environmental Data Project, New Orleans, LA
All authors contributed equally.
https://doi.org/10.38126/JSPG250106
Corresponding author: ldelga94@gmail.com
Keywords: fertilizer; decarbonization; food security; agriculture; climate change; regenerative; sequestration

Executive Summary: Decarbonization of agriculture is critical to reshaping the US economy as climate-resilient and less carbon-intensive. Decarbonizing nitrogen fertilizers specifically is increasingly important for the US to achieve its climate targets while feeding a growing population in a changing climate, as around 5% of global greenhouse gas emissions result from nitrogen fertilizers alone. Carbon dioxide equivalent emissions from fertilizer come from non-renewable energy use, chemical processes, transportation, and on-farm applications. These emissions typically take the form of carbon dioxide or nitrous oxide, potent greenhouse gasses. To reduce emissions from nitrogen fertilizers, the United States Department of Agriculture (USDA), Environmental Protection Agency (EPA), and Department of Energy (DOE) should 1) create federal regulations for nitrogen fertilizer use, 2) provide financial incentives for farmers transitioning to less-intensive nitrogen fertilizer use, and 3) create a research grant solicitation focused on regional methods for reducing nitrogen fertilizer use and the creation of green hydrogen.

I. Introduction: The problem

The Biden Administration (The White House 2023) and twenty-four states, plus the District of Columbia, have set ambitious targets for decarbonization (i.e., the reduction of greenhouse gasses emitted into the atmosphere), including some net-zero pledges where emissions are counterbalanced by greenhouse gasses (GHGs) eliminated from the atmosphere (Center for Climate and Energy Solutions 2022). Nitrogen fertilizer production and use account for 1-3% of annual United States (US) GHG emissions, more than the cement or steel industries. Thus, decarbonization of the fertilizer sector is critical to meeting climate goals (EPA 2024; Menegat, Ledo, and Tirado 2022). Climate change is disrupting agriculture and food systems in the US and is projected to decrease the availability and affordability of nutritious food (Bolster et al. 2023). Agriculture is both a sector responsible for climate mitigation and a sector that must adapt to the effects of climate change. Adaptation implications in agriculture pose a concern since 14.7% of US households already experience low or very low food security (Rabbitt et al. 2023).

In the current US agricultural system, nitrogen fertilizers are critical to meet increasing food demand (Beltran-Peña, Rosa, and D'Odorico 2020). However, relying on fossil fuel-based nitrogen fertilizers to sustain crop yield has downsides beyond GHG emissions. First, the industry is susceptible to price shocks caused by geopolitics and/or supply chain issues (Rosa and Gabrielli 2023; Kee, Cardell, and Abrehe Zereyesus 2023; Zereyesus et al. 2023). Second, it leads to loss of soil biodiversity and nutrient imbalances, which can lower both crop yields and nutritional values (NASEM et al. 2019; FAO 2015). Lastly, the vast amount of nitrogen fertilizers used to grow crops have altered biogeochemical flows, leading to downstream ecosystem impacts such as the loss of plant diversity and excessive algal blooms (Richardson et al. 2023; de Vries, 2021).

Given the central role of nitrogen fertilizers in the agricultural industry and increasing interest in reducing fertilizer-related emissions (NASEM et al. 2019), it is crucial to understand the landscape of decarbonization efforts around fertilizer production and use. Through informed regulations and incentives, policymakers can reduce the use of nitrogen fertilizer, lessen the GHG intensity of nitrogen fertilizer production and use, and improve agriculture's ability to sequester carbon.

II. Current status

In this memo, we focus on policies that apply to nitrogen fertilizer creation, transportation, and use. We discuss the range of US agencies and legislation regulating, incentivizing, and overseeing emissions throughout the synthetic fertilizer lifecycle. Additionally, we consider the perspectives of stakeholders resistant to new practices within agriculture, as their cooperation is essential to decarbonization efforts.

i. Fertilizer creation

In the US, fertilizer sourcing and manufacturing are regulated through the Environmental Protection Agency (EPA), which sets pollution standards at the factory level via the Clean Air and Clean Water Acts (EPA 1986). Specific regulations relating to fertilizer production include mandatory GHG emissions reporting, standardized GHG emissions calculations, and monitoring and quality control requirements, like continuous monitoring of feedstock consumption (EPA 2018).

New technologies can reduce emissions from nitrogen fertilizer production. Two end-member methods are used to produce nitrogen fertilizers: traditional (Haber-Bosch) and green. Traditional methods isolate hydrogen from fossil fuels (most commonly natural gas), which is then combined with nitrogen from the air at high temperature and pressure to synthesize the key component in nitrogen fertilizer, ammonia (NH_3). This traditional ammonia production releases carbon dioxide during the creation of hydrogen, from the energy needed to heat and pressurize the system for combining nitrogen and hydrogen, and from indirect methane emissions from natural gas extraction. Green production, on the other hand, swaps out fossil fuel inputs for water, synthesizing hydrogen via electrolysis, and only uses renewable energy. These qualities of green production result in up to a 90% reduction in carbon dioxide emissions per unit of ammonia produced (Liu et al., 2020; Panchenko et al., 2023).

The Department of Energy (DOE) aims to make green hydrogen produced from water cost-competitive by 2030, and a tax credit has been included in the IRA to support this goal[1]. Though the DOE is interested in green hydrogen for energy purposes, significantly reducing its cost could also spur advances in green ammonia production.

ii. Fertilizer transport

Although transportation accounts for a large portion of GHG emissions across sectors, only 2.6% of synthetic nitrogen fertilizer lifecycle emissions are from transportation–often considered negligible (Wood and Cowie 2004; Menegat, Ledo, and Tirado 2022). Moreover, increasingly stringent vehicle emissions standards mandate reductions of 29% during the next decade (EPA 2024).

iii. Fertilizer application

One-size-fits-all regulations on fertilizers used in croplands are often considered ineffective, because farming methods vary widely and the regulatory framework for managing nitrogen intensity at the farm level is not robust (Ribaudo et al. 2011). However, other governing bodies like the EU have implemented fertilizer reduction requirements, showing that it is not impossible to regulate in this space.

---

[1]For more info on hydrogen production by electrolysis and its development pathway see this explainer (EERE 2024). For the current state of green hydrogen, see Schelling (2023).

In the US, crop agriculture is considered a diffuse source of pollutants, so the EPA does not regulate on-farm fertilizer use (EPA 2018). Most existing regulations work to reduce toxic compounds in fertilizer formulations as opposed to limiting later emissions potential. In place of regulations, the EPA has voluntary programs for nutrient pollution reduction, with low uptake (EPA 2013).

The US has legislation in place to promote certain fertilizer usage through incentives. To make farming more resilient, for example, the Inflation Reduction Act (IRA) of 2022 authorized several billion dollars to encourage farmers to adopt science-based practices to store carbon in the soil and increase its resilience to floods and droughts, like rotating crops and planting perennial and cover crops (Union of Concerned Scientists 2017). Moreover, the act allocates $300 million to quantify the effects and feasibility of carbon sequestration in farmland.

Numerous conservation programs, including the USDA's Environmental Quality Incentives Program, Conservation Stewardship Program, and Soil Health Initiative, provide financial incentives for farmers to adopt conservation practices that reduce emissions such as precision application of fertilizer or alternative fertilizers that minimize nutrient loss (GAO 2014; 2023a; IEA 2021).

US incentives currently favor carbon credits and sequestration for agricultural emissions reductions. The only compulsory carbon markets in the US exist at the state level and operate within a cap-and-trade system like those in California and Washington. Further, compulsory markets like the Regional Greenhouse Gas Initiative do not apply directly to agriculture, but instead are applied to the power sector (RGGI 2024). All other carbon markets in the United States are voluntary.

iv. Resistance to change

In order to reduce emissions on farms, farmers and other stakeholders must be engaged and their viewpoints must be considered.

Some farmers are hesitant to switch from synthetic fertilizer use to alternatives, citing costs when describing their experiences: "Right now the bottom line is money…You can't put money into something and not get something back." (Eash 2021) and "If [cover cropping] is an imperative, then somebody is going to have to pay for it" (McFetridge 2023). Given this sentiment, it is not surprising that only 3% of farmers participate in carbon markets, despite incentives (USDA 2023). Farmers tend to act in ways to maximize short-term profit, whereas efforts to decarbonize farms often represent a more long-term cost-saving strategy (Boardman, Foster, and Dearing 1990).

However, the economic reality is not as bleak as some farmers assume. Profits can be higher on farms using a range of regenerative agriculture methods (i.e., more than just cover-cropping) versus conventional methods (Project Drawdown 2024). However, the transition period between conventional and regenerative practices can cause temporary revenue loss (Doug Petry et al. 2023).

To combat this trade-off between long- versus short-term benefits, in 2023, the USDA spent $44 million in payments to farmers to plant cover crops through the Natural Resources Conservation Service. Even so, it remains more profitable– in the short term– to grow crops to sell rather than to grow subsidized cover crops on that same land, despite long-term soil health benefits and lower emissions.

The USDA also encourages farmers to reduce emissions through the dissemination of robust information about future climate conditions (GAO 2014; 2023a). However, while this information helps farmers understand the importance of decarbonization, it does little to assuage concerns about bottom lines.

Given this landscape of weak regulation and a distaste toward decarbonization at the farm level, it is critical for policymakers to bolster current incentives to reduce and offset fertilizer use.

III. Policy options

i. Option 1: Make no changes

A number of programs and incentive structures exist to decarbonize the production and use of fertilizers, as described above. Maintenance of the status quo will certainly contribute to a partial and short-term decarbonization of fertilizers. However, it will be insufficient to achieve the US goal of net zero emissions by 2050, especially with the expected growth in population and food demand.

Advantages

- Politically low-cost to maintain the status quo.
- Fiscal advantages in the short-term (no increase to funding).
- No structural reorganization required.

Disadvantages

- Insufficient to meet net-zero emissions by 2050.
- Lack of preventative action can lead to large fiscal and environmental costs in the future.
- Static funding and policies restrict both innovation and flexible capacity-building toward climate resilience (limited job creation).

ii. Option 2: Industrial decarbonization

Industrial decarbonization primarily consists of decarbonizing nitrogen fertilizer production through the use of green ammonia produced without fossil fuels.

Currently, 80% of ammonia worldwide is used in agriculture, making the agriculture industry a powerful player in the chemical synthesis market (Afif et al. 2016). While still a nascent technology (used to create less than 1% of global ammonia), the US has committed to rapidly increasing green production in the coming decades (DOE 2021). As agriculture becomes greener, its purchasing power in the hydrogen market could incentivize hydrogen decarbonization across sectors.

Beyond incentives for green ammonia production, increased enforcement of and increasingly stringent emissions requirements in the Clean Air Act (CAA) can be leveraged to better regulate the fertilizer industry or retailers (Kanter et al. 2020; Ribaudo et al. 2011). Currently, most farms do not fall within the CAA's legislative definition of "major" pollutant sources (emitting 10 or more tons per year of one air pollutant or a combined 25 tons of multiple air pollutants) and so are not beholden to the CAA's requirements to meet emission standards set by the EPA (1970). Thus, it is critical to crack down on nitrogen fertilizer emissions before the fertilizers reach the farm, while the EPA still has existing regulatory authority from the CAA. One strategy to increase enforcement is underway at the EPA through Next Generation Compliance, powered by remote monitoring and data (OECA EPA 2014).

Advantages

- Reduces US GHG emissions by ~0.6% if all nitrogen fertilizers are produced using green ammonia[2].
- No additional cost or time lost to farmer education, either at the expense of government or farmers: Change happens off-farm, business as usual on-farms.
- Supports domestic production, reducing exposure to global supply and price shocks.

Disadvantages

- Several forms of nitrogen fertilizers are dangerous to transport and use.
- Scaling barriers: Startup costs; Large green energy needs; Competition from other sectors using ammonia to decarbonize (e.g. shipping industry).
- Doesn't address soil health declines.
- Continued downstream impacts (e.g. particulate pollution, algae blooms).
- Only addresses ⅓ of GHG emissions from fertilizers, with the remainder being produced during use (Menegat, Ledo, and Tirado 2022).
- Industrial pollution (e.g. excess salts and accidental ammonia leaks can endanger the health of local communities and environments) (Jones 2022).

iii. Option 3: Incentivize transformational decarbonization

Regenerative agriculture practices like planting cover and perennial crops, rotating crops, using natural fertilizers like manure and compost, and reducing tillage can all decrease reliance on carbon-intensive synthetic fertilizers, and may also reduce nitrous oxide emissions on farms (e.g., Omonode et al. 2011, Newell Price et al. 2011). However, the specific effects on fertilizer needs and other important metrics, like yield, can vary depending on the exact method (e.g. the variety of

[2] Ammonia for fertilizers emits ~40 Mt CO2 per year, with US emissions ~6300 Mt CO2 per year (EPA 2024; Menegat, Ledo, and Tirado 2022).

cover crop) and the specific characteristics of the farm (e.g., the soil type)(Deines et al. 2023).

Enhanced efficiency fertilizer application, a precision agriculture practice, also shows high emissions-mitigation potential. Implemented via remote sensing platforms, in-ground sensing, targeted spray systems, or machine learning-assisted automation, precision agriculture reduces fertilizer use, increases profits after the initial transition period, and boosts environmental benefits.
Combining regenerative and precision agriculture offers a promising pathway for transformational change. Policy can uphold a combination of these methods toward decarbonization. Moreover, reduced fertilizer use can provide benefits for both farm profits and the environment.

Advantages

- Potential environmental co-benefits: Sequesters carbon; improves soil health and farms' resilience to climate change; better for human and environmental health.
- Increases financial health at farm-level by increasing profits per yield after 3-5 years (Doug Petry et al. 2023).
- Investment in new low-carbon intensive technologies opens opportunities for training of a highly-skilled and well-paid workforce, with virtuous effects throughout the supply chain and the economy (UNFCC 2016, 13).

Disadvantages

- Major shift in practices: requires education and transition funding.
- Multi-sector collaboration: requires multi-stakeholder coordination to develop adoption of a more circular fertilizer cycle.
- Existing lock-ins: established business models, infrastructures, investments, and stakeholders may make it difficult to transition away from current status-quo.

IV. Policy recommendations

The ultimate decarbonization solution for nitrogen fertilizer is to push for major changes: optimizing its use and eventually phasing it out. We suggest that policymakers emphasize *Option 3: Incentivize transformational decarbonization.* Because farmers often act in the interest of short-term profit due to the risk inherent in the industry, incentives and regulations should codify short-term rewards for farmers who make decisions with positive long-term impacts.

To do this with concrete steps, we recommend the below policy/policies be implemented individually or through collaboration between the USDA, EPA, and DOE:

1. The EPA should create federal guidelines for fertilizer use to avoid overconsumption, including establishing USDA monitoring standards building from existing international and domestic practices (OECA EPA 2014, EC 2020). The European Commission set a goal in 2020 to reduce fertilizer-related emissions 50% by 2030, and have concluded they can achieve this with a combination of nutrient recycling from manure, sewage, and bio-waste and increased enforcement of existing clean air and water legislation (equivalent to the Clean Air and Clean Water Acts in the US) across the fertilizer lifespan (European Commission. Joint Research Centre., 2023). In the US, stricter overconsumption standards should be set by the EPA within its existing authority in the Clean Air and Clean Water Acts. A long-term solution would be to expand the definition of "point sources" that are already regulated under these acts to include farms. Fertilizer use monitoring responsibility should be given to the USDA as the existing on-the-ground agriculture expert.
2. Create start-up funding and insurance programs within the USDA to encourage farms to reduce synthetic fertilizer use through either natural fertilizers or other regenerative agriculture techniques. Programs should target farms that cannot take the risk without help (esp. during the first 3-5 years of transition). This can take the form of grants or insurance as a lever to lower premiums for regenerative agriculture-adopting farms. The USDA already subsidizes farm insurance, so no revolutionary changes in regulating

authority are needed for implementation (GAO, 2023b).

3. Create a collaborative research agenda across the DOE and USDA to determine best practices to regionally reduce reliance on synthetic fertilizer use, considering different climates, geography, and soil types across the country. The USDA should partner with DOE to encourage continued research in green hydrogen, which will benefit both the greener production of ammonia and greener fuels for transportation. Utilize existing sustainable agriculture research funds and free up additional funds to determine how effectively crop rotation, cover crops, no-till, and precision agriculture reduce the need for synthetic fertilizers without harming yield. Increased funding at the USDA specifically could come from reduced insurance subsidies for newly converted land (i.e. grasslands converted to croplands, which increases emissions) (NSAC, 2023). This funding should also support the creation of a coordinator position within the USDA Research, Education, and Economics Office to ensure that new studies are filling gaps in the public and private research, relevant research at the DOE is being synthesized into agricultural best practices, and that results are being communicated to farmers as regional best practices.

We recommend a proactive approach by the DOE, USDA, and EPA to leverage their preexisting regulatory authority and interagency collaboration to help meet the bold emissions aims of the White House. Short-term, this could take the form of a shift in insurance incentives for farmers and explicit standards for fertilizer overconsumption. Mid- to long-term, targeted research funding on fertilizer best practices and expanding applicable pollution regulations can ensure responsible decarbonization of fertilizer production and use in the US. Any successful implementation of these recommendations must include early and frequent consultation with agricultural communities across the country.

References

Afif, Ahmed, Nikdalila Radenahmad, Quentin Cheok, Shahriar Shams, Jung H. Kim, and Abul K. Azad. 2016. "Ammonia-Fed Fuel Cells: A Comprehensive Review." *Renewable and Sustainable Energy Reviews* 60 (July):822–35. https://doi.org/10.1016/j.rser.2016.01.120.

Beltran-Peña, Areidy, Lorenzo Rosa, and Paolo D'Odorico. 2020. "Global Food Self-Sufficiency in the 21st Century under Sustainable Intensification of Agriculture." *Environmental Research Letters* 15 (9): 095004. https://doi.org/10.1088/1748-9326/ab9388.

Boardman, John, Ian DL Foster, and John A Dearing. 1990. *Soil Erosion on Agricultural Land*.

Bolster, C.H., R. Mitchell, A. Kitts, A. Campbell, M. Cosh, T.L. Farrigan, A.J. Franzluebbers, et al. 2023. "Chapter 11 : Agriculture, Food Systems, and Rural Communities. Fifth National Climate Assessment." U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH11.

Center for Climate and Energy Solutions. 2022. "State Climate Policy Maps." *Center for Climate and Energy Solutions* (blog). 2022. https://www.c2es.org/content/state-climate-policy/.

Deines, Jillian M., Kaiyu Guan, Bruno Lopez, Qu Zhou, Cambria S. White, Sheng Wang, and David B. Lobell. 2023. "Recent Cover Crop Adoption Is Associated with Small Maize and Soybean Yield Losses in the United States." *Global Change Biology* 29 (3): 794–807. https://doi.org/10.1111/gcb.16489.

Doug Petry, Stefania Avanzini, Alain Vidal, Francesco Bellino, Jack Bugas, Helena Conant, Sonya Hoo, Shalini Unnikrishnan, and Matt Westerlund. 2023. "Cultivating Farmer Prosperity: Investing in Regenerative Agriculture." Boston Consulting Group, One Planet Business for biodiversity, World Business Council for Sustainable Development. https://www.wbcsd.org/contentwbc/download/16321/233420/1.

DOE. 2021. "Hydrogen Shot: An Introduction. Department of Energy - Hydrogen and Fuel Cell Technologies Office." Department of Energy - Hydrogen and Fuel Cell Technologies Office. 2021. https://www.energy.gov/eere/fuelcells/articles/hydrogen-shot-introduction

Eash, Lisa. 2021. "The Bottom Line: Are Incentives Enough to Offset the Costs of 'Carbon-Smart' Farming Practices? – Sustainability." 2021. https://sustainability.colostate.edu/humannature/incentives-enough-offset-costs-farming-practices/.

EC. 2020. "Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System." European Commission. https://food.ec.europa.eu/document/download/472acca8-7f7b-4171-98b0-ed76720d68d3_en?filename=f2f_action-plan_2020_strategy-info_en.pdf.

EERE. 2024. "Hydrogen Production: Electrolysis." Government. Energy.Gov. 2024. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

EC Joint Research Centre. 2023. "Knowledge for Integrated Nutrient Management Action Plan (INMAP)." JRC129059. LU: Publications Office of the European Union. https://data.europa.eu/doi/10.2760/692320.

EPA. 1970. *Clean Air Act. Federal Regulations.* https://www.epa.gov/laws-regulations/summary-clean-air-act.

EPA. 1986. *Fertilizer Manufacturing Point Source Category*. *Code of Federal Regulations*. https://www.ecfr.gov/current/title-40/part-418.

EPA. 2013. "EPA's Ongoing Efforts to Reduce Nutrient Pollution." Overviews and Factsheets. February 21, 2013. https://www.epa.gov/nutrientpollution/epas-ongoing-efforts-reduce-nutrient-pollution.

EPA. 2018. *Ammonia Manufacturing*. *Code of Federal Regulations*. https://www.ecfr.gov/current/title-40/part-98/subpart-G.

EPA. 2024. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 U.S." 430R-24004. Environmental Protection Agency, EPA. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

FAO. 2015. "Status of the World's Soil Resources: Main Report."

GAO. 2014. "Climate Change: USDA's Ongoing Efforts Can Be Enhanced with Better Metrics and More Relevant Information for Farmers" GAO-14-755. United States Government Accountability Office. https://www.gao.gov/products/gao-14-755.

GAO. 2023a. "Climate Change: Options to Enhance the Resilience of Agricultural Producers and Reduce Federal Fiscal Exposure." United States Government Accountability Office. https://www.gao.gov/products/gao-23-104557.

GAO. 2023b. "Crop Insurance: Update on Opportunities to Reduce Program Costs" GAO-24-106086. United States Government Accountability Office. https://www.gao.gov/products/gao-24-106086

IEA. 2021. "Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production." Paris: International Energy Agency. https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

Jones, Nicola. 2022. "From Fertilizer to Fuel: Can 'Green' Ammonia Be a Climate Fix?" *Yale E360*, January 20, 2022. https://e360.yale.edu/features/from-fertilizer-to-fuel-can-green-ammonia-be-a-climate-fix.

Kanter, David R., Fabio Bartolini, Susanna Kugelberg, Adrian Leip, Oene Oenema, and Aimable Uwizeye. 2020. "Nitrogen Pollution Policy beyond the Farm." *Nature Food* 1 (1): 27–32. https://doi.org/10.1038/s43016-019-0001-5.

Kee, Jennifer, Lila Cardell, and Yacob Abrehe Zereyesus. 2023. "Global Fertilizer Market Challenged by Russia's Invasion of Ukraine." *USDA ERS* (blog). 2023. https://www.ers.usda.gov/amber-waves/2023/september/global-fertilizer-market-challenged-by-russia-s-invasion-of-ukraine/.

Liu, Xinyu, Amgad Elgowainy, and Michael Wang. 2020. "Life Cycle Energy Use and Greenhouse Gas Emissions of Ammonia Production from Renewable Resources and Industrial By-Products." *Green Chemistry* 22 (17): 5751–61. https://doi.org/10.1039/D0GC02301A.

McFetridge, Scott. 2023. "Cover Crops Help the Climate and Environment, but Most Farmers Say No. Many Fear Losing Money." *AP News*, November 2, 2023, sec. Climate. https://apnews.com/article/cover-crops-farming-carbon-nitrogen-1648449f90b7072be50b95a21d733618.

Menegat, Stefano, Alicia Ledo, and Reyes Tirado. 2022. "Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture." *Scientific Reports* 12 (1): 14490. https://doi.org/10.1038/s41598-022-18773-w.

NASEM, Committee on Science Breakthroughs 2030: A Strategy for Food and Agricultural Research, Board on Agriculture and Natural Resources, Board on Atmospheric Sciences and Climate, Board on Life Sciences, Water Science and Technology Board, Division on Earth and Life Studies, et al. 2019. "5. Soils." In *Science Breakthroughs to Advance Food and Agricultural Research by 2030*, 25059. Washington, D.C.: National Academies Press. https://doi.org/10.17226/25059.

Newell Price, JP, D Harris, M Taylor, JR Williams, SG Anthony, D Duethmann, RD Gooday, et al. 2011. "An Inventory of Mitigation Methods and Guide to Their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture." User Guide. https://repository.rothamsted.ac.uk/download/942687eab7ec4b83751c7e241d62f0fa8472d72adcd25a149bb891b7c30d55d0/1595300/MitigationMethods-UserGuideDecember2011FINAL.pdf.

NSAC. 2023. "NSAC's 2023 Farm Bill Platform." Washington, DC: National Sustainable Agriculture Coalition. https://sustainableagriculture.net/wp-content/uploads/2022/11/2023-Farm-Bill-Platform.pdf.

Panchenko, V. A., Yu. V. Daus, A. A. Kovalev, I. V. Yudaev, and Yu. V. Litti. 2023. "Prospects for the Production of Green Hydrogen: Review of Countries with High Potential." *International Journal of Hydrogen Energy* 48 (12): 4551–71. https://doi.org/10.1016/j.ijhydene.2022.10.084.

OECA EPA. 2014. "Next Generation Compliance." Overviews and Factsheets. September 25, 2014. https://www.epa.gov/compliance/next-generation-compliance.

Omonode, Rex A., Doug R. Smith, Anita Gál, and Tony J. Vyn. 2011. "Soil Nitrous Oxide Emissions in Corn Following Three Decades of Tillage and Rotation Treatments." *Soil Science Society of America Journal* 75 (1): 152–63. https://doi.org/10.2136/sssaj2009.0147.

Project Drawdown. 2024. "Regenerative Annual Cropping." 2024. https://drawdown.org/solutions/regenerative-annual-cropping.

Rabbitt, Matthew P., Laura J. Hales, Michael P. Burke, and Alisha Coleman-Jensen. 2023. "Household Food Security in the United States in 2022." https://ageconsearch.umn.edu/record/338945/.

Regional Greenhouse Gas Initiative (RGGI). 2024. "Program Review." https://www.rggi.org/

Ribaudo, Marc, Jorge Delgado, LeRoy Hansen, Michael Livingston, Roberto Mosheim, and James Williamson. 2011. "Nitrogen in Agricultural Systems: Implications for Conservation Policy." Economic Research Report No. (ERR-127). USDA. http://www.ers.usda.gov/publications/pub-details/?pubid=44919.

Richardson, Katherine, Will Steffen, Wolfgang Lucht, Jørgen Bendtsen, Sarah E. Cornell, Jonathan F. Donges, Markus Drüke, et al. 2023. "Earth beyond Six of Nine Planetary Boundaries." *Science Advances* 9 (37): eadh2458. https://doi.org/10.1126/sciadv.adh2458.

Rosa, Lorenzo, and Paolo Gabrielli. 2023. "Energy and Food Security Implications of Transitioning Synthetic Nitrogen Fertilizers to Net-Zero Emissions." *Environmental Research Letters* 18 (1): 014008. https://doi.org/10.1088/1748-9326/aca815.

Schelling, Kamala. 2023. "Green Hydrogen to Undercut Gray Sibling by End of Decade." *BloombergNEF* (blog). August 9, 2023. https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/.

The White House. 2023. "President Biden to Catalyze Global Climate Action through the Major Economies Forum on Energy and Climate." Fact Sheet. https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/20/fact-sheet-president-biden-to-catalyze-global-climate-action-through-the-major-economies-forum-on-energy-and-climate/.

Union of Concerned Scientists. 2017. "Turning Soils into Sponges: How Farmers Can Fight Floods and Droughts." Union of Concerned Scientists. https://www.jstor.org/stable/resrep17252.

UNFCC. 2016. "Just Transition of the Workforce, and the Creation of Decent Work and Quality Jobs." United Nations. https://unfccc.int/sites/default/files/resource/Just%20transition.pdf.

USDA. 2023. "A General Assessment of the Role of Agriculture and Forestry in U.S. Carbon Markets." https://www.usda.gov/sites/default/files/documents/USDA-General-Assessment-of-the-Role-of-Agriculture-and-Forestry-in-US-Carbon-Markets.pdf.

Vries, Wim de. 2021. "Impacts of Nitrogen Emissions on Ecosystems and Human Health: A Mini Review." *Current Opinion in Environmental Science & Health* 21 (June):100249. https://doi.org/10.1016/j.coesh.2021.100249.

Wood, S. W., and Annette Cowie. 2004. "A Review of Greenhouse Gas Emission Factors for Fertiliser Production." https://figshare.utas.edu.au/articles/report/A_review_of_greenhouse_gas_emission_factors_for_fertiliser_production/23197847/1/files/40893614.pdf.

Zereyesus, Yacob Abrehe, Lila Cardell, Constanza Valdes, Kayode Ajewole, Wendy Zeng, Jayson Beckman, Maros Ivanic, Reem N. Hashad, Jeremy Jelliffe, and Jennifer Kee. 2023. "International Food Security Assessment, 2022–32." GFA-33. Food Security Assessment Situation and Outlook. http://www.ers.usda.gov/publications/pub-details/?pubid=104707.

Luis Delgado is a Ph.D. Candidate in the Department of Mechanical Engineering at Pennsylvania State University. He received a B.S. in Mechanical Engineering from The University of Texas at El Paso and a M.S. in Civil Engineering with a minor in Public Policy from Pennsylvania State University.

Mason Klemm is a fifth-year Ph.D. candidate in the Department of Physics and Astronomy at Rice University. His research focuses on the interplay of exotic electronic, magnetic, and structural phenomena in crystalline

materials via a combination of neutron scattering and angle-resolved photoemission spectroscopy experiments.

Matias Milia is a Postdoctoral Research Assistant at the University of Notre Dame and a Research Fellow for the Open Environmental Data Project. He has a Ph.D. in Social Science Research from the Latin American Faculty of Social Sciences in Mexico. From translational lenses, he works on the overlap between digital technologies and environmental challenges.

Dr. Alyssa Rudelis earned her Ph.D. in atomic physics from the Massachusetts Institute of Technology in 2023. During her Ph.D., Alyssa developed a new hardware platform for quantum computing based on high-finesse optical cavities and neutral atom quantum bits. Alyssa has also advised Chair David Hochschild on energy policy at the California Energy Commission and was honored as a Mirzayan Science and Technology Policy Fellow at the National Academy of Sciences. Alyssa is now a AAAS Science and Technology Policy Fellow in the U.S. Congress.

Emilie Sinkler is a Ph.D. Candidate in Geophysics at the University of Alaska Fairbanks. She researches ice flow in Antarctica through borehole deformation in order to improve ice flow models, which can be used to date ice cores or predict future sea level rise.

Acknowledgments
We thank Robin Schoen, Director of the Board on Agriculture and Natural Resources at the National Academy of Sciences, and Alex Reich, Program Officer at Climate Crossroads, for their valuable comments and suggestions while framing this work. Their insights have significantly enhanced the quality of our work, and we are grateful for their contribution.

Disclaimer
The order in which the authors are listed is based on alphabetical order and does not represent the contribution of any individual author. All authors have contributed equally to this piece. Any views expressed in this article reflect those of the authors and should not be seen as official position statements by any of the affiliated institutions, departments or fellowship programs.