frontiers in Sustainable Food Systems

TYPE Policy and Practice Reviews
PUBLISHED 02 June 2026
DOI 10.3389/fsufs.2026.1771142

OPEN ACCESS

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RECEIVED 19 December 2025
REVISED 11 May 2026
ACCEPTED 14 May 2026
PUBLISHED 02 June 2026

CITATION
Wood SA, Loring PA, Machalaba C, Lovdal A, Gennet S, Collins B, Cardwell S, Keerthi S, Kazanski CE and Johnson K (2026) Improving agricultural production as a public health strategy in the United States: a framework for integrated policy.
Front. Sustain. Food Syst. 10:1771142.
doi: 10.3389/fsufs.2026.1771142

Improving agricultural production as a public health strategy in the United States: a framework for integrated policy

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Agri-food management in the U.S.—including crop and livestock practices—directly influences health outcomes through drinking water quality, air pollution, pesticide exposure, and pathogen transmission. The broader food system also shapes nutrition and dietary health. Certain management practices can mitigate environmental and human health impacts by reducing input use or preventing input losses to the environment. Despite these interconnections, policies and incentives remain fragmented across food, health, and environmental sectors. In this policy and practice review, we propose three strategies to scale conservation agriculture practices that benefit human health: (1) interagency collaboration to expand agricultural incentives that advance environmental and public health, (2) public procurement reforms that reward sustainable production, and (3) enhanced traceability linking farm practices to health and environmental outcomes. Cross- and multi-sector policy alignment can accelerate adoption of practices that improve health outcomes, strengthen environmental performance, and support agricultural sustainability.

KEYWORDS
agriculture, air quality, conservation, drinking water, public health, public policy

1 Introduction

Globally, agriculture accounts for a substantial share of land use, exerting profound effects on ecosystems and the benefits they provide to people (Ramankutty et al., 2018). The magnitude of the ecological consequences of human land use, including agriculture, has increased markedly in recent decades, especially with the advent of industrialized farm inputs (Ellis, 2021). The planet has now exceeded the sustainable operating space for two-thirds of its planetary boundaries (Richardson et al., 2023), in part due to agriculture. These impacts are particularly pronounced in major agricultural regions, like the United States Midwest, Central Europe, Northern China, Brazilian Cerrado, Argentinian Pampas, and more.

The United States (U.S.) exemplifies particularly high patterns of agricultural expansion and intensification, in part because of its large size and industrialization (Li et al., 2023). Row crops occupy 390 million acres and grazing lands 760 million, totaling over half of U.S. land area (Winters-Michaud et al., 2024). In 2024, the U.S. contributed around 10% of global agriculture, both by production and value (Food and Agriculture Organization of the United Nations, 2024). At this scale, agri-food management has a strong impact on groundwater contamination (Pennino et al., 2020), surface water contamination (Paudel and Crago, 2021), land conversion and habitat degradation (Wright and Wimberly, 2013; Wright et al., 2017; Olimb and Robinson, 2019; Lark et al., 2020), and degraded air quality (Domingo et al., 2021).

Beyond environmental impacts, there is long-standing, and growing, concern over the impacts of food and agriculture on human health in the U.S. The recent *Make America Healthy Again Commission* raised concerns over toxic exposures through food alongside potential opportunities to improve nutrition nationwide (Williams, 2025). These concerns over toxicity, diets, and health echo those that spurred the founding of the organic farming movement in the mid-20th century (Heckman, 2006). Unlike the largely grassroots origins of organic farming, current momentum around food and health also reflects increasing engagement from the public and private sectors. The medical sector – from health providers to the insurance industry – have begun to champion and fund health interventions through food as part of a growing Food is Medicine movement (Mozaffarian et al., 2022). While this movement has focused primarily on food consumption, there is also recognition of the importance of food production in contributing to human health outcomes (Rahman et al., 2024).

A growing body of evidence shows that agri-food management practices that aim to build or restore environmental resources can also mitigate and even improve human health outcomes. However, incentives for adopting these practices remain limited, in part because of lack of coordination and alignment across environmental, health, and agricultural sectors, though frameworks like One Health and Planetary Health emphasize the importance of links among these sectors. In this paper, we synthesized the existing literature on the link between agriculture, environment, and human health (Section 2). We then conducted a policy assessment (Section 3) to understand the interrelationships among agencies and programs governing agriculture, land, water, and human health in the U.S. We were then able to identify promising policy actions (Section 4) through which U.S. agencies and government could further support these programs, increasing efficiency and achieving multiple public benefits.

2 Agriculture as a determinant of health

A growing body of evidence demonstrates the links between food production, environmental conditions, and human health, including the potential for specific agricultural practices to mitigate adverse impacts (Table 1). Health effects occur across individual, community, and ecosystem scales and are driven by multiple, interacting pathways (Figure 1A). Here, we examine areas with strong evidence connecting agricultural land management to exposure to specific chemicals, pollutants, or disease vectors, alongside evidence from systematic reviews or meta-analyses of epidemiological studies linking these exposures to human health outcomes. We further assess where changes in land management may reduce exposure and, in turn, lower acute or chronic health risks. To review this literature, we began by reviewing seven high-level, often global reviews of the connection points between agriculture, environment and health (Wallinga, 2009; Neff et al., 2015; Frison and Clément, 2020; Yan et al., 2022; Ramkumar et al., 2024; Ridberg et al., 2025; Vos et al., 2025). We used this to identify key links that we wanted to explore further. We then conducted more targeted reviews for key topics by carrying out searches through Web of Science based on target outcomes (e.g., drinking water quality, nitrate and drinking water, etc.). We narrowed the list of papers to those published on agriculture in the United States. We reviewed papers that covered reviews, observational studies, and experimental studies.

2.1 Drinking water nitrate

A strong link between agriculture and human health in the U.S. is nitrate contamination in drinking water (Figure 1B), which is strongly

TABLE 1 Summary of health and environmental impacts of conservation agriculture practices.

Agricultural source	Health impact	Environmental impact	Conservation solution
Synthetic fertilizer Manure runoff	Nitrate-attributable disease	Groundwater and surface water pollution Biodiversity loss from excess nutrients	Cover crops (340) Nutrient management (590) Riparian buffers (390/391) Wetlands (656/657)
Ammonia from manure and fertilizer Crop burning Diesel exhaust	Particulate matter driven respiratory and cardiovascular disease	Air pollution – PM2.5	No-till (329) Residue management (345) Emission reduction (376) Combustion System Improvement (372)
High-density livestock Inappropriate use of antimicrobials Manure runoff Wildlife habitat removal	Infectious disease outbreaks and antimicrobial resistance	Biodiversity loss Pathogen spillover Soil and water contamination	Riparian buffers (390/391) Hedgerows (422) Pest management (595) Waste management (318)
Chemical pesticide use	Cancer, neurological disorders, endocrine disruptions from pesticide exposure	Soil and water contamination Biodiversity loss	Integrated pest management (595) Crop diversification (328) Constructed wetlands (656)

The number next to the conservation solution refers to the USDA Natural Resources Conservation Service Conservation Practice Standard code. The impact of these solutions will vary by context and should be appropriately tailored. Solutions can also have trade-offs for health, agriculture, or environment. Most health impacts are based on a mix of observational evidence and reviews; environmental impacts also include experimental evidence.

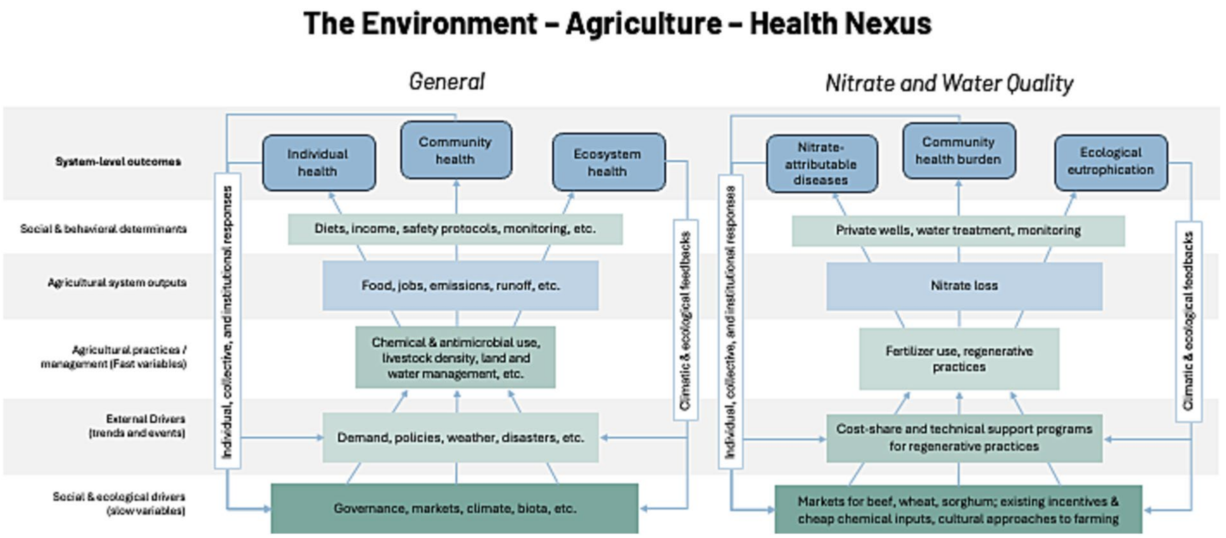

FIGURE 1
Conceptual framework linking agriculture, health, and environment. A general framework (Panel **A**) shows how social and ecological drivers and external drivers influence agricultural practices and how they contribute to human, community, and ecological health impacts. There are potential trade-offs and co-benefits for human, animal, and environmental health, demonstrating the importance of improved coordination across sectors, as is advocated for by the One Health perspective. This framework is applied to the example of drinking water quality in Panel **B**.

connected to land management (Pennino et al., 2020). Nitrogen runoff from synthetic fertilizers and manure is a major source of surface and groundwater pollution (Paudel and Crago, 2021; Kirk et al., 2024). Nitrate is a known precursor of N-nitroso compounds, a class of compounds classified as probable human carcinogens by the International Agency for Research on Cancer, following sufficient epidemiological evidence in animals and limited human evidence of carcinogenicity (IARC, 2010; Ward et al., 2018). In addition to cancer, nitrate ingestion is associated with other serious health outcomes, including methemoglobinemia in infants and birth defects (Ward et al., 2018), demonstrated through several cohort-level and population scale epidemiological and exposure assessment studies (McElroy et al., 2008; Jones et al., 2019; Temkin et al., 2019). Chambers et al. (2022) conducted a meta-analysis of six recent epidemiological studies and show a statistically significant increased risk of colon and colorectal cancer from nitrate in drinking water.

Drinking water is regulated under the Safe Drinking Water Act, which established limits for 88 contaminants. The U.S. Environmental Protection Agency (EPA) creates regulatory thresholds for drinking water contamination and devolves enforcement and monitoring to states, which can lead to variation in monitoring and enforcement of public supply wells that fall under municipal water management authorities. The EPA has a drinking water standard of 10 mg NO_3-N L^{-1} for nitrogen, which was established based on studies of when blue baby syndrome emerged. However, there is evidence that other health impacts, like colorectal cancer, thyroid disfunction, and neural tube defects, can emerge at lower concentrations of nitrate (Ward et al., 2018). Drinking water contamination disproportionately impacts poorer and non-white communities, highlighting important environmental justice concerns (Balazs et al., 2011; Schaider et al., 2019).

A U.S. Geological Survey report found that one-in-five samples from public wells contained contaminants that exceeded human health benchmarks for drinking water (Toccalino and Hopple, 2010). Private wells are not regulated by the EPA and are not consistently monitored. In agricultural regions, nitrate levels have been shown to exceed EPA safety thresholds in over 20% of private wells and 40% of public systems (Ward et al., 2018; Pennino et al., 2020). While it is possible to remove nitrates from drinking water, it is often cost prohibitive (Vedachalam et al., 2019). The most promising methods for improving drinking water come from reducing nitrogen application rates and reducing nitrate loss from agriculture into drinking water sources, thereby reducing total nitrogen concentration in waterways and ultimately, drinking water. Conservation practices such as cover cropping, no-till farming, and nutrient management can reduce nitrogen losses on farms by up to 50%; edge-of-field interventions—including riparian buffers, saturated buffers, bioreactors, and constructed wetlands—further limit nitrate loss and reduce the need for costly water treatment by reducing nitrate inputs into drinking water sources (Davidson, 2011).

2.2 Particulate matter and air quality

Air pollution from agriculture also poses a public health challenge. The human health impacts of air quality generally stem from fine particulate matter ($PM_{2.5}$), which is associated with a range of health outcomes and has no safe level of exposure. There is strong evidence linking and describing the mechanisms through which $PM_{2.5}$ exposure results in a cascade of health impacts (Feng et al., 2016). These impacts range from lung disease with strong associations with chronic diseases, examined through cohort- and population epidemiological studies, and further verified through meta-analyses such as increased risk of hospitalization from chronic obstructive pulmonary disease from short-term $PM_{2.5}$ exposure (Delavar et al., 2023), a 25% increased risk of lung cancer incidence per 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ (Ghazipura et al., 2019) and increased cardiovascular disease risk (Hayes et al., 2020). Further, it can exacerbate existing health impacts in vulnerable populations such as asthma patients and in children impacting neurological development.

U.S. agriculture is associated with up to 16,000 deaths annually from $PM_{2.5}$ exposure, which is approximately 20% of all U.S. $PM_{2.5}$-related deaths (Domingo et al., 2021). $PM_{2.5}$ is found through direct and indirect sources. Direct sources of $PM_{2.5}$ are dust from tillage, crop residue burning and dust from intensive livestock operations. $PM_{2.5}$ is also formed indirectly from emissions of ammonia (NH_3) and nitric oxides (NO_x). Ammonia emissions come primarily from livestock waste and fertilizer application (Burns et al., 2023), while NO_x comes primarily from fossil fuel combustion in farm equipment (Domingo et al., 2021), though there is evidence that fertilizers can also be a significant source of NO_x (Almaraz et al., 2018).

Fifty-seven percent of the 16,000 annual deaths from $PM_{2.5}$ in agriculture are attributed to crop production and 43% from livestock. Around 4,000 annual deaths are attributed to maize (corn) production alone, concentrated in the Upper Midwest Corn Belt and Chesapeake Bay regions (Hill et al., 2019). Since many crops also contribute to livestock feed, 80% of those deaths from crops are attributable to animal-based food systems, mainly from the creation of ammonia from manure and urine in livestock systems fed maize (Domingo et al., 2021). There is strong concentration in the greatest sources of damage, with the top 10% of most damaging counties responsible for 47% of total deaths. These are mainly located in California, Pennsylvania, North Carolina, and the Upper Midwest Corn Belt (Domingo et al., 2021).

Agricultural air pollution also highlights health and environmental justice concerns. Areas with the highest level of $PM_{2.5}$, due to high concentrations of animal feedlots, correlate with areas where populations have low health insurance coverage, lower educational attainment, and higher proportion Latino (Chamanara et al., 2025). Rural agricultural communities and farm workers are at higher risk of long-term exposure to low concentrations of NH_3, NO_x, and $PM_{2.5}$ and the associated health impacts, particularly those working in confined animal operations who have increased risk of acute exposure to high levels of these pollutants (Wyer et al., 2022). Children and the elderly living in agricultural communities are particularly sensitive, with several studies reporting an increased prevalence of asthma in children exposed to agricultural air pollution (Karr, 2012; Pavilonis et al., 2013; Holst et al., 2018).

The particulate matter-associated impact of red meat is twice greater than eggs, three-times greater than dairy, seven-times greater than poultry, and over ten-times more than nuts, seeds, and other plant foods (Domingo et al., 2021). Certain agri-food management practices—such as improved manure and fertilizer management, reduced tillage, and emission-reducing field operations—could cut agriculture-related $PM_{2.5}$ mortality by half if adopted on all U.S. farmland (Domingo et al., 2021).

2.3 Pesticides

Pesticide use in the U.S. is extensive and intensive. Atrazine application alone exceeds 70 million pounds annually, primarily for corn production (Jablonowski et al., 2011). Glyphosate use has increased more than 200-fold since the 1970s, and recent studies show that over 81% of the U.S. population aged six or older has detectable glyphosate exposure (Ospina et al., 2022). While the use of some highly toxic compounds, such as organophosphates, has declined due to regulation, swapping often occurs after individual chemicals are regulated, and overall pesticide application and intensity have continued to rise (Shattuck et al., 2023). Herbicides account for roughly half of all pesticide applications, with atrazine and glyphosate among the most widely used (Arabi et al., 2025). Glyphosate and atrazine are classified as "probably carcinogenic to humans" by the International Agency for Research on Cancer, though the EPA has concluded that glyphosate is not likely to be carcinogenic to humans (Benbrook, 2019). Benbrook (2019) found that the difference in the conclusion around glyphosate can be partially attributed to EPA's focus on exposure to the general population under legal, food crop use while IARC considered both typical dietary and higher occupational and elevated risk scenarios. Some foundational evidence around the safety of glyphosate has been retracted over ethical concerns in the publishing process (Kaurov and Oreskes, 2025).

Pesticides vary widely in chemical composition and mode of action (Shekhar et al., 2024), some of which are highly persistent and bioaccumulate in fatty tissues, causing neurological disorders and endocrine disruption (Zhou et al., 2025). For example, organophosphates and carbamates interfere with nervous system function and can cause acute poisoning and chronic respiratory and neurological issues (Shekhar et al., 2024). Pyrethroids disrupt electrical signaling in the nervous system and have been linked to immune and neurobehavioral effects (Shekhar et al., 2024). Health outcomes associated with exposure are diverse and can be severe. Chronic and acute exposures linked to a range of medical conditions have been studied through cohorts of long-term exposure (e.g., Eskenazi et al., 2023). Documented effects from case–control and cohort studies include memory and cognitive defects, psychiatric disorders, endocrine disruption (e.g., diabetes), cardiovascular and reproductive issues, cancers such as leukemia and non-Hodgkin lymphoma, and neurological disorders including Parkinson's disease (Pezzoli and Cereda, 2013; Stayner et al., 2017; Shekhar et al., 2024; Zhou et al., 2025). Emerging evidence also links pesticide exposure to epigenetic effects that may persist across generations (Arabi et al., 2025).

Humans can be exposed to pesticides through residues in food or drinking water, via airborne drift, or through skin contact during application (Shekhar et al., 2024). Importantly, many compounds persist in soil and water for decades, allowing them to enter groundwater and surface water systems long after application (Jablonowski et al., 2011; Maggi et al., 2023). Some pesticides are systemic—absorbed into plant tissues—meaning residues cannot be removed by washing foods (Shekhar et al., 2024).

Disparities in pesticide exposure can present environmental injustices. Farmworkers and occupational pesticide applicants have a higher risk of acute pesticide exposure, with farm families also at risk of low-dose chronic exposure from pesticide residues brought home (McCauley et al., 2001). Various studies document higher concentrations of pesticides in biomarkers of non-white compared to white demographic subgroups (Donley et al., 2022). Children in agricultural communities have an increased risk of pesticide exposure compared to children living in non-agricultural communities (Fenske et al., 2000) and associated adverse health effects such as asthma (Karr, 2012). Children of occupational pesticide applicators are also at higher risk of developing cancers such as lymphoma, likely due to their increased exposure at home (Flower et al., 2004).

Interactive effects between pesticides and other contaminants, such as nitrate, even at concentrations below current regulatory standards, can amplify health risks, including elevated rates of non-Hodgkin lymphoma and adverse birth outcomes (Rhoades et al., 2013; Stayner et al., 2017). Monitoring gaps and underreporting of seasonal spikes in contamination further complicate risk assessment (Hansen et al., 2019; Shattuck et al., 2023). The changing composition of pesticides—such as formulations containing per- and polyfluoroalkyl substances—introduces new uncertainties about long-term health impacts (U.S. Environmental Protection Agency, 2025).

Conservation practices such as crop and habitat diversification can reduce reliance on chemical inputs overall, reducing pollutants at their source (U.S. Environmental Protection Agency, 2025). Edge of field mitigation practices, such as vegetated buffers, can also be highly effective, depending on the design and the composition of the chemicals (Zhang et al., 2010).

2.4 Infectious disease

Agricultural systems are closely linked to the emergence and transmission of infectious diseases, including foodborne pathogens, zoonotic diseases, and antimicrobial resistance. Since 1940, at least 50% of zoonotic disease emergence has been associated with agriculture, through on-farm activities and broader food system impacts such as land clearing and waste management (Hayek, 2022). The U.S. Centers for Disease Control and Prevention tracks major pathogens—including *Salmonella, E. coli, Listeria,* and *norovirus*—which caused 53,000 hospitalizations and 931 deaths in 2019, using surveillance and inventory data (Walter et al., 2025). Outbreak data in the U.S. suggest that children and the elderly most at risk (Lipman et al., 2024). Cost-of-illness economic models estimate an annual economic cost of foodborne illness in the U.S. between $50 and $78 billion (Scharff, 2012; Hoffmann et al., 2024), with 56% of costs from premature deaths (Hoffmann et al., 2024). Outbreak data suggests that leafy greens alone account for 10% of foodborne illnesses and up to $5.3 billion annually in economic losses (Yang and Scharff, 2024).

Pathogen introduction occurs during production, handling, and processing of food via contaminated irrigation water, high-density livestock operations, and inadequate waste management. Food safety regulations are critical for reducing contamination. However, regulations can have unintended ecological consequences, highlighting links between food safety and environmental conservation. For example, an observational study showed that vegetation removal around fields in California following an *E. coli* outbreak degraded 13% of riparian habitat in five years, reducing ecosystem services that help regulate pathogen and vector populations (Gennet et al., 2013; Karp et al., 2015). This may be counterproductive because vegetative buffers can reduce pathogen loads in runoff and surface water (Winkworth et al., 2008).

While pathogen management with antibiotics is necessary to human health, it can create additional human health threats through anti-microbial resistance (AMR). There is a wide range of estimates for global antibiotic use in agriculture; but all sectoral projections have the sector expanding significantly by 2030, both in the U.S. and globally (Pokharel et al., 2020; Tiseo et al., 2020). In some cases, antibiotics are used in higher doses than necessary or prophylactically, which can create antibiotic resistance genes that can transfer to people; humans can also be exposed to antibiotics directly because many of them pass through livestock and end up in water (Kumar et al., 2020). A meta-analysis shows that restricting antibiotic use in livestock reduces resistant infections in humans by 24% (Tang et al., 2017). The World Bank estimates AMR could result in $1 trillion in additional health care costs and up to 3.8% loss in global economic output by 2050 (Ahmed et al., 2017).

The U.S. Department of Agriculture's (USDA) Strategy to Reduce Antimicrobial Resistance is a positive example of a joint approach to human and environmental health and agriculture, calling for on-farm land and herd management measures that reduce human health risks, information sharing across sectors, and interdisciplinary research and partnerships.

2.5 Trade-offs and context dependency

Although agricultural practices present important opportunities to reduce environmental exposures and improve human health, they are unlikely to deliver universal benefits across all health, environmental, and production outcomes in all contexts (Kazanski et al., 2025). Efforts to mitigate one risk can exacerbate others if practices are not carefully designed and implemented. For example, cover crops can substantially reduce nitrate losses to groundwater and improve drinking water quality; however, in some systems, cover crop termination may require increased herbicide use, potentially elevating chemical exposure risks. Conversely, reducing herbicide use to limit pesticide exposure may increase reliance on tillage for mechanical weed control, which can increase sediment-bound nutrient losses to surface waters and particulate matter emissions from additional field operations.

These tradeoffs depend on how practices are implemented within specific production systems. The health and environmental performance of agricultural practices varies across crops, soils, climates, hydrologic settings, farm size, and management capacity—factors that jointly shape both feasibility and outcomes. As a result, policies that promote health-protective agricultural practices must support flexible, place-based implementation rather than prescriptive approaches. Effective frameworks should encourage combinations of complementary practices, invest in technical assistance and monitoring systems, and enable adaptive management over time. Tailoring solutions to local ecological and social conditions is essential to maximizing co-benefits while minimizing unintended health and environmental tradeoffs.

3 Policy options and implications

As highlighted in Section 2, agri-food management practices can improve human and environmental health; agricultural, environmental and public health policies—through alignment—could support expanded implementation of these practices. However, policies and programs that take full advantage of the synergies between agriculture, public health, and environmental health have been limited. Federal and state agencies responsible for agriculture, fisheries and aquaculture, human health, public land management, and environment often operate independently, each advancing parallel programs with distinct mandates, regulatory responsibilities, stakeholder groups, metrics, and funding streams (see Section 3.1). This structure can result in missed opportunities to align and bolster incentives across agencies to achieve the scale of adoption of agri-food management and supply chain practices needed to transform the U.S. food system to optimize outcomes for human health and the environment, and reduce health disparities among different sub-populations. For instance, U.S. federal agriculture conservation cost share programs focus on promoting environmental outcomes by promoting practices like cover crops and no-till. These practices and others can benefit public health through improvements to water quality and particulate matter (Davidson, 2011; Domingo et al., 2021) but are rarely supported directly through public health initiatives or programs. Also, groundwater laws, like the Sustainable

Groundwater Management Act in California, typically focus on enhancing groundwater quantity or environmental impact, but do not specify a drinking water protection goal, which could be achieved alongside environmental goals.

Furthermore, advancing equitable outcomes at the intersections of environment, food production, and health will require recognizing and including those most affected, sharing power in decision making and policy generation with communities, and attending to the distribution of impacts, both positive and negative, of different policies (López Cifuentes et al., 2026). While assessing and promoting more equitable distribution of impacts has been of increasing interest in conservation (Friedman et al., 2018), incorporating recognitional and procedural dimensions of equity into policy development and implementation is critical (Ruano-Chamorro et al., 2022; Raymond et al., 2026).

There are examples of programs that emphasize collaboration and partnership between and within public agencies and private partners to achieve environmental and health co-benefits. For example, Minnesota's Department of Public Health collaborates with other agencies and local partners such as the Soil and Water Conservation Districts to work with local landowners around source water protection for vulnerable Drinking Water Supply Management Areas. The EPA's Clean Water State Revolving Funds and Drinking Water State Revolving Funds provide mechanisms for states to fund non-point source pollution reduction activities including in agriculture, to address public health concerns.

Our analysis focuses on U.S. policy and program alignment opportunities that operate on the production side of the food system and have demonstrated benefits for environmental and human health. Although food and dietary choices can strongly influence environmental outcomes (Tilman and Clark, 2014) and yield health and environmental co-benefits through shifts in demand (Song et al., 2017; Domingo et al., 2021; Hayek, 2022), we focus here on agricultural production rather than demand-side policies. Production-related policies provide a more direct link between land management and environmental outcomes and build on a long history of agricultural conservation and cost-share programs that are already embedded in U.S. policy frameworks, alongside growing public interest in agriculture–health connections. By contrast, demand-side interventions, such as dietary guidelines, consumption incentives, pricing policies, and food access programs, operate through more complex and indirect pathways, influencing availability, affordability, and preferences before potentially shaping farm-level practices (Biesbroek et al., 2023). These mechanisms are important for food systems transformation, but involve additional layers of social, economic, and behavioral mediation that complicate attribution to environmental outcomes. We are not aware of concrete evidence tracing specific dietary policy instruments to measurable environmental outcomes, suggesting that this important class of interventions merits further research. As such, our aim is a targeted assessment of how agricultural production policy can more explicitly enable public health outcomes, rather than a comprehensive food system review.

3.1 The problem of policy silos

Despite growing recognition of the interconnectedness of public health, agriculture, and environmental sustainability, U.S. federal and state policy remains largely fragmented across these domains. The USDA, the EPA, and the U.S. Food and Drug Administration (FDA) all pursue different statutory objectives, enforce different regulations, and administer different grant programs. To protect soil health, water quality, wildlife habitat, and other resource concerns, USDA administers a wide array of conservation programs, including cost-share for practices on agricultural lands, land retirement, and easements (Stubbs, 2022). However, other key USDA programs like commodity support programs, federally subsidized crop insurance, and federal food procurement generally operate independently of the Department's soil health and environmental quality objectives. The EPA administers major environmental statues that protect public water supplies from contaminants, regulate waste discharges, and establish drinking water and air quality standards (Bearden et al., 2013). The EPA also offers grants to state and tribal agencies to reduce nonpoint source pollution, including from crop and livestock production. EPA water quality targets, however, are a focus for a relatively small subset of USDA conservation program spending (e.g., the USDA Natural Resource Conservation Service (NRCS) National Water Quality Initiative). EPA's pesticide regulations have begun only recently, through the EPA Workplan to Protect Endangered and Threatened Species from Pesticides (U.S. Environmental Protection Agency, 2016), to incorporate the potential mitigation benefits of NRCS conservation practices.

Food safety and labelling authorities are also segmented. The USDA Food Safety Inspection Service (FSIS) has regulatory authority over the safety of meat, poultry, and processed egg products and regulates the mandatory labeling of those products (Johnson, 2016). The USDA Agricultural Marketing Service (AMS) regulates Certified Organic labeling and also all voluntary marketing labels (e.g., "Grassfed") through their Process Verified Program. The Health and Human Services Department's FDA, meanwhile, has regulatory jurisdiction over safety of shell eggs and most other food products and enforces nutritional labeling, but is not involved in regulating or incentivizing agricultural practices.

Layered on top of this web of federal regulations and incentives is a mosaic of state programs. While many regulations in the U.S. are set at the federal level, such as for drinking water, food safety and pesticides, federal regulators typically delegate implementation, monitoring and enforcement to state agencies. States can set their own regulatory standards that exceed federal requirements and any issues not regulated by federal law are left to the states. State incentive programs often augment or complement federal efforts to address issues of agri-food management. For example, forty-two states administer their own agricultural conservation programs (Donovan and Dempsey, 2023). Federalism does allow for innovation and for regulations and incentives to be more tailored to local conditions than would a single, national standard. However, structural disparities in regulatory enforcement or access to incentives, within and across states and at the federal level, can exacerbate environmental justice and equity challenges (Donley et al., 2022; Bae et al., 2025).

To illustrate the fragmented nature of the current policy landscape in the U.S., we used a global database of agri-environmental policies through 2020 to identify overlap with human health (Wuepper et al., 2024). We updated this through 2023 via an advanced search of Congress.gov, searching for Legislative Status of "Became Law" and policy areas of "agriculture and food", "health", and "environmental protection." This produced a final list of 56 federal and state-level policies that we coded and categorized into three sectors: environment, agriculture and food systems, and people and society (inclusive of health) (see Supplementary Material and Methods;

Supplementary Tables S1, S2). We defined environmental policies as those targeting environmental protection, conservation, or quality; people and society policies as those addressing human health, safety, or economic outcomes; and agriculture and food systems policies as those influencing food production or other aspects of the food system. Policies were assigned multiple codes when appropriate (e.g., food security policies were coded as both agriculture and food systems and people and society). Subthemes were organized hierarchically beneath these top-level sectors. Because the database focuses on agri-environmental policies, it may exclude policies focusing on agricultural workers or labor. Further, it is possible that labor issues exist in some included policies but that they are not sufficiently prominent in the policy to show up in policy abstracts or keywords, which were used for analysis. The primary analytical approach was code co-occurrence across sectors. All coding and analysis were conducted using MaxQDA v24.2.0.

While not a complete set of policies – the database and our manual additions are recent as of 2023—the policies reviewed span a wide range of regulatory and incentive-based approaches, including foundational federal statutes such as the Clean Air Act, Safe Drinking Water Act, Organic Food Production Act, and the Inflation Reduction Act. We highlight some of the successful examples of cross-sector work in the following section on policy recommendations.

Of the 56 policies reviewed, only eight contain language that connect all three sectors, while nearly half are siloed to a single sector (Figure 2). This lack of cross-cutting legislation is further indication that U.S. policy tends to treat these issues in isolation, rather than as components of a shared system. For example, environmental policies frequently target air and water quality, climate change, and habitat protection, while health-related policies focus on sanitation, disease prevention, and public health infrastructure, often in differing formats that does not readily allow for integration to detect the role, if any, of environmental risk factors for health outcomes. Food system policies address agriculture, pesticide regulation, and animal health but rarely intersect with human health or environmental objectives in a coordinated way.

Thematic co-occurrence analysis of the 56 policies (Supplementary Table S2) also reveals minimal overlap between human health and agri-environmental themes. Health-related content is more commonly associated with societal outcomes such as economic development and food security, rather than with environmental or agricultural domains. Only seven U.S. policies in this dataset address some aspect of food security, such as food safety and nutrition, and none of these make direct connections to human or public health. Moreover, labor- and worker-related issues are absent from the dataset we used, representing a blind spot in the policy landscape, especially considering environmental and occupational exposures related to farm worker health.

While the U.S. policy landscape includes laws, regulation, and funding in environmental and agricultural sectors, its integration with public health objectives remains limited. Addressing this disconnect will require deliberate efforts to craft policies that recognize and operationalize the interdependence of agricultural, ecological and human health systems. Additional efforts to include deliberate consideration of and collaboration with those most affected and those who could most benefit from environmental, food, and health system improvements will also be important.

3.2 From silos to systems: aligning policy for agriculture, health and environment

The siloed U.S. policy landscape presents a strong opportunity to increase collaboration across agencies to deliver systemic benefits for agriculture, public health and the environment. A science-informed,

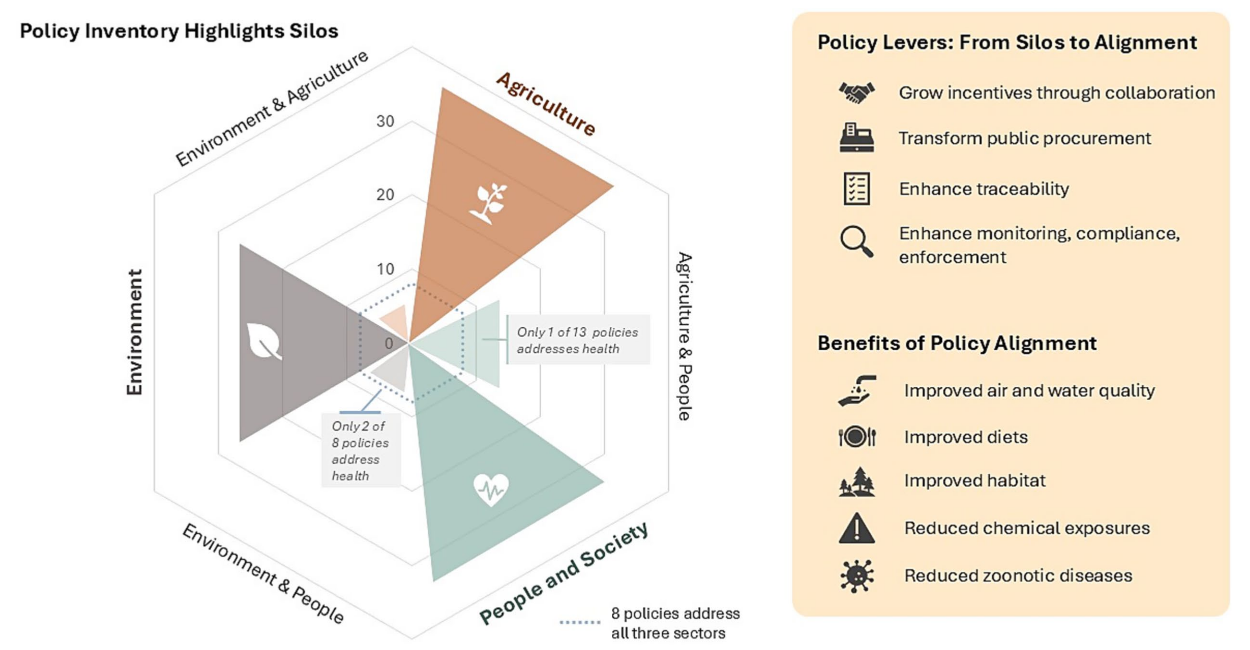

FIGURE 2
Opportunities for integrated policy to support agriculture to contribute to human and environmental health. Past policies in the United States have been siloed, with each sector working towards its own goals. Alignment of these silos can help increase adoption of conservation agriculture practices by leveraging resources from different sectors.

integrated policy approach would align investments in agricultural production and food systems with national health and environmental goals, alongside economic benefits to communities, municipalities and health systems that are left to grapple with the consequences from environmental contamination. Addressing environmental justice concerns and opportunities will likely require both agency-specific and systematic approaches throughout federal and state efforts, as was intended with the Biden administration's Justice 40 initiative (Executive Office of the President, 2021; Conley et al., 2023). While many policy pathways could advance joint goals for agriculture, health, and environment, we highlight three particularly impactful strategies rooted in existing programs and aligned agency priorities.

The effectiveness of policies aimed at expanding conservation agriculture practices depends on whether those programs are feasible for farmers and administrators to implement in practice. Administrative burden, staffing constraints, delays in reimbursement, limited technical assistance capacity, and uneven farmer awareness routinely constrain participation in otherwise well-designed programs. These implementation barriers are central determinants of whether policy reforms translate into on-the-ground adoption and public benefit.

3.2.1 Growing conservation incentives through interagency collaboration

Farmers across the U.S. benefit from public cost-share and incentive programs that support farming and ranching practices that provide public benefits, such as water quality, air quality, and environmental health. However, producer demand consistently exceeds available funding for these programs. Adding new revenue streams to leverage existing federal programs—like USDA's Environmental Quality Incentives Program (EQIP)—has been shown to increase adoption (Rosenberg et al., 2025). Cross-agency collaboration at federal and state levels could expand total investment by aligning separate agency budgets around shared goals.

State-level examples of cross-agency collaboration can be modeled and expanded. The Kansas Clean Water State Revolving Fund is a federal-state partnership to finance projects that improve water quality. This funding supported a collaboration between the Kansas Department of Health and Environment, City of Wetmore, and the Glacial Hills Resource Conservation and Development Region to increase farmer access to high-cost cover crop inter-seeders that make cover crop planting more viable. In Minnesota, the Department of Health, Pollution Control Agency, and Department of Agriculture jointly developed a work plan to address nitrate contamination in aquifers. Their strategy includes free private well testing and mitigation and long-term revisions to agricultural and environmental policies, including a universal buffer law. The plan leverages existing funding and local partnerships, such as the TAP-IN safe drinking water program, which brings together public health departments and Soil and Water Conservation Districts in southeastern Minnesota to tailor solutions to local contexts. While expanding and aligning cost-share funding is necessary, it is not sufficient to drive adoption. Farmers may opt out of conservation programs due to limited awareness or trusted technical support (Reimer and Prokopy, 2014), administrative constraints such as understaffed agencies, complex application processes, or delayed reimbursements, and limited program flexibility relative to farm-level realities (Houser et al., 2024). These barriers can be even more limiting for farmers who meet USDA definitions of "Historically Underserved Producers", including producers who are non-white, beginning, limited-resource, or military veterans (Russell et al., 2021; Kadam et al., 2025). If unaddressed, these barriers can significantly undermine the effectiveness of cross-agency investment and collaboration. For cross-agency collaboration to be effective, it must therefore increase efficiency and directly alleviate these implementation constraints, not merely expand funding.

The recent adoption of national and state frameworks to operationalize a One Health approach—acknowledging the connections between human, animal, and ecosystem health – may also offer pathways to assess and connect agriculture-related risk factors for disease to inform policy decisions. The National One Health Framework to Address Zoonotic Diseases and Advance Public Health Preparedness in the U.S., adopted in 2025, and legislation such as Illinois' One Health Framework Task Force Act, which goes into effect in 2026, create formal mechanisms for inter-agency coordination on issues including antimicrobial resistance. The coordination enabled under the frameworks could provide systems for enhanced data integration and a greater understanding of how on-farm practices can support public health outcomes.

3.2.2 Transforming public procurement

Public procurement holds significant potential to influence farming and ranching practices at scale (Loring et al., 2024). Federal agencies such as USDA's AMS and the Department of Defense's Defense Logistics Agency account for over 90% of federal food purchasing—more than $30 billion between 2018 and 2022 (U.S. Government Accountability Office, 2024). These purchases supply schools, food banks, military installations, and correctional facilities, making federal purchasing power a significant lever for promoting foods produced in ways that support human and environmental health. Procurement decisions are typically guided by nutrition standards, such as those set by the National School Lunch Program. Integrating environmental and public health criteria—such as water quality, soil health, and air pollution reduction—could significantly enhance procurement's positive impact. By aligning procurement criteria with environmental and public health, agencies can stimulate private enterprise market demand for products produced through conservation agriculture and reward producers who invest in sustainable practices. Increased funding for local food procurement assistance—such as through the proposed Strengthening Local Food Security Act—can further support this transition, especially for small and mid-sized producers. A related former program – the Local Food Purchase Assistance Program – also provided equity benefits by prioritizing half of all purchases from socially disadvantaged producers.

3.2.3 Enhancing traceability and transparency

Traceability in the U.S. food system to date has primarily focused on backwards tracing when there is a food safety concern or outbreak. The FDA's Food Traceability Rule mandates enhanced recordkeeping for foods on the Food Traceability List, creating a policy foundation for broader innovation. In livestock, USDA's Animal and Plant Health Inspection Service recently finalized a rule requiring electronic identification ear tags for cattle moved interstate, an initial step toward strengthening the Animal Disease Traceability system for disease tracking and control.

Building on this infrastructure, public policy in collaboration with supply chain partners can support the development of complementary, voluntary transparency and traceability systems that allow producers to document and communicate conservation agriculture practices. These systems would enable producers to be fairly compensated for environmental and health benefits as their products move through the supply chain. For example, traceability platforms could integrate data on practices such as cover cropping, nutrient management, antimicrobial use, animal husbandry practices, or grazing practices—linking them to procurement eligibility, sustainability certifications, or ecosystem service markets.

Public policy can accelerate this momentum by funding open-source traceability infrastructure and enabling producers and/or companies to incorporate farm management data and environmental and health outcomes into tracking systems. These systems could have data privacy protections and integrate into voluntary sustainability programs aligned with the U.S. Roundtable for Sustainable Beef and federal procurement programs such as the USDA Department of Defense Fresh Fruit and Vegetable Program, which already requires traceability and could expand to include conservation practices. They could also link to the USDA's Antimicrobial Resistance Strategy, which already operates across multiple agencies and departments and links environment and human health, though data on environmental dissemination of residues and resistant material is not yet robust. At the state level, the California Leafy Greens Marketing Agreement requires detailed traceability systems for outbreak response. These systems could be expanded to include practices like edge-of-field habitat restoration, which can reduce pathogen vector transport onto crops (Karp et al., 2018). Mandatory public traceability systems necessary for disease monitoring and control can be paired with parallel voluntary traceability systems that drive financial incentives to farmers and ranchers who choose to participate and derive added revenue from producing foods that are both sustainable and healthy.

Public-private partnerships can help to de-risk adoption by co-investing in infrastructure and offering tax incentives or matching grants for companies that integrate traceability across environmental, health, and safety domains. These systems empower consumers to make informed choices and enable retailers and food service providers to differentiate products based on production practices. Achieving traceability around agricultural practices requires norms and standards around how to define which practices should be included and how they are documented; there is currently a growing number of standards for regenerative agriculture as well as existing standards around other systems like organic agriculture. Embedding sustainability into traceability systems would not only support more strategic public procurement but also accelerate the development of ecosystem service markets and reward producers for delivering public goods. Traceability may also improve price transparency and a fairer distribution of value across the supply chain, with benefits for smaller-scale producers (Mühl et al., 2025).

4 Actionable policy recommendations

The policy recommendations below are designed not only to advance alignment across agriculture, environmental, and public health goals, but to address the implementation barriers that routinely limit program effectiveness. Streamlining administrative processes, expanding technical and staffing capacity, improving program reliability through timely reimbursement, and increasing flexibility for diverse farm contexts are essential to ensuring that policy reforms translate into durable adoption and measurable public benefit. While this set of recommendations would go a long way to advancing outcomes for agriculture, environment, and public health and likely benefit many, we did not assess which recommendations would most contribute to reducing environmental injustices. Future collaboration with environmental justice organizations and leaders is necessary to ensure policy approaches include underrepresented perspectives in policy design, reduce disproportionate burdens and channel benefits to historically and currently underserved populations.

4.1 Strengthening federal conservation programs

Federal agencies should prioritize expanding and modernizing conservation programs to accelerate adoption of farming practices that benefit environmental and human health. Improved administration, staffing, reimbursement timelines, and targeting of these programs represents a "low-hanging fruit" policy opportunity, much of which could be accomplished under current legal authorities. Federal agricultural conservation programs at USDA arose in the 1930s as a response to a specific resource concern (the Dust Bowl). Since then, the programs' goals have expanded to encompass other objectives, such as protecting wildlife habitat and reducing greenhouse gas emissions. Presidential administrations have also directed USDA conservation program funding to on-farm practices that address administrative priorities: most recently through the NRCS Regenerative Pilot Program, which plans to direct $700 million in 2026 to contracts including one or more of fifteen prioritized conservation practices. While there are potential human health benefits of USDA conservation programs, as described above, those benefits have nonetheless historically been secondary to other program goals. Continuing to improve the delivery of USDA programs and initiatives and their alignment with health goals would enhance benefits of existing programs.

A near-term legislative priority for Congress should be to reauthorize the Farm Bill – the current law expired in 2023 and has been extended three times as of 2026. For a new Farm Bill to strengthen federal conservation programs and more fully align them with public health objectives, Congress should begin by protecting its significant 2025 investment in voluntary, incentive-based conservation programs, which increased permanent funding to these popular and oversubscribed programs by approximately $2 billion per year. In the next Farm Bill, Congress should ensure that all authorized conservation funding remains dedicated to conservation programs and not redirected to other uses. Congress can also optimize the impact of this additional investment by prioritizing the health benefits of agriculture conservation practices. For example, Congress could authorize EQIP to reimburse 100 percent of costs—rather than the standard 75 percent—for a subset of priority, health-promoting practices such as wetland restoration, vegetated buffers and denitrifying bioreactors that offer significant public health returns but limited direct benefit to farm profitability. Ensuring that reimbursements for these practices are timely and predictable would be critical to farmer participation, particularly for smaller operations with limited upfront capital.

In the medium term, Congress should consider modernizing the Highly Erodible Land (HEL) conservation compliance provisions of the Farm Bill. To be eligible for farm safety net programs like federal crop insurance, HEL provisions require producers to follow a conservation plan when farming highly erodible land. Updating the law to incorporate contemporary weather data and erosion science would improve accuracy of HEL determinations, improve the targeting of assistance to producers most at risk, and reduce wind and water erosion related health impacts. These federal incentive program actions would directly expand access to farming practices that benefit human and environmental health while aligning conservation policy with public health outcomes.

4.2 Expanding state programs and public–private partnerships

Federal programs alone are insufficient to implement health-promoting conservation agriculture practices at scale. State governments play a critical role in tailoring conservation agriculture programs to local contexts, yet they often lack sufficient resources and administrative capacity to deliver programs efficiently and equitably. The private sector also has significant influence on agricultural practices, but policies are needed to help de-risk transitions to more sustainable business models.

To support states in the near term, Congress could authorize supplemental federal funding, through appropriations or USDA grants, to bolster state-led conservation programs without duplicating federal efforts. Indeed, section 2302 of a current Farm Bill draft (H.R. 7,567) proposes to do just that. Additionally, EPA's State and Tribal Assistance Grants should be funded at their fully authorized levels to ensure that state departments of agriculture have the capacity to enforce pesticide regulations and to implement Clean Water and Drinking Water State Revolving Funds, thereby protecting air, water, and human health.

Federal, state, and local governments are also reliant on private-sector partners to promote and implement conservation agriculture practices. For example, NRCS-certified Technical Service Providers (TSPs), who are often private businesses or individuals, help implement NRCS programs by planning, designing, and implementing conservation practices for producers, but there are not enough TSPs to ensure fast and consistent program delivery. To address this shortage, Congress could simplify the TSP certification process, ensure adequate compensation for TSPs, and expand the pool of qualified advisors as in section 2502 of the currently pending H.R. 7,567. These reforms would directly address one of the most persistent bottlenecks in conservation program delivery: insufficient technical assistance capacity to meet farmer demand.

Demand for USDA conservation programs and technical assistance routinely exceeds available funding and USDA staff capacity. There is a strong need for trusted farm and ranch advisors in the private sector to meet the growing demand for conservation practice adoption. USDA and states could partner with private companies seeking to build a workforce of conservation agriculture consultants, who will need access to new technical resources and training, deep knowledge of public and private incentive and market opportunities, and peer-to-peer support. In a parallel vein, USDA could increase its support for farmer peer networks and rancher-led collaboratives that are becoming important resources for producers overcoming practical and social barriers as they adopt and expand their use of conservation agriculture practices. To facilitate this, Congress could enact the Farmer-to-Farmer Education Act (S.1769) to strengthen these key learning hubs.

Lastly, there is substantial private-sector interest in federal conservation programs such as the Regional Conservation Partnership Program (RCPP). RCPP has generated roughly $4 billion in partner contributions since its inception and has included participants from agri-businesses, consumer-packaged goods companies, and a wide range of other for-profit and non-profit entities.

Streamlining programs like RCPP—which can be administratively complex for both agencies and partners—would reduce transaction costs, accelerate project deployment, and enable greater private-sector engagement in promoting conservation agriculture practices. Collectively, these measures would ensure that state, local, and private partners have the financial and institutional support needed to scale conservation agriculture.

4.3 Innovation in markets, finance, and risk management

Beyond directly subsidizing practice adoption, policy can also shift market and financial signals to reward producers for conservation agriculture practices and their associated benefits to environmental and public health. For example, Congress can leverage federal purchasing power to stimulate demand for foods grown with health-promoting practices. In the near term, this could look like authorizing a multi-state pilot program through the Agricultural Marketing Service to prioritize, in a subset of their annual procurements, foods grown with conservation agriculture practices. A procurement preference coupled with a price premium would be an even stronger signal. Another near-term opportunity for Congress is to reduce equipment access barriers to conservation practice adoption by offering more favorable loans to farmers. Legislation such as the Precision Agriculture Loan Act (S.1618) would make precision agriculture equipment eligible for guaranteed conservation loans, facilitating the adoption of technologies like no-till planters and variable-rate applicators.

In the longer term, legislative and administrative improvements to the Federal Crop Insurance Program (FCIP) could encourage farmer adoption of conservation agriculture practices that benefit human health. Several states, including Iowa, Illinois, and Indiana, have already launched state programs that provide crop insurance premium reductions per cover cropped acre (Sawadgo, 2024). In 2022, a one-time Pandemic Cover Crop Program provided a similar premium reduction for cover cropped acres nationally. Congress could create permanent authority for this discount. Congress could also pass other FCIP innovations aligned with promoting health. For example, Congress could modernize Actual Production History calculations to incorporate within-field yield maps, disincentivizing production on marginal land more prone to erosion and contaminant runoff. Lastly, Congress could add FCIP endorsements – optional insurance policy amendments that customize coverage—that recognize the yield-stabilizing benefits of conservation agriculture practices. These actions would align market incentives, credit, and risk management tools with the broader goal of embedding conservation agriculture into the U.S. food system.

5 Limitations and conclusions

5.1 Limitations

This study has several methodological limitations. First, our policy analysis relies on an existing, peer-reviewed database of agri-environmental policies developed by Wuepper et al. (2024). Because we were not involved in the assembly of this database, we cannot independently verify that all relevant U.S. policies were captured. Our analysis depends on the policy abstracts, keyword assignments, and categorizations provided by the original authors, which did not include categories for agricultural labor or social equity. Our findings may under-represent the role of state-specific innovation and federal–state partnerships. Future work could build on this foundation by conducting more detailed analyses of policies, specifically state policy and multi-level governance dynamics. Second, our literature review is intended to provide an integrative overview of evidence linking agricultural practices to environmental exposures and human health outcomes, rather than a comprehensive or systematic review of any single exposure pathway. Each domain examined—such as drinking water contamination, air quality, pesticide exposure, and infectious disease—has a large and evolving literature that warrants more focused synthesis. Third, the policy recommendations were not developed primarily in accordance with environmental justice priorities, nor do they include thorough environmental justice assessment. Future analysis of equity in policies aimed at improving agriculture, environment, and health outcomes (Hampton-Smith et al., 2024) would help identify gaps and areas of opportunity. Direct collaboration with affected communities and environmental justice organizations would also result in a suite of policy recommendations that reflect the policy priorities of the communities impacted. Finally, establishing causal links between agricultural management and human health outcomes remains challenging due to multifactorial drivers of disease and limitations in exposure and health surveillance data. While this paper emphasizes production-side interventions, demand-side and dietary policies also shape health outcomes and merit future analysis.

5.2 Conclusion

Agriculture is a powerful determinant of public health and environmental quality in the U.S., though links between food and health go beyond food production to also include access, distribution, and demand. The impacts of agriculture on drinking water safety, air quality, dietary health, and disease risk are well-documented. These impacts are also greatest for children, who are uniquely vulnerable because they are more physiologically sensitive than adults. Farmworkers and communities surrounding farmland, including many low-income and non-white communities, are at highest risk because of the closer proximity to hazards. At the same time, there is a growing body of evidence and practical tools—ranging from conservation practices to novel public-private partnerships—that can accelerate a shift to food production systems that would mitigate these harms and generate co-benefits for people and the planet. Successfully implementing these solutions requires ambitious and coordinated policy across health, environment, and agriculture agencies at the federal and state levels.

Importantly, much progress can be achieved under existing statutory authorities. Federal and state agencies already administer conservation, water quality, air quality, food safety, and public health programs that could be more intentionally aligned to prioritize health outcomes, improve targeting, strengthen implementation, and enhance interagency coordination. Improved monitoring of environmental exposures and health outcomes—including nitrate contamination, pesticide drift, particulate matter, and infectious disease risk—can further support more effective use of current tools and resources.

At the same time, fully realizing the public health potential of agriculture will also require new policy actions. Legislative priorities include expanding public-private initiatives and shifting approaches to public procurement that enable procurement that aligns with and incentivizes health-promoting production practices. These actions would provide durable funding, expand incentives, and reduce structural barriers that cannot be addressed through administrative action alone.

Realizing the full potential of agriculture to support public health and environmental sustainability will require more than new programs—it will require a shift in how agencies collaborate, how outcomes are measured, and how existing tools are aligned toward shared goals. Ultimately, transforming agriculture into a proactive public health strategy will require both near-term action using existing authorities and longer-term legislative change. By embedding health and environmental priorities into agricultural policy and implementation, the U.S. can build a healthier food system for people and the environment.

Author contributions

SW: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. PL: Data curation, Formal analysis, Visualization, Writing – review & editing. CM: Visualization, Writing – review & editing. AL: Visualization, Writing – review & editing. SG: Investigation, Writing – review & editing. BC: Investigation, Writing – review & editing. SC: Investigation, Writing – review & editing. SK: Investigation, Writing – review & editing. CK: Writing – review & editing. KJ: Conceptualization, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The authors would like to acknowledge support from Craig McCaw and William and Tracy Frist to The Nature Conservancy.

Acknowledgments

We would like to acknowledge Saswati Bora, Deborah Bossio, Christine Griffiths, Briene Lermitte, Rob Manes, and Kari Marciniak for helpful comments.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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