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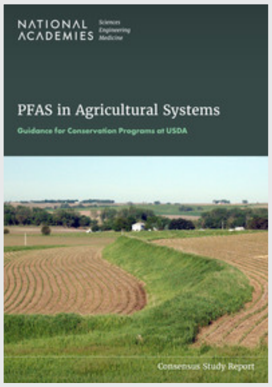

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PFAS in Agricultural Systems

Guidance for Conservation Programs at USDA

Committee on Assistance to the U.S. Department of Agriculture in Building a Framework for Addressing PFAS on Agricultural Land

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

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Consensus Study Report

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COMMITTEE ON ASSISTANCE TO THE U.S. DEPARTMENT OF AGRICULTURE IN BUILDING A FRAMEWORK FOR ADDRESSING PFAS ON AGRICULTURAL LAND

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Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

CRAIG DERICKSON, U.S. Department of Agriculture–Natural Resources Conservation Service (retired)
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this

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report nor did they see the final draft before its release. The review of this report was overseen by **JOHANNES LEHMANN,** Cornell University, and **SUSAN BRANTLEY,** The Pennsylvania State University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Preface

The daunting task of providing technical assistance to land managers on more than 1 billion acres of privately owned farm, ranch, and forested lands falls upon personnel within the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA). Utilizing a suite of programs and practices to help landowners protect precious natural resources, USDA–NRCS supports science-based land uses and management that fit the limits of economic practicality. For working lands, this approach focuses on agricultural production along with conservation, while for sensitive lands (e.g., wetlands) the approach is protection and restoration. The programs and practices currently utilized by the agency help target a myriad of challenges (e.g., nutrient, residue, and tillage management; contour farming; wetland reclamation) that are common to many who depend on these lands for their livelihoods.

Per- and polyfluoroalkyl substances (PFAS) contamination within working lands is a new challenge faced by federal conservation agencies. PFAS are an extensive suite of anthropogenic organic compounds containing perfluorinated moieties that, once released into the environment, are persistent, span the spectrum of mobility, fate, and transport, and may be linked to potential health effects. Because of their widespread use in everyday products and in products that help save lives (e.g., firefighting foams), in conjunction with their varied fate and transport mechanisms, PFAS can be found within all four corners of the globe. PFAS have been detected in pristine locations such as Antarctic snow, ice, and seawater. U.S. working lands might also contain PFAS; thus, means for addressing PFAS within the programs and practices to protect natural resources are warranted.

The task of characterizing the scope of PFAS challenges across working lands and understanding the capabilities (and their unique pros and cons) of conservation programs, practices, and initiatives to address PFAS contamination and mitigation via practical approaches were not inconsequential topics to address. Committee members,

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from a wide range of disciplines under which PFAS may fall, sacrificed evenings and weekends over the past year, focusing on the known and (many) unknowns with respect to PFAS fate and transport within the soil–plant–animal–environment nexus. Writing this report required over a year of volunteer service from its committee members to provide the best possible paths forward with respect to managing PFAS across U.S. working lands, be it by considering prevention of PFAS introduction to lands, on-site mitigation, or reducing off-site PFAS movement. The committee should be proud of the time and effort put forth in the creation of this report. On behalf of the committee, I want to express our thanks and appreciation to the study director, Kara Laney. Kara's patience was seemingly endless as the committee wove its path side to side and, eventually, forward over this past year. Kara merged the committee's various schools of thought into a cohesive final report, and we are ever thankful. We also express our thanks to Mitchell Hebner, who listened intently during our year-long discussions and provided research and writing support whenever called upon. It was obvious that Mitch was paying a great deal of attention throughout the entire process and for that we are grateful. The committee would also like to thank Annie Manville and Samantha Sisanachandeng for their technical support over the past year and Eric Edkin for his assistance with the report graphics. Finally, we would also like to thank those who reviewed our draft report and provided comments that have made this work a better product for our sponsors and for those who are concerned about PFAS across working lands, be they in the United States or abroad.

On behalf of the committee, I hope this report helps forge a path forward for federal conservation agencies and other organizations who may face PFAS challenges in the soils, waters, and air that support plants, animals, humans, and life on this planet. I further hope that this report becomes a working document, and as new knowledge is found, that the report may morph into a deeper understanding of how to properly act and lessen the impact of PFAS, while maintaining or enhancing (agro)ecosystems that support our planet's precious life.

Jim Ippolito, *Chair*
Committee on Assistance to the U.S. Department of Agriculture
in Building a Framework for Addressing PFAS in Agricultural Land
December 2025

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Acronyms and Abbreviations

ACEP	Agricultural Conservation Easement Program
AFFF	aqueous film-forming foam
ARS	Agricultural Research Service
AUC	area under the curve
AWI	air–water interface
CEMA	conservation evaluation and monitoring activities
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CIG	Conservation Innovation Grant
CO_2	carbon dioxide
CPPE	conservation practice physical effects
CREP	Conservation Reserve Enhancement Program
CRP	Conservation Reserve Program
CSP	Conservation Stewardship Program
diPAP	fluorotelomer phosphate diester
DoD	Department of Defense
DWTR	drinking water treatment residuals
ECF	electrochemical fluorination
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
EtFOSA	N-ethyl perfluorooctane sulfonamide
EtFOSAA	Ethylfluorosulfonyloxyacetic acid

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FASA	perfluoroalkane sulfonamides
FDA	Food and Drug Administration
$FeCl_3$	ferric chloride
Fe_3O_4	magnetite
FPAC	Farm Production and Conservation
FSA	Farm Service Agency
FSIS	Food Safety and Inspection Service
FT	fluorotelomerization
FTS	fluorotelomer sulfonic acid
FTOH	fluorotelomer alcohol
HFPO-DA	hexafluoropropylene oxide dimer acid
HI	hazard index
ITRC	Interstate Technology & Regulatory Council
MAE	monitoring, assessment, and evaluation
MCL	maximum contaminant level
MeFOSAA	methylfluorosulfonyloxyacetic acid
NDAA	National Defense Authorization Act
NRCS	Natural Resources Conservation Service
PAH	polycyclic aromatic hydrocarbons
PASF	perfluoroalkane sulfonyl fluoride
PBT	persistence, bioaccumulation, and toxicity
PCB	polychlorinated biphenyl
PFAA	perfluoroalkyl acid
PFAI	perfluoroalkyl iodide
PFAL	perfluoroalkyl aldehyde
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutanesulfonic acid
PFC	perfluorinated compounds or chemicals
PFCA	perfluoroalkyl carboxylic acid
PFDA	perfluorodecanoic acid
PFDoDA	perfluorododecanoic acid
PFDS	perfluorodecanesulfonic acid
PFEA	perfluoroalkyl ether
PFHpA	perfluoroheptanoic acid
PFHpS	perfluoroheptanesulfonic acid
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexane sulfonate
PFNA	perfluorononanoic acid

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PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFPA	phosphonic perfluoroalkyl acid
PFPE	polymeric perfluoropolyether
PFPeA	perfluoropentanoic acid
PFPeS	perfluoropentanesulfonic acid
PFPiA	phosphinic perfluoroalkyl acid
PFPrA	perfluoropropanoic acid
PFSA	perfluoroalkyl sulfonic acid
PFSiA	sulfinic perfluoroalkyl acid
PFUnA	perfluoroundecanoic acid
PM	particulate matter
ppb	parts per billion
REACH	European Union Registration, Evaluation, Authorization and Restriction of Chemicals
RSL	regional screening level
SOM	soil organic matter
SSA	specific surface area
SWAPA	soil, water, air, plants, and animals
TFA	trifluoroacetate
TOP	total oxidizable precursor
TMF	trophic magnification factors
TSP	technical service providers
USDA	U.S. Department of Agriculture

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Summary[1]

Per- and polyfluoroalkyl substances (PFAS) are a diverse family of synthetic compounds with valuable properties, such as high thermal and chemical stability; oil, water, and stain repellency; and lubricity. The exact number of PFAS is unknown in part because there is no single accepted definition of PFAS, but by some estimates there are more than 14,000. They are present in numerous consumer and industrial products, including nonstick cookware, textiles, packaging, and firefighting foams. The strength of the carbon–fluorine bond and the presence of multiple fluorine atoms per carbon contribute to their valuable properties but also allow them to persist in the environment. The resistance of the carbon–fluorine bond to breaking has earned PFAS the nickname "forever chemicals."

Their widespread use facilitates a myriad of mechanisms via which they can enter and cycle in the environment. The compounds are dispersed via aqueous and atmospheric processes resulting in occurrence in soil, surface water, groundwater, sediment, and air. Even at low concentrations, PFAS may create potential hazards not only to human health but also to the nation's natural resources and the economic enterprises and ecosystem services that these resources support, such as agriculture, forestry, and wildlife habitat. In agricultural settings, PFAS contamination of soil and water can render farmland unusable for crops or grazing if there are no viable mitigation options. There are cases in the United States of farms that have suffered tremendous economic losses because PFAS have moved from groundwater and soil into drinking water, forage, and feed of livestock and caused levels of PFAS in animals to be so excessive that subsequent milk and meat products were declared unsafe for human consumption. In some states, health advisories have been issued warning people not to consume fish, waterfowl, turkey, or deer caught or hunted from locations with high levels of PFAS in

[1] This summary does not include references. Citations for the information presented herein are provided in the main text.

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the water or soil. Some instances of PFAS contamination in agricultural systems can be linked to a known source, but contamination can also originate from diffuse sources or the introduction of contaminated material from off site, such as organic soil amendments or animal feed and bedding. At present, much remains unknown about the extent, types, toxicity, and concentrations of PFAS in the landscape, and there are few viable options for addressing contamination.

Several U.S. federal agencies have roles in the stewardship of the nation's natural resources. With regard to natural resources on privately owned working lands, the primary agency responsible is the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA). Its mission is to "deliver conservation solutions so agricultural producers can protect natural resources and feed a growing world"—that is, protect the condition of soil, water, air, plant, and animal systems while maintaining agricultural productivity and other ecosystem services, such as wildlife habitat. The persistent and toxic nature of some PFAS may threaten the ability of the managers of privately owned working lands to achieve either of these objectives. NRCS, which provides technical and financial conservation assistance to landowners, faces a daunting challenge: it strives to help producers avoid or mitigate PFAS impacts despite limited data, incomplete toxicological understanding, and a lack of cost-effective mitigation or remediation technologies. NRCS does not have regulatory authorities or responsibilities; any technical services or financial assistance offered by the agency are accessed by producers and other customers on a voluntarily basis.

Therefore, USDA asked the National Academies of Sciences, Engineering, and Medicine (hereafter referred to as the National Academies) to provide an initial framework to guide key programs administered by NRCS, as well as a conservation program operated under the Farm Service Agency (FSA), to respond to the impacts of PFAS contamination on agricultural and other privately owned working lands. The National Academies formed a committee of experts to examine the scope of PFAS challenges in agriculture, evaluate the capacity of specific existing conservation programs to address on-farm PFAS contamination and mitigation, and provide guidance for decision-making under uncertainty. The committee's task included offering considerations for the development of an agricultural working definition of PFAS, identifying options that could mitigate or avoid PFAS contamination within agricultural systems, and outlining applied research needs. Although the committee recognized that the problems of PFAS in food and agriculture are extensive and affect human health and livelihoods, it focused on its charge to provide guidance on PFAS issues that are within the remit of specified USDA Farm Production and Conservation (FPAC) programs that directly deal with conservation on the land. The committee devised a framework built on the three phases of NRCS's conservation planning process and provided conclusions on opportunities regarding research, available data, and conservation practices and programs to address the impacts of PFAS on contaminated agricultural land.

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PFAS IN AGRICULTURAL SYSTEMS

PFAS occur in two broad classes, polymers and non-polymers, with the latter including well-known compounds such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). PFOA and PFOS are legacy substances that have been phased out of production in the United States, yet they remain widely detected in the environment and in human blood because of their persistence and because they are terminal transformation products of precursor PFAS degradation. Precursor PFAS, such as perfluorooctane sulfonamide and 8:2 fluorotelomer alcohol, are polyfluoroalkyl substances that break down into terminal PFAS, such as PFOS and PFOA, respectively. Because PFAS are transported through air, water, soil, and biota, their presence is now widespread, even in areas with no obvious sources. Studies suggest that background levels exist globally because of atmospheric deposition.

PFAS behavior is strongly shaped by their chemical structure. Long-chain compounds tend to bind tightly to soil and accumulate in living tissue, while short-chain compounds are more mobile and likely to leach into water or be absorbed by plants. Some PFAS present in fire-fighting foams are cationic or zwitterionic, which highly sorb to soils regardless of chain length. The fate and transport of PFAS also depend on soil type, organic content, pH, climate, land management, and other factors.

PFAS enter the environment through point sources—such as industrial manufacturing facilities and military facilities using firefighting foam—and nonpoint sources. Nonpoint sources on farms may include contaminated biosolids, manures, pesticides, fertilizers, and water supplies, as well as atmospheric deposition. Once introduced, PFAS cycle within farms: they move into soils, are taken up by plants, pass into livestock feed and water, and reappear in manure that is reapplied to fields (Figure S-1). They also migrate off farm through runoff, leaching, atmospheric deposition, and sale of contaminated products. Some PFAS are persistent and bioaccumulative, so even low-level contamination can create risks to human and ecological health.

FEDERAL CONSERVATION SUPPORT AND PFAS IN AGRICULTURAL SYSTEMS

Since the 1930s, USDA has provided technical and financial support for conservation on privately owned working lands to customers who seek out these services. Today, NRCS focuses on delivering technical and financial assistance to customers to voluntarily plan and implement conservation practices, while FSA primarily provides financial incentives for the retirement of highly erodible and sensitive lands from agricultural production for the duration of the contract between the agency and the customer. The customer base for conservation support is broad, including farmers, ranchers, forest stewards, nonprofits, businesses, and governments.

Conservation planning is central to NRCS's work. The planning process typically begins with discussions between the planner and the customer, leading to identification of site-specific concerns. NRCS defines a resource concern as degradation of soil, water, air, plant, or animal systems that impairs their sustainability or intended use; more than 40 such concerns are recognized and grouped under these five categories.

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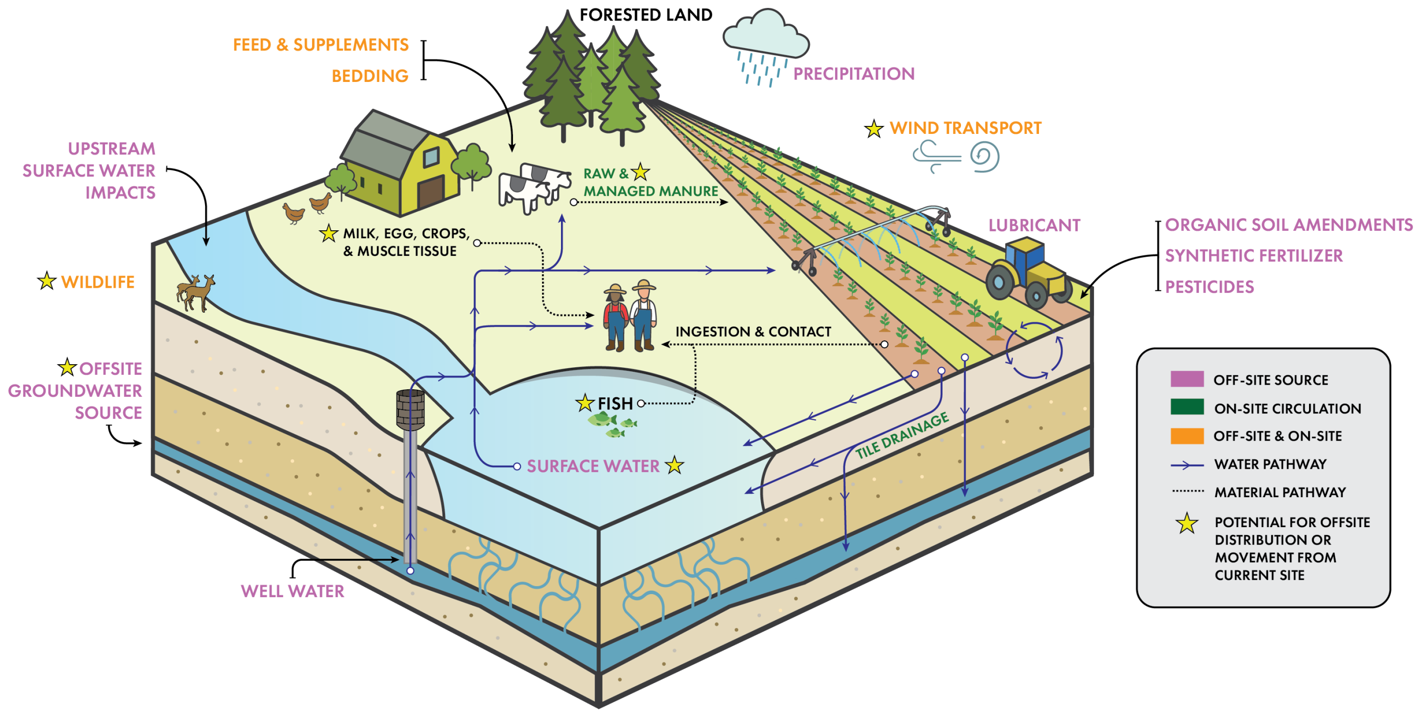

FIGURE S-1 Conceptual model of the entry and cycling of PFAS on agricultural land.

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Once a resource concern is identified and inventoried, planners and landowners collaborate to select conservation practices that address it and create a plan that belongs to the customer. More than 160 national conservation practice standards exist, ranging from nutrient management to water and sediment control basins, all intended to improve environmental performance with some also maintaining or enhancing productivity.

Capabilities and Limitations for Conservation Programs and Practices to Address PFAS Concerns

Producers who pursue conservation technical and financial assistance do so through a number of FPAC conservation programs and subprograms. The committee was asked to characterize the capability of four programs—the Environmental Quality Incentives Program (EQIP), the Conservation Stewardship Program (CSP), the Agricultural Conservation Easement Program (ACEP), and the Conservation Reserve Program (CRP)—to address on-farm PFAS contamination and mitigation. NRCS administers EQIP and CSP, which are working lands programs, as well as ACEP, which protects farmland and wetlands through easements. FSA administers CRP, which takes environmentally sensitive cropland out of production, while NRCS provides conservation technical assistance to the program.

Among these, EQIP offers the broadest opportunities for addressing PFAS because it is widely used, covers most practice standards, and provides significant cost-share. It also supports Conservation Innovation Grants that could be leveraged to develop PFAS-specific mitigation practices. CSP can build upon EQIP by funding enhancements of conservation practices and bundles of enhancements, potentially including those targeting PFAS. CRP may provide another pathway by retiring contaminated land and mitigating PFAS impacts through vegetative covers, pilot projects, or partnerships under the Conservation Reserve Enhancement Program. ACEP, however, cannot be used for PFAS-contaminated land due to statutory restrictions tied to the risk of hazardous substances, namely PFOS and PFOA.

Though EQIP, CSP, and CRP have potential, they face practical limitations, including oversubscription and eligibility rules. Even when funds are available, producers may lack the initial capital to implement practices before financial assistance reimbursement, or they may fear added visibility by identifying a resource concern that could draw the attention of regulatory entities despite the purely voluntary nature of USDA conservation programs.

The committee was also asked to characterize the capability of conservation practices to address on-farm PFAS contamination and mitigation. Its assessment is that conservation practices may both help and harm in the PFAS context. For example, measures that reduce erosion can limit PFAS transport but may simultaneously increase leaching of PFAS to groundwater. Practices that involve importing organic soil amendments to the farm risk introducing new PFAS contamination. Careful selection and adaptation of practices to specific site conditions through conservation planning are essential.

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Opportunities to Address PFAS Concerns through Conservation Support

There are opportunities for NRCS to explicitly integrate PFAS into its conservation framework. In the conservation planning stage, PFAS concerns could be incorporated explicitly or implicitly into existing categories of resource concerns, such as those that address pathogens and chemicals from manure, biosolids, or compost applications transported to groundwater and surface water. Another option would be to recognize PFAS as a distinct resource concern, similar to the way in which nutrient transport to water bodies is recognized, which would allow NRCS to directly evaluate the effects of practices on PFAS. The principal rationale for this approach is that PFAS contamination could be directly evaluated by NRCS for the effect of each conservation practice on this concern and would not be dependent on surrogate evaluations through the results for related resource concerns. Designating PFAS as a resource concern would help to ensure it receives proper consideration in the conservation planning process and that the most effective conservation practice solutions are planned for a specific site to mitigate PFAS contamination. However, calling out PFAS as a standalone resource concern could bring unwanted attention to customers affected by the issue or make customers less inclined to work with NRCS because of concerns of being singled out. As the fate and transport of different PFAS in the environment is not uniform, addressing PFAS as a specific resource concern in the conservation planning process is challenged by the variety of behaviors that could occur in response to conservation practices.

In terms of conservation practices, NRCS could explore both new and adapted approaches. Subprograms that support innovation could be used to test new practice standards, such as crop choices that minimize PFAS uptake, or to improve existing standards, such as filter strips designed to intercept contaminants before they reach water bodies. Currently, only one practice standard, Soil Carbon Amendment, explicitly references PFAS. Expanding references to PFAS across other standards, as is already done with nutrients and pesticides, could highlight risks and ensure planners are alert to the issue.

Addressing PFAS across diverse agricultural landscapes will be complex. Still, by creating new practices, revising practice standards, modifying existing resource concerns, supporting innovation, and strategically applying conservation programs, NRCS can begin providing its field staff with the tools needed to guide its customers in mitigating PFAS risks. Success will depend on integrating PFAS into conservation planning, balancing tradeoffs among conservation practices, and using innovative programmatic approaches, field trials, and research mechanisms to test and refine solutions.

Conclusion 3-1: There are opportunities within the statutory, policy, and operational frameworks of EQIP, CSP, and CRP to help address on-farm PFAS contamination and mitigation. For example, PFAS could be identified as a priority for funding through existing program features and procedures. Pilot initiatives could be pursued within programs to target the avoidance or mitigation of PFAS contamination on agricultural lands.

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Conclusion 3-2: PFAS could be addressed in a conservation plan through existing resource concerns, such as those pertaining to the transport of pathogens and chemicals to water, or through the creation of a standalone resource concern, much as nutrient transport to surface water and groundwater are standalone resource concerns. There are pros and cons to either approach.

Conclusion 3-3: There are opportunities for NRCS to increase the capabilities of conservation practices to address on-farm PFAS contamination and mitigation. These include:

- *Supporting on-farm conservation field trials, such as through EQIP's Conservation Innovation Grant subprogram, on the basis of proven research to improve existing conservation practice standards or develop new standards that address PFAS concerns.*
- *Including PFAS as an explicit contaminant of concern in existing conservation practice standards whose purpose and the conditions where the practice applies have relevance to PFAS contamination, mitigation, or both.*

DECISION-MAKING UNDER UNCERTAINTY

The lack of data regarding the extent and magnitude of PFAS contamination on agricultural land, combined with uncertainties about what different potential PFAS sources may contribute to farm contamination and the fate and transport of different PFAS, poses a challenge to advising farmers on how to manage PFAS risks. This challenge is further complicated by the absence of a working definition for PFAS in agricultural contexts. Such a definition may need to consider PFAS structural features, the ability to detect a specific PFAS, and thresholds for deciding when detected concentrations merit further investigation. Currently, one of the most pressing challenges is the lack of consistent regulatory criteria for PFAS in agricultural soils, including considerations for occurrence of PFAS mixtures. Due to the variation in regulations at the state level, federal guidance on thresholds in agricultural lands would be beneficial to assist conservation planners and others in contextualizing PFAS occurrence at agricultural facilities. Notably, all considerations that would inform a definition—structure, analytical methods, regulatory criteria, or the exceedance of a set threshold for some combination of PFAS persistence, bioaccumulation, toxicity, and mobility—are evolving areas of study and will require review and revision as the science advances.

Regarding the unknown magnitude of PFAS contamination, predictive models based on known PFAS sources and soil and hydrogeologic data could help identify at-risk agricultural lands. Machine-learning approaches have already been used to map groundwater contamination probabilities in several states and at the national scale. Extending these models to soils and agricultural contexts could assist NRCS planners and producers in assessing risks where site-specific data are unavailable.

The committee took this potential for predictive modeling and what is known about the occurrence, fate, and transport of PFAS and integrated these with the conservation planning process and how conservation practices, programs, and initiatives could

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influence PFAS introduction and movement on agricultural lands. This approach led to the committee creating a decision-making framework that the FPAC agencies could potentially use to guide their responses to PFAS contamination on agricultural land.

The framework illustrated in Figure S-2 is connected to NRCS's nine-step conservation planning process. The process is depicted as an iterative and cyclical effort with three phases, reflecting how experienced planners move in and out of steps as new information surfaces. The framework accommodates two possible realities: PFAS could be the explicit focus of a conservation planning conversation between NRCS and a customer, or it could be a background consideration while another resource concern drives the plan. The committee added a grid to the original NRCS image to describe in each phase considerations that might be made, resources that are available, and resources that are needed for the FPAC agencies to move forward in the face of uncertainty and lack of consensus information about PFAS contamination on agricultural land.

Phase 1 is the opportunity to identify the degree to which PFAS are a concern (if they are not the central concern of the planning process from the start). If testing for PFAS has not been carried out, it could be conducted at this time if the customer elects to do so. Planners could use existing datasets of PFAS sources and soil and hydrogeologic characteristics to determine if PFAS are potentially a problem for the specific site and resource in question. Ideally, NRCS would work with other agencies that could build models specific to agricultural land, adding relevant features (such as distances from known sources, prior application of organic soil amendments, and soil and climate characteristics) from public sources, and then use the resulting curated data to train and test predictive models. NRCS has already made a start by adding information about potential PFAS movement and attenuation in soils to its Web Soil Survey.

As planners move into Phase 2, they can formulate and compare alternatives with PFAS risk explicitly in view—avoiding new PFAS inputs (such as certain organic soil amendment sources) and avoiding practices that could mobilize or spread existing contamination—while weighing these considerations alongside the original resource concern (if PFAS are not the primary issue). Phase 3 focuses on implementation with built-in evaluation. Practices could move forward with clear documentation of how PFAS were considered. If monitoring information, observations, or outcomes raise concerns about PFAS risk or unintended consequences, the process loops back to Phase 2 to adjust practices. The emphasis is on adaptive management—for example, switching water or soil amendment sources or revising practice selections—to avoid causing or exacerbating a PFAS problem. Innovative trials, monitoring, and evaluation could be implemented in this phase.

Overall, the framework is a planning aid rather than a prescriptive algorithm. It respects the customer's role as the decision-maker, the voluntary nature of programs, and current constraints, such as the absence of uniform federal thresholds for PFAS and the confidentiality of PFAS test results (which belong to the customer and may or may not be disclosed back into planning). The framework's purpose is to help field staff fold PFAS awareness into the work they already do—whether PFAS are the central issue or simply a prudent factor to consider—so that conservation actions do not inadvertently create new PFAS risks. Full operationalization of the framework will require additional data and development of tools as well as training for NRCS field conservationists in the basics of PFAS and agriculture and to have familiarity with federal and state resources

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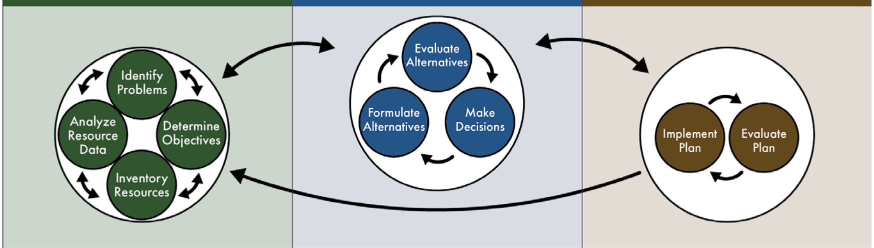

	PHASE 1 Collection & Analysis	PHASE 2 Decision Support	PHASE 3 Application & Evaluation
Considerations	Are PFAS a significant concern at this site? What is the source of irrigation water used on the farm? Has organic material from an off-site source been applied to the land? Is there a source of PFAS proximate to the farm?	What is known about the effects of PFAS on the condition of the soil, water, air, plant, and animal resource bases? For example, are the PFAS present long-chain and likely to stay in soil or short-chain and likely to be taken up by plants? Do the proposed conservation practices have the potential to: • mitigate a PFAS problem? • limit transport of PFAS off-site? • introduce PFAS? • exacerbate a PFAS problem? • transport PFAS off-site?	When implementing the practice, take care not to: • introduce PFAS. • exacerbate a PFAS problem. • transport PFAS off-site. When evaluating, employ adaptive management for new information (e.g., new practices or adjustments to existing practices)
Existing Resources	Prescreening tools (examples provided in Table 4-3) Web Soil Survey information on PFAS behavior in soil PFAS testing (available as a cost-share activity through Conservation Evaluation and Monitoring Activity 209 or from the Environmental Protection Agency or state environmental agencies)	Table 3-2 is an initial resource that could be further developed. It could also be expanded to include the practices listed in Appendix D.	Table 3-2 is an initial resource that could be further developed. It could also be expanded to include the practices listed in Appendix D. Conservation Innovation Grant program to • advance conservation measures and approaches that show promise for PFAS mitigation. • introduce innovative conservation measures or approaches from one geographic area to a new area. • evaluate and refine existing conservation practice standards for PFAS mitigation purposes. • assess systems of conservation practices and their impact on PFAS mitigation. Cooperative agreements to monitor, assess, and evaluate conservation projects related to PFAS on land enrolled in the Conservation Reserve Program.
Needed Resources	Standards (screening and action levels) Inclusion of PFAS as a consideration in Conservation Practice Standards or designation of PFAS as a separate Resource Concern Agricultural working definition of PFAS Predictive modeling of PFAS in soil and water PFAS site index tool to evaluate potential for PFAS loss from fields to water bodies Research on: • fate and transport of various PFAS in different soil types and under different climatic conditions • PFAS sorbents that could be effective under field conditions • plant uptake of PFAS, accounting for different crops (vegetables to trees to forage) and different soils, under field conditions • animal PFAS uptake and elimination to inform relevant conservation practices related to livestock Development of conservation practices standards designed specifically to capture PFAS (e.g., removal structures, bioreactors) PFAS-specific training for NRCS field conservationists	Application of results on fate and transport research to assessment of positive and negative effects of conservation practices. Determination that agricultural land affected by PFAS can be eligible for the Conservation Reserve Program.	New pilot programs in the Conservation Reserve Program to mitigate PFAS contamination. PFAS contamination identified as a conservation challenge of concern under the Conservation Reserve Enhancement Program.

FIGURE S-2 Framework for conservation planning and practice implementation to address PFAS concerns, accounting for uncertainty.
SOURCE: Based on NRCS, https://www.nrcs.usda.gov/state-offices/tennessee/nine-step-conservation-planning-process.

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available to affected customers. NRCS could work with other agencies and entities to establish nationwide screening levels for different types of agricultural production facilities, soil types, and climatic systems. Machine-learning models could be trained, similar to those underlying current PFAS groundwater maps, using nationwide data on PFAS in agricultural soils and information in the Web Soil Survey, combined with data on proximity to PFAS sources, agricultural land uses, climate, and other features. Applied research could expand the capability of existing practices and the development of new practices to address PFAS concerns. In cases where decision-makers determine that PFAS risks are unacceptably high, FPAC programs that support farmers in taking land out of production may be necessary.

Conclusion 4-1: A working definition of PFAS for agriculture may need to consider structural features of the compounds, the ability to detect a specific PFAS, and thresholds for deciding when detected concentrations merit further investigation. Federal guidance on thresholds of PFAS in agricultural lands would benefit conservation planners in contextualizing PFAS occurrence at agricultural operations.

Conclusion 4-2: Based on existing data-driven efforts to predict PFAS occurrence in groundwater and soil, it is possible to develop large, regional models that could help identify agricultural land at risk of PFAS contamination. NRCS could work with other agencies to build, train, and test such predictive models.

Conclusion 4-3: Even though many knowledge gaps about PFAS exist, there are sufficient opportunities within the conservation planning process, the conservation practice standards, and the conservation programs, as well as sufficient data about PFAS, for the FPAC agencies to create a framework for responding to the impacts of PFAS contamination on agricultural land. The development of federal guidance on PFAS thresholds in agricultural lands and the evaluation of additional data on PFAS in agricultural soils nationwide—which could be used to train predictive models—would enhance the ability of conservation planners to respond to PFAS concerns.

Conclusion 4-4: There is a need for coordinated training of NRCS field conservationists in the basics of PFAS and agriculture and for each NRCS state office to maintain a list of available resources for PFAS-affected farmers and contacts.

APPLIED RESEARCH GAPS

In the context of conservation on the land, applied research needs to focus on minimizing PFAS uptake into plants and animals, in situ sequestration, and removal of PFAS to the greatest extent possible. The committee identified four areas of research that could advance the ability of conservation practices to address PFAS contamination on agricultural land.

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Discerning PFAS Fate and Transport in Varying Soil Types

Understanding how PFAS move through soils across the United States is complex because a combination of soil characteristics—including clay and oxide content, organic matter, pH, soil texture, cations, and water relationships—interacts with climate conditions such as precipitation, wind, and temperature to influence PFAS behavior. Climate in particular plays a critical role. Laboratory studies have shown that higher temperatures increase plant metabolism and transpiration, which in turn raises PFAS concentrations in plant tissues, especially leaves. Precipitation is also a major driver of PFAS leaching and mobility, though long-term field data linking rainfall patterns to PFAS behavior are lacking. Many greenhouse studies do not allow leaching from the pots, thereby leaving short-chain PFAS in close contact with roots longer than would occur under natural conditions, which limits the accuracy of those findings.

The type of PFAS present also matters. Short-chain PFAS tend to move more freely in soils, while long-chain compounds sorb more strongly. Less is known about zwitterionic PFAS, but evidence suggests that soil pH alters their charge and sorption magnitude. Differences between clay types also affect sorption, with kaolinite and montmorillonite behaving differently. Although significant research has examined sorption, less attention has been given to desorption. Studies of historically contaminated soils show that compounds such as PFOS can resist release even after multiple desorption steps, while lab-spiked soils show less persistence. These discrepancies highlight the need for further investigation into desorption hysteresis and its implications for PFAS persistence.

To advance understanding, a coordinated, national network of researchers could be created to study PFAS fate in diverse soils and climates. Using tools such as predictive modeling and the NRCS Web Soil Survey, scientists could identify vulnerable soils, expand data fields in the Web Soil Survey with respect to PFAS sorption and movement, and refine conservation practice standards based on these insights. Such a coordinated effort would help fill research gaps and provide practical knowledge for managing PFAS contamination in U.S. agricultural systems.

Opportunities to Trap or Sequester PFAS

Research on PFAS sequestration in agricultural settings points to several promising sorbents and complementary field strategies, though there are large evidence gaps. The benefits to sequestering PFAS include the potential to reduce plant uptake as well as leaching. Potential disadvantages are that PFAS are held in place, which may hinder success of future removal or destruction strategies. There is also the potential for changes in the PFAS sequestering sorbents over time that may lead to unforeseen release of PFAS.

Several designer sorbents have been tested at the bench-scale to target high PFAS sorption capacity; however, scalability in terms of provision and cost at the landscape scale are unlikely. Therefore, much attention has turned toward biochar that can be produced in large volumes. The intrinsic performance of biochar as a sorbent depends on feedstock, pyrolysis temperature and hold time, surface area, and the carbon–oxygen ratio. Higher temperatures generally increase specific surface area, resulting in biochars

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that achieve near-complete long-chain PFAS removal, while very high temperatures and tailored pore structures are needed to capture short-chain PFAS. Studies show that some hardwood or high temperature–derived biochars can rival activated carbon for long-chain PFAS sorption and, in select cases, approach also being effective in sorbing short-chain PFAS. Modifications such as iron salts or iron oxides can further boost sorption through combined electrostatic, physical, and hydrophobic interactions, although additional modification raises costs and may reduce biochar yield. Most findings come from laboratory settings; field trials are needed to test long-term efficacy, desorption behavior, reapplication schedules, minimum depth of incorporation needed, and performance across soil types and climates. Other sorbents that have potential to sequester PFAS include clays (particularly modified clays) and drinking water treatment residuals (such as aluminum-based residuals from the use of alum salts during water treatment), which are abundant and potentially low cost. Combining residuals with biochar or other media may improve performance, but the approach requires more applied and field research.

Reducing PFAS discharges to surface waters can build on nutrient control methods while tailoring designs to the chemistry and behavior of PFAS. Removal structures adapted from phosphorus management are one opportunity. Modular boxes, ditch filters, confined beds, cartridges, pond filters, and tile-drain filters can be packed with sorptive media and sized to site hydrology. Effective design depends on media capacity and kinetics, expected mass loads, contact time, and the likelihood of desorption. Costs, availability, and the risk of leaching other contaminants must also be weighed. Unlike phosphorus, PFAS targets vary by chain length and functional group, so media must be matched to local contaminant profiles and discharge goals set with wildlife, livestock, and downstream exposure in mind. Higher flow rates in tile drainage compared with percolation through soil demand robust removal structure sizing and point to the value of PFAS-specific design manuals and software modeled after existing phosphorus tools.

Denitrifying bioreactors provide a complementary approach. Wood chip systems that support denitrifying microbes increase residence time and can be deployed to treat outflow before entering water bodies. While nitrogen removal is well established, PFAS degradation remains difficult. Laboratory studies show slow and incomplete microbial breakdown, particularly for perfluoroalkyl sulfonates. Promising directions include pairing biotic processes with abiotic catalysts, adding sorptive media such as biochar to retain PFAS while fostering microbial communities, and experimenting with low-cost, flexible in-ditch configurations. Success will hinge on sustaining appropriate microbes in field conditions and accommodating variable flows.

Another strategy could be a PFAS Site Index modeled on state phosphorus indices. By scoring soil properties, hydrology, proximity to water, management practices, and the specific PFAS present, planners could rank fields by off-site risk and steer investments toward the most cost-effective combinations of removal structures and sorbent placements. Together, these strategies would move PFAS control from ad hoc trials toward standardized, site-responsive conservation practices.

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Understanding Plant Characteristics That Affect PFAS Uptake and Accumulation

In the context of conservation practices, the selected planting of specific crops or other vegetative cover could address PFAS contamination on agricultural land via plant uptake in one of two ways: (1) by trying to minimize PFAS accumulation in harvested and grazed crops or (2) by trying to maximize plant uptake for phytoremediation. For either approach to be successful, there is an urgent need to better understand the variation in PFAS uptake among agricultural and conservation plants and of the various plant characteristics that influence that uptake. Studies could address quantification of soil-to-plant transfer of PFAS across a broader range of crops and growing conditions than currently exist in the literature. To be most useful for crop selection decisions, these studies should be conducted in the field under real-world conditions and preferably over multiple years to capture year-to-year variability.

Transpirational flow is seen as the primary driver of PFAS uptake and accumulation into the plant. Although sorption to soil serves as a control for what is available in the porewater for transpiration, plant features such as protein and lipid contents, root macrostructure, and root exudates have all been proposed as plant-based mechanisms that lead to PFAS uptake differences among plant species and cultivars. Further research is needed to investigate the relative importance of these factors, as well as the influence of selective membranes and other transfer barriers in roots and shoots. Research into transpiration rates could also explain differences observed in the amount of PFAS plant uptake among crop species and across seasons.

How crop management affects plant PFAS uptake is a topic that has barely been addressed but is of great importance in the context of conservation practices. Researchers have investigated fertilization and intercropping on crop PFAS uptake with mixed effects. No known studies exist on how PFAS uptake is influenced by conservation tillage/no-till, which is known to affect root distribution under certain conditions, crop rotation, crop density, or irrigation.

Research is also needed to determine and use appropriate vegetative covers that are not detrimental to the health of wildlife by their consumption. Harmful exposure of wildlife (or grazing livestock) to PFAS because of plant uptake would be at odds with conservation practices developed to provide habitat.

PFAS Mitigation in Livestock

Mitigating PFAS contamination in livestock remains a significant challenge, as animals exposed through water or feed can accumulate these chemicals in meat and milk. Dairy consumption is a primary agricultural exposure pathway of concern because forages (leafy crops) are important feed sources for dairy animals, and PFAS bioaccumulate and biomagnify in animals and their milk. Guidance developed in Maine offers some practical steps. PFAS levels in animals can decline once exposure ends, with PFOS in milk and beef tissues showing half-lives of 8–12 weeks. Switching cattle to uncontaminated feed or pastures during finishing can reduce risk. Diluting contaminated feed with clean feed can also help, though it requires careful tracking of hay and silage

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sources to avoid uneven exposure. Soil testing, rather than forage testing, is advised for risk assessment because PFAS often remain undetectable in forage even when present in soil and animal products.

Research gaps remain wide. Most livestock studies have focused on a few well-known PFAS, such as PFOS and PFOA, with limited attention to other compounds. Elimination occurs primarily through lactation, urine, and feces, and longer-chain PFAS persist longer in serum. Physiologically based pharmacokinetic models estimate withdrawal intervals but need updating to reflect new regulatory thresholds and broader PFAS profiles. Additionally, research should target opportunities to interrupt PFAS cycling on farms through manure management. Advancing these areas of research will be critical for developing management practices that can effectively mitigate risks in animal agricultural systems.

Conclusion 5-1: Applied research that advances understanding of PFAS fate and transport in different types of soils, develops better mechanisms by which to trap or sequester PFAS, and minimizes PFAS uptake in plants and animals could improve the ability of conservation practices to address PFAS contamination on agricultural land.

Conclusion 5-2: A coordinated, national network of researchers focused on the identified areas of applied research would help close information gaps and provide practical knowledge for managing PFAS contamination in U.S. agricultural systems.

Conclusion 5-3: The results of such research and coordination could be used to continually improve existing resources and provide needed resources identified in the suggested framework to advance the ability of the FPAC agencies to respond to the impacts of PFAS contamination on agricultural land.

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Introduction

Per- and polyfluoroalkyl substances (PFAS) are a diverse family of synthetic compounds with valuable properties, such as high thermal and chemical stability; oil, water, and stain repellency; and lubricity (ITRC 2023). The acronym PFAS was coined in 2011 to specifically describe the subset of fluorinated chemicals in which fluorine atoms have replaced hydrogen atoms in the molecules (Buck et al. 2011). Though the acronym is a relatively recent term, PFAS have been in use since the 1940s and have been known by earlier monikers—for example, organic fluorocompounds, fluorinated organic compounds, fluorochemicals, and perfluorinated compounds or chemicals (PFCs). The exact number of PFAS is unknown in part because there is no single accepted definition of PFAS, but by some estimates there are more than 14,000.[1] They are used in many products and applications, including electronics, construction materials, medical devices, pharmaceutical drugs, stain-repellant textiles and carpets, paper and paper products, food packaging, cosmetics and personal care products, nonstick cookware, cleaning products, paints, sealants, inks, refrigerants, and manufacturing of semiconductors. PFAS are also found in aqueous film-forming foams used by fire departments, airports, and the military to extinguish hydrocarbon fires. The widespread use of these substances facilitates a myriad of mechanisms via which they can enter and cycle in the environment.

PFAS have also been referred to colloquially as "forever chemicals" because the strength of their carbon–fluorine bond, which is the basis of their valuable properties, allows them to persist in some form in the environment without bond degradation (Allen 2018). These synthetic compounds can be either highly mobile or immobile, are prone to accumulation in living tissue, and, because of their persistence, are found everywhere in the world, even in locations not inhabited by humans. Many PFAS have

[1] See https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCT and https://comptox.epa.gov/dashboard/chemical-lists/PFASDEV1.

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been identified as toxic to humans and other life (Lee et al. 2020; NASEM 2022; NTP 2022). The compounds are dispersed via aqueous and atmospheric processes resulting in occurrence in soil, surface water, groundwater, sediment, and air. Even at low concentrations some PFAS may create potential hazards not only to human health but also to the nation's natural resources and the economic enterprises and ecosystem services that these resources support, such as agriculture, forestry, and wildlife habitat.

Several U.S. federal agencies have roles in the stewardship of the nation's natural resources, but with regard to natural resources on privately owned working lands, the primary responsible agency is the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA). Its mission is to "deliver conservation solutions so agricultural producers can protect natural resources and feed a growing world,"[2]—that is, protect the condition of soil, water, air, plant, and animal systems while maintaining agricultural productivity and other ecosystem services, such as wildlife habitat. The persistent and toxic nature of some PFAS may threaten the ability of the managers of privately owned working lands to achieve either of these objectives. Some farmers have halted the production of food or forage crops because of soil PFAS contamination resulting from historical applications of contaminated biosolids and papermill waste (Perkins 2022). There are examples of other U.S. farms that have suffered tremendous economic losses because PFAS have moved from groundwater and soil into drinking water, forage, and feed of livestock and caused levels of PFAS in animals to be so excessive that subsequent products were declared unsafe for human consumption (Clayton 2022). In some cases, when it is not economically or logistically feasible to switch feed or watering sources and wait for PFAS levels in animals to decline over time, livestock have been euthanized (State of New Mexico 2022). In some states, health advisories have been issued, warning people not to consume fish, waterfowl, turkey, or deer caught or hunted from locations with high levels of PFAS in the water or soil.[3]

After investigation, the above examples could all be traced to a known source or introduction of PFAS into the agricultural operation or habitat. However, proactively identifying other PFAS-impacted locations is challenging because the extent, types, toxicity, and concentrations of PFAS in the landscape are unknown. These uncertainties also exist for the water, feed, and other products that may be brought into agricultural systems, making the prevention of contamination difficult as well.

NRCS supports conservation programs on privately owned working lands through technical and financial assistance. The agency faces many constraints when it comes to achieving these aims. First, there is no systematic survey of PFAS in the environment. What kinds of PFAS can be found in a location and at what concentration are largely unknown across the United States. Second, there are knowledge gaps regarding the fate, transport, and especially toxicity of all but a subset of well-studied PFAS (Guelfo et al.

[2] See *About NRCS*, https://www.nrcs.usda.gov/about.

[3] Maine has issued advisories for deer and turkey harvested from PFAS-impacted locations (Maine Department of Inland Fisheries & Wildlife 2024). New Mexico has issued an advisory for waterfowl and other wildlife harvested from Holloman Lake (New Mexico Department of Health 2025). Maine and several other states have issued advisories for fish in impacted water bodies. See ECOS (2025) for more information.

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2021; Evich et al. 2022). For many PFAS, analytical standards and standard methods are lacking for measuring concentrations in environmental media, including soil, water, plants, and animals (Shojaei et al. 2022; Rehman et al. 2023). Third, there are few viable options for remediating land or water contaminated by PFAS at diffuse concentrations (Verley et al. 2025). For example, there are no affordable means of easily degrading these compounds into benign products. Even extreme treatments, such as pyrolysis, may not fully eliminate all PFAS (Winchell et al. 2024). Capturing and sequestering PFAS is also difficult because the characteristics of these compounds and the media they are in vary tremendously and contamination is often diffuse, requiring treatment of large volumes of impacted media and use of multiple sorbents to remove PFAS by immobilizing agents (Gagliano et al. 2020; Dickman and Aga 2022; Bui et al. 2024; Verley et al. 2025). In this information-poor environment, USDA asked the National Academies of Sciences, Engineering, and Medicine (hereafter referred to as the National Academies) to provide an initial framework to guide programs administered by NRCS, as well as a conservation program operated under the Farm Service Agency (FSA), to respond to the impacts of PFAS contamination on agricultural and other privately owned working lands.

THE COMMITTEE'S CHARGE AND PROCESS

The committee was charged with examining PFAS on agricultural lands within the context of specific programs and conservation practices administered under USDA's Farm Production and Conservation (FPAC) mission area. The request included an assessment of the capability of existing conservation programs—namely, the Environmental Quality Incentives Program, the Conservation Stewardship Program, and the Agricultural Conservation Easements Program administered by NRCS and the Conservation Reserve Program administered by FSA—as well as conservation practices and initiatives to address on-farm PFAS contamination and mitigation. It also asked the committee to consider what factors FPAC agencies might consider when evaluating the risk that on-farm actions supported by conservation programs could cause or exacerbate PFAS contamination on or off the farm. The committee was further tasked with identifying options within and outside the remit of the conservation programs to support PFAS mitigation or avoid PFAS contamination in agricultural systems and providing guidance on decision-making with regard to PFAS on agricultural land when so much remains to be learned about the fate and transport of these contaminants. Finally, USDA sought input on an agricultural working definition of these compounds as definitions of PFAS abound and none apply uniquely to agriculture. The committee's complete statement of task can be found in Box 1-1.

The National Academies appointed a committee with the diverse experience and expertise necessary to tackle this statement of task. In addition to PFAS, the committee members had expertise in soil chemistry, environmental toxicology, agricultural engineering, conservation practices and programs, risk assessment, and agricultural economics. The committee members served as volunteers and as individuals on this study, not as representatives of any institutions at which they may have been employed

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BOX 1-1
Statement of Task

A committee appointed by the National Academies of Sciences, Engineering, and Medicine (National Academies) will provide an initial framework to guide the efforts of the U.S. Department of Agriculture's Farm Production and Conservation (FPAC) programs that directly deal with conservation on the land, including the Environmental Quality Incentives Program, the Conservation Stewardship Program, the Conservation Reserve Program, and the Agricultural Conservation Easements Program, to respond to the impacts of per- and polyfluoroalkyl substances (PFAS) contamination of agricultural land. In a consensus report, the committee will:

- Characterize the scope of PFAS challenges in agriculture and the capability of the conservation programs, practices, and initiatives to address on-farm PFAS contamination and mitigation.
- Identify what factors FPAC agencies may consider when evaluating the risk that on-farm actions supported by FPAC conservation programs could cause or exacerbate PFAS soil or water contamination on or off the farm.
- Identify cost-effective and implementable options within the FPAC remit to support PFAS mitigation on farms (e.g., crop changes, land retirement, changes to on-farm water infrastructure), the research needed to inform the efficacy of these options, and considerations of actions to mitigate risk and the impacts of contamination in agricultural systems.
- Identify other actions, including conservation practices, that could mitigate or avoid PFAS contamination in agricultural systems but are outside the FPAC remit or may not yet be economically or technically feasible to implement at a large scale.
- Identify applied research gaps for land management of PFAS contamination as they relate to conservation practices on the ground.
- Provide guidance for decision making based on what is currently known as well as emerging information about the fate and transport of different PFAS in agricultural systems.
- Provide considerations for the development of an agricultural working definition of PFAS in the context of PFAS for which the U.S. Environmental Protection Agency has determined Regional Screening Levels.

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or organizations to which they may have belonged. The biography of each committee member can be found in Appendix A.

The committee met several times in 2025 to complete its task. All information-gathering meetings were open to the public, live streamed, recorded, and posted on the study's website. Agendas for these meetings can be found in Appendix B. In addition to hearing from invited speakers, the committee reviewed the scientific literature and pertinent government publications and federal legislation. The committee's draft report underwent peer review before the final report was publicly released.

STUDY SCOPE AND REPORT ORGANIZATION

PFAS are widespread in the environment and in daily life. Many health conditions—including kidney and testicular cancers and thyroid and cardiovascular diseases—are associated with PFAS exposure, and more are suspected (NASEM 2022). PFAS are found in wildlife around the world (Giesy and Kannan 2001) and are known to have effects on plants and soil microorganisms (NASEM 2024). Methods for detecting some PFAS and measuring their potential toxicity are still in development, and replacement and remediation efforts are nascent both in scale and practicality. Addressing the problem will require herculean efforts on multiple fronts, from chemical substitution to removal and destruction.

Even when narrowing the focus on PFAS to its intersection with food and agriculture, there are many issues to tackle. The health of those at high risk of exposure from working or living on contaminated land is of utmost concern, which will require appropriate action to reduce exposure and support related health care needs. PFAS contamination of food—whether through plant uptake, bioaccumulation in livestock, aquatic species (farmed or caught), and game, or transfer from food-packaging materials—also must be addressed. Determining when working lands must be removed from food or feed production, adequately compensating farmers for land retirement, and identifying options for returning PFAS-contaminated land to working status, whether that be wildlife habitat, livestock grazing, or crop production, are all problems that have yet to be solved. Similar challenges exist for assessing when products from contaminated animals must be removed from the market and herds depopulated.

This study concentrates on the segment of the broader PFAS contamination challenge that lies within the specific remit of USDA's FPAC programs that directly deal with conservation on the land. The agencies that administer these programs, NRCS and FSA, are nonregulatory. NRCS is charged with delivering conservation solutions to customers who voluntarily engage the agency's services. Neither NRCS nor FSA has jurisdiction over farmer or farmworker health. The committee was aware that there are individuals experiencing adverse health effects related to on-farm PFAS exposure[4] (NASEM 2022) and that Maine in particular is taking steps to provide support to affected individuals (Maine Department of Agriculture, Conservation & Forestry 2025).

[4] Personal communication, A. Nordell, Campaign Manager, Defend Our Health. "Statement to the committee," February 20, 2025. https://www.nationalacademies.org/projects/DELS-BANR-24-03/event/44521.

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PFAS in Agricultural Systems: Guidance for Conservation Programs at USDA

However, the committee was not charged with the task nor was it composed with the necessary expertise to evaluate ways by which farmer or farmworker exposure to PFAS may be mitigated.

Similarly, while the report does explore available conservation practices on working lands—such as irrigation water management, crop residue use, and conservation crop rotation—that could be implemented in a way that minimizes PFAS accumulation in crops or food products or that reduces wildlife exposure to PFAS, the FPAC mission area does not have authority regarding food safety. The safety of the U.S. food supply is mostly overseen by the U.S. Food and Drug Administration (FDA) and USDA's Food Safety and Inspection Service (FSIS). In 2025, FSIS conducted exploratory sampling of meat, poultry, and catfish and found that less than 0.3 percent of samples contained detectable PFAS. The agency had plans to expand the number of PFAS in its tests and lower its minimum level of applicability (Weyrauch et al. 2025). At the time of the committee's work, FDA had not set a threshold for PFAS contamination in food but on at least one occasion had tested milk at a dairy with known PFAS contamination and deemed PFAS levels in the milk as unsafe for human consumption (State of New Mexico 2022). FDA was also developing models for predicting PFAS in meat (Edhlund et al. 2025). The committee members recognized that continued testing and development of analytical methods to test PFAS in food are needed, but protecting the safety of the food supply was not part of their charge.

USDA cannot make potential customers seek out the advice or use the recommendations provided by its conservation specialists. Even if readily available and affordable remediation methods existed for PFAS contamination, the agencies under the FPAC mission area would have no authority to make a landowner or land manager implement such methods. The customer remains the decision-maker for solutions to address conservation needs within eligibility criteria. In its role as a provider of financial and technical assistance that supports conservation on the land, NRCS can recommend and financially support practices that customers then choose to implement to protect, or at least minimize harm to, natural resources and agricultural productivity from a group of contaminants that are mobile, recalcitrant, bioaccumulative, and not fully characterized. USDA sought the committee's guidance on how its conservation programs and practices could be used to this end.

The primary customer base for FPAC agencies is farmers, ranchers, and owners of forested land, but the services of these agencies are available to all landowners or land managers who seek to implement conservation practices on privately owned working lands. For-profit businesses, nonprofit organizations, foundations, owners of urban, suburban, and developing lands, land users, communities that pursue conservation objectives, and units of government at all levels with responsibilities for natural resource use and management are part of the customer base. Furthermore, the FPAC agencies sought guidance for all the kinds of land uses within their remit. The land may be planted to crops, grazed by livestock, established as forests, protected as habitat for wildlife, or conserved as wetlands. The agencies were also concerned about the quality of water for uses such as irrigation, livestock watering, and aquaculture.

Thus, while recognizing that there are many other areas of concern with PFAS

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PFAS in Agricultural Systems: Guidance for Conservation Programs at USDA

when it comes to food and agriculture, this report seeks to provide guidance on PFAS issues that are within the remit of FPAC programs that directly deal with conservation on land that is privately owned. To accomplish this task, Chapter 2 reviews the structure, classification, persistence, and environmental behavior of PFAS, as well as pathways by which PFAS enter and cycle in agricultural systems. Chapter 3 explains the conservation programs administered by NRCS and FSA that are specifically identified in the statement of task, the conservation practices supported by NRCS, and the ways in which both the programs and the practices intersect with PFAS contamination in agricultural systems. Chapter 4 outlines a framework by which decisions can be made about programs and practices to minimize PFAS contamination in these systems when so much uncertainty exists about the extent, types, toxicity, and concentrations of PFAS in the landscape. Chapter 5 reviews four areas of research that could advance the ability of conservation practices to address PFAS contamination on agricultural land.

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2

PFAS in Agricultural Systems

Among chemicals of concern, per- and polyfluoroalkyl substances (PFAS) have garnered a spotlight due to their persistence, links to adverse health effects, high usage, and the difficulty in identifying adequate replacements in a timeframe that will not affect U.S. economic competitiveness and national security. To provide an initial framework to guide the efforts of the Farm Production and Conservation (FPAC) programs that directly deal with conservation on the land, it is essential to understand the underlying science of how PFAS enter and interact with environmental media. This chapter provides foundational information on the structure, classification, and environmental behavior of PFAS—key elements that influence occurrence, mobility, persistence, and potential impacts of PFAS in agricultural systems. The committee uses *agricultural systems* as a shorthand to describe all the lands on which relevant FPAC agencies—namely, the Natural Resources Conservation Service (NRCS) and the Farm Service Agency—may work. As described by NRCS at one of the committee's meetings, the term agricultural system applies to a farm-level system and does not extend beyond the physical boundary of a farm operation.[1]

Understanding the characteristics and behavior of PFAS is critical for evaluating how PFAS contamination may affect the natural resource base—that is, soil, water, air, and plant and animal systems—and how PFAS may enter and cycle within agricultural systems. This chapter outlines the entry pathways for PFAS into agricultural settings, including point and nonpoint sources, and examines how PFAS move through agricultural landscapes and potentially leave the farm through surface water, groundwater, air, and food and other farm products.

[1] Personal communication, B. Reck, National Environmental Engineer, Natural Resources Conservation Service, U.S. Department of Agriculture. "Presentation to the committee," April 3, 2025. https://www.nationalacademies.org/projects/DELS-BANR-24-03/event/44748.

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PFAS STRUCTURE

PFAS can be differentiated from other synthetic compounds by the presence of one or more perfluorinated carbons, typically present as or within a branched or linear alkyl chain of varying carbon chain lengths, bound to a polar functional group, such as a carboxylate, sulfonate, alcohol, phosphate, amino, or other group (Figure 2-1). Polyfluorinated substances also have non-fluorinated, hydrocarbon moieties present within the alkyl chain or attached to the polar functional group. PFAS are manufactured primarily through (1) fluorotelomerization (FT), which results in a $–CH_2CH_2–$ linkage between the perfluoroalkyl chain and the polar functional group, and (2) electrochemical fluorination (ECF), which directly connects the perfluoroalkyl chain and the polar functional group (Buck et al. 2011). In addition, perfluoroalkyl ethers are manufactured through esterification and dehalocarbonylation. These processes, the type of polar functional group, and additional hydrocarbon moieties lead to several unique PFAS classes and varied environmental fate.

There are two broad classes of PFAS, namely polymers and non-polymers (Figure 2-2). Non-polymers are further divided into two subclasses: perfluoroalkyl substances (fully fluorinated) and polyfluoroalkyl substances (not fully fluorinated). Each of these subclasses contain different PFAS groups (Buck et al. 2011). Within perfluoroalkyl substances, the group perfluoroalkyl acids (PFAAs) contains the most well-known and well-studied PFAS—perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS)—which fall, respectively, into the two subgroups of PFAAs: perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) (Box 2-1). There are other PFAA classes, such as phosphonic (PFPAs, $-PO_3H_2$), sulfinic (PFSiAs, $-SO_2H$), and phosphinic (PFPiAs, $-PO_2H$) acids. Notably, these acids exist as anions in

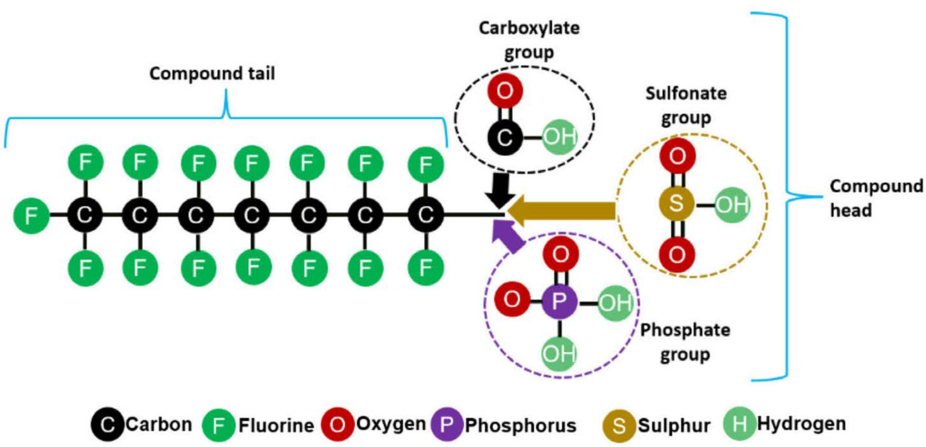

FIGURE 2-1 General structure example of neutral, non-polymeric, perfluorinated PFAS.
NOTE: PFAS structures shown here are present in the environment as anions due to the low pK_a of their acidic functional groups.
SOURCE: © 2023 The Pennsylvania State University. All rights reserved. See https://extension.psu.edu/understanding-pfas-what-they-are-their-impact-and-what-we-can-do.

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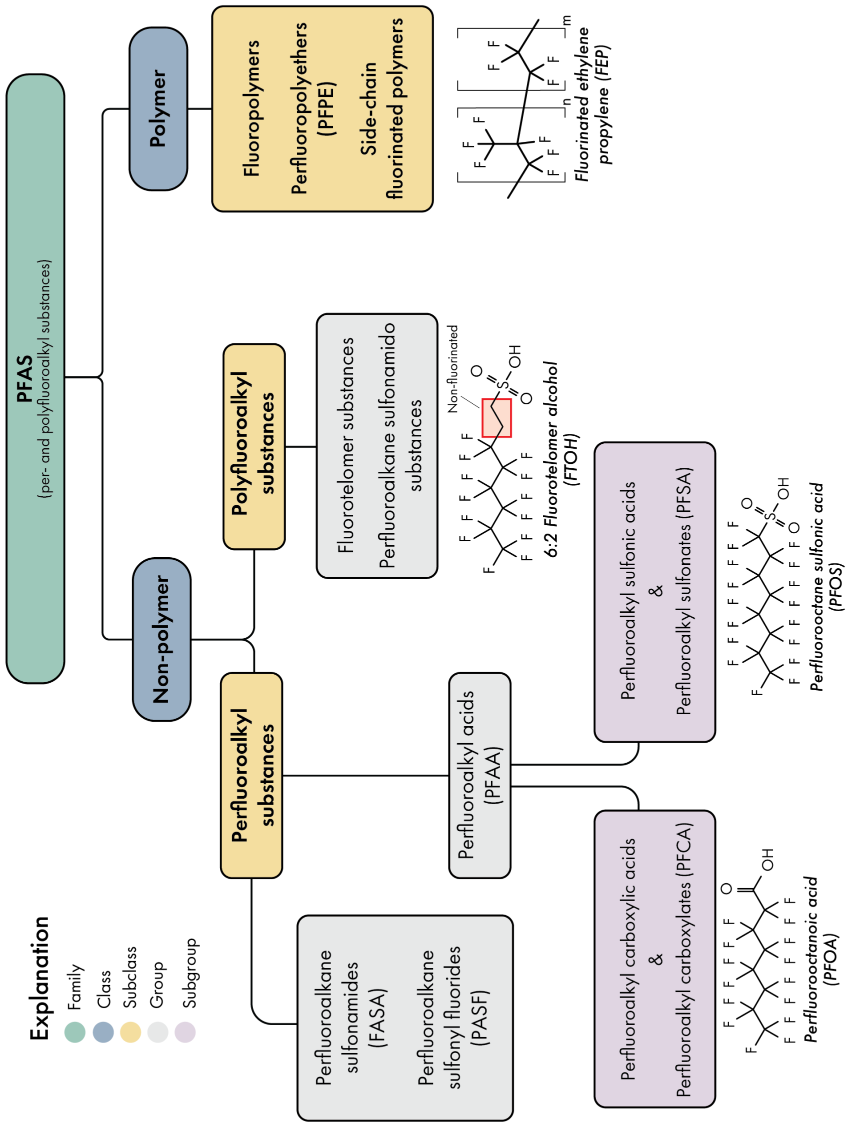

FIGURE 2-2 PFAS family tree.
SOURCE: McAdoo et al. 2022.

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BOX 2-1
Legacy PFAS: PFOA and PFOS

Of the thousands of PFAS that exist, the two most studied are perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). These were widely used for decades in products as processing aids for some nonstick coatings, stain-resistant fabrics, and aqueous film-forming foam (Lindstrom et al. 2011). With mounting evidence of the toxicity, persistence, and bioaccumulation of these long-chain PFAS, the U.S. Environmental Protection Agency began working with manufacturers in 2000 to end production of these substances (EPA 2000; Lindstrom et al. 2011). Most U.S. production of PFOA and PFOS was phased out by 2015 (EPA 2024a). Because they are no longer in mass production, these compounds are often referred to as *legacy PFAS*.

PFOA and PFOS are detected in the blood of nearly all participants in surveys of the U.S. general population, although the amount of PFOS and PFOA in samples has declined between the first survey at the beginning of the 21st century and surveys conducted two decades later. The downward trend might be expected with the phasing out of these substances from consumer products (Botelho et al. 2025). Nevertheless, detectable amounts of these compounds were still found in the blood of most adolescents, even though many in this cohort were born after phase-out efforts began (Botelho et al. 2025). The detection of legacy PFAS in this subpopulation, and its continued detection in the U.S. adult general population, likely results from the compound persistence and because PFOA and PFOS are terminal transformation products of precursor PFAS degradation. Precursor PFAS are polyfluoroalkyl substances that can degrade into terminal PFAS such as PFOA and PFOS. Examples include perfluorooctane sulfonamide and N-ethyl perfluorooctane sulfonamide, which degrade ultimately to PFOS, and fluorotelomer PFAS like 8:2 fluorotelomer alcohol and 8:2 diPAPs, which degrade ultimately to PFOA. In some cases, precursor PFAS were introduced to replace legacy PFAS. Degradation can occur in the environment or through biotransformation in the body (Sunderland et al. 2019; ITRC 2023).

the environment because of their low acid dissociation constants (pK_a); for example, PFOS exists and is often referred to in the literature as perfluorooctane sulfonate. Additional perfluoroalkyl substances include perfluoroalkane sulfonamides (FASAs), perfluoroalkyl aldehydes (PFALs), perfluoroalkyl iodides (PFAIs), perfluoroalkane sulfonyl fluorides (PASF), and perfluoroalkyl ethers (PFEAs).

Groups within the subclass of polyfluoroalkyl substances include FT-based PFAS and semi-fluorinated n-alkanes and alkenes, and ECF-based perfluoroalkane sulfonamido derivatives.[2] Polyfluoroalkyl substances differ from perfluoroalkyl substances

[2] Greater detail of the PFAS family tree can be found in Appendix C.

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because they contain both perfluorinated carbons and hydrocarbon segments. In ECF-derived polyfluoroalkyl substances, a perfluorinated chain is typically bonded to one side of a central functional group (e.g., a sulfonamide) with hydrocarbon moieties on the other. As noted above, FT-based PFAS consist of a single alkyl chain with a hydrocarbon spacer separating the functional group from the perfluorinated carbons. As a result, FT-based PFAS use nomenclature such as n:2 or n:3, indicating the ratio of perfluorinated carbons (n) to hydrocarbon carbons (2 or 3). For example, 6:2 fluorotelomer sulfonic acid (6:2 FTS) contains six perfluorinated carbons and two hydrocarbon carbons in one alkyl chain linked to a sulfonic acid group.

Polymer PFAS include fluoropolymers, polymeric perfluoropolyethers (PFPE), and side-chain fluorinated polymers. Most polymer PFAS are not easily broken down into monomer PFAS that can mobilize or bioaccumulate (Russell et al. 2008; Washington et al. 2009; Russell et al. 2010; Rankin et al. 2014; Washington and Jenkins 2015; Washington et al. 2015). Exceptions exist for certain side-chain fluoropolymers, some of which have relatively short environmental half-lives of less than 1 year (OECD 2022). Beyond these cases, there remains considerable debate regarding the persistence of polymeric PFAS, with reported half-life estimates ranging from several decades to millennia (Russell et al. 2008, 2010; Rankin et al. 2014; Washington and Jenkins 2015; Washington et al. 2015; Dasu and Lee 2016). Therefore, exposure pathways leading to adverse impacts on human and animal health are assumed to be lower compared with non-polymer PFAS. However, environmental data are sparse, and there is a lack of consensus on this topic (Lohmann et al. 2020). Occurrence data on side-chain fluorinated polymer surfactants is limited, but they have been found at up to several hundred parts per billion (ppb; equivalent at µg/kg) in Canadian biosolids (Letcher et al. 2020). In addition, the residual monomer PFAS that may be present in fluorinated polymers can be released during product use (OECD 2022).

Concerns with polymer PFAS are more about occupational exposure to and environmental emissions of non-polymer PFAS during polymer manufacturing processes as well as potential non-polymer PFAS residuals in finished products containing polymer PFAS. For example, atmospheric release of PFOA during application of dispersed fluoropolymer coatings and subsequent deposition has caused soil and groundwater impacts in regions such as eastern New York and western Vermont (Schroeder et al. 2021). Studies have also found that non-polymeric fluorotelomer alcohols (FTOHs) can be released from polymers (Dinglasan-Panlilio and Mabury 2006), which have been shown to contribute substantially to long-range, atmospheric PFAS transport (Wallington et al. 2006). Dispersal of non-polymer PFAS residuals in finished products containing polymer PFAS has been intentionally reduced over the past two decades. Some groups are also concerned about the unknown longevity of polymer PFAS after product disposal (Lohmann et al. 2020; Lohman and Letcher 2023).

Regulatory agencies have added chain length as a delineator of PFAS because the length of the carbon chain is a primary factor that influences the behavior of a PFAS in the environment and its potential to accumulate in living tissue (Figure 2-3). For example, the U.S. Environmental Protection Agency (EPA) characterizes PFCAs ($C_{n-1}F_{2n-1}$–COOH) as long chain if the substances have a chain of at least seven perfluorocarbon atoms; PFSAs ($C_nF_{2n+1}SO_3H$) are long chain with six or more perfluorocarbon

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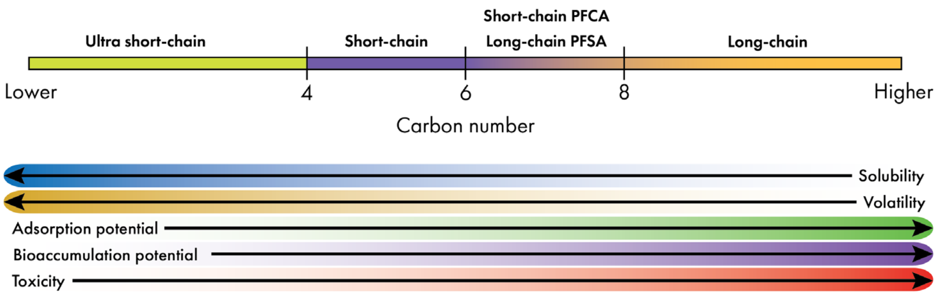

FIGURE 2-3 PFAS chain length in relation to carbon number, solubility, volatility, adsorption, bioaccumulation, and toxicity.
NOTE: The toxicity trends with chain length are not robust due to limited toxicity data for short-chain PFAS and the growing evidence of different toxicity mechanisms between short-chain and long-chain PFAS (Solan et al. 2023; Wang et al. 2024).
SOURCE: McAdoo et al. 2022.

atoms (Pulster et al. 2024). Ultra short-chain PFAS have fewer than four carbons (e.g., trifluoroacetic acid to perfluoropropionic acid). While the approach described here designates short-chain versus long-chain PFAS, there is no universally accepted definition for these two groupings.

OCCURRENCE OF PFAS IN U.S. SOILS

The scope of the PFAS challenge in U.S. agriculture is not well characterized as there are no national systematic surveys of PFAS concentrations in soil, groundwater, or surface water. EPA maintains an integrative map of data available on PFAS manufacturers, release, regional monitoring data, and occurrence in drinking water.[3] It contains only 234 soil sample data points—all taken from one location in Minnesota in 2008. Furthermore, as described below, there are datasets in addition to those compiled by EPA that suggest PFAS will be ubiquitous at low levels in many, if not most, soils. The widespread detection of PFAS raises key questions about what soil concentrations should be considered impacted or potentially harmful and what levels should be considered background or unimpacted.

Determining background PFAS concentrations and identifying a range of PFAS concentrations in contaminated ecosystems can help NRCS or a private landowner evaluate whether PFAS present on agricultural lands result from ambient deposition or represent impacts of nearby sources or use of PFAS-impacted materials on site. Studies have assessed PFAS in impacted soils and at sites without a known PFAS source. Rankin et al. (2016) analyzed soil samples collected across the United States (including Hawaii, Alaska, and Puerto Rico), Canada, and Mexico, from locations with no or limited human impact. In North America, total PFCA and PFSA concentrations were found in the 0.15–6.08 µg/kg and 0.04–2.0 µg/kg ranges, respectfully. There were quantifiable concentrations of at least three PFCAs in all locations, and PFOA and PFOS were detected in samples from all 29 locations in the United States. Washington et al. (2019)

[3] See *EPA PFAS Analytic Tools*, https://awsedap.epa.gov/public/extensions/PFAS_Tools/PFAS_Tools.html.

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subsequently implemented a statistical analysis of the Rankin et al. (2016) dataset and found that mean PFCA background concentrations in the northern hemisphere were 0.0114 µg/kg (perfluorodecanoic acid [PFDA]) to 0.0583 µg/kg (perfluorohexanoic acid [PFHxA]). The mean background concentration of PFOS in the northern hemisphere was 0.0555 µg/kg. These data support the conclusion that, even without direct application of PFAS-contaminated inputs, PFAS can accumulate in the environment through long-range air transport (see section "Transport Via Water and Air" below; Rankin et al. 2016).

Background PFAS levels have also been assessed in some states. In Vermont, data were generated from 68 surface soil samples collected from state and municipal parks, forests, greens, and lawns within urban areas (Zhu et al. 2019). Perfluorononanoic acid (PFNA) and PFOS were detected in 100 percent of soil samples at concentrations of 0.051–5.0 µg/kg and 0.106–9.7 µg/kg, respectively. EPA statistical software ProUCL was used to establish background threshold values for 10 PFAS detection frequencies greater than 10 percent. The proposed values were 0.150 µg/kg (perfluorodecanesulfonic acid [PFDS]) to 3.40 µg/kg (PFOS). These values are higher than those estimated by Washington et al. (2019), which may reflect analysis of samples from urban areas rather than those with little to no human impact.

In Massachusetts, samples were collected from 100 sites that were distant from known or potential PFAS sources (e.g., state and municipal parks, woodlands, and other conservation areas; McIntosh et al. 2025). PFOA and PFOS were detected in 100 percent of soil samples at concentrations of 0.072–4.20 µg/kg and 0.190–6.00 µg/kg, respectively. Four other PFAS were detected in at least 80 percent of samples. Background threshold values for 12 PFAS-detection frequencies greater than 10 percent were estimated as the upper 95-percent confidence level on the 95th percentile of the concentration distribution (known as the upper tolerance level). The resulting values were 0.079 µg/kg (PFBS) to 3.25 µg/kg (PFOS). The study authors concluded that, based on the types and relative abundances of PFAS present, these background PFAS likely originated from long-range atmospheric transport, not from regional industrial or other sources. Based on samples collected from Maine and New Hampshire, McIntosh et al. (2025) also proposed background threshold values of 0.080 µg/kg (perfluoropentanoic acid [PFPeA]) to 0.648 µg/kg (PFOS) for Maine and 0.061 µg/kg (hexafluoropropylene oxide dimer acid [HFPO-DA]) to 2.41 µg/kg (PFOS) for New Hampshire.

Brusseau et al. (2020) compiled published literature data from more than 30,000 soil samples and from more than 2,500 sites throughout the world focused on maximum reported total PFAS, PFOA, and PFOS concentrations. The data included background soil concentrations from more than 1,400 sites (including Rankin et al. 2016) and from hundreds of primary source sites (e.g., PFAS manufacturing sites, fire-training areas, and locations where aqueous film-forming foam [AFFF] had been used) and secondary source sites (e.g., sites adjacent to primary sites or sites where PFAS-contaminated materials were utilized) where PFAS were directly or indirectly utilized. Data compiled by Brusseau et al. (2020) included samples from urban areas (e.g., parks) similar to those described in the Vermont study (Zhu et al. 2019) and samples from pristine areas with minimal human impact as described in Rankin et al. (2016). Maximum reported

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PFOA and PFOS concentrations from background sites in the compiled datasets were 0.5–33 μg/kg and 3.1–126 μg/kg, respectively. Maximum PFOA or PFOS concentrations from locations categorized as background by Brusseau et al. (2020) tended to be one to three orders of magnitude lower than those found in primary or secondary contaminated sites (Table 2-1). However, the range of reported background concentrations is 1–2 orders of magnitude higher than studies summarized above. This difference likely reflects the inclusion of varied site types and the focus on maximum reported concentrations. Importantly, no statistical analyses of this compiled dataset have been implemented to understand what concentrations are likely to be most representative of background PFAS.

Information on background PFAS in soil and other media can help inform whether a site contains PFAS from ambient PFAS deposition (e.g., precipitation) or PFAS sources (e.g., manufacturing discharge, biosolids) and may help contextualize PFAS detections at agricultural facilities. However, results of studies to date highlight challenges in establishing background PFAS concentrations. There is no consensus regarding sampling location types that are defined as background, and studies summarized above suggest different results will be obtained from relatively pristine locations versus urban sampling locations that are not proximal to known PFAS sources. Additionally, studies have used varied sample preparation approaches and analytical methods, included different PFAS analyte lists, achieved different detection limits, and used different

TABLE 2-1 Maximum Reported PFAS in Soils Worldwide and in the United States

	Background Sites	Primary-Source Contaminated Sites	Secondary-Source Contaminated Sites
	μg/kg		
Global			
Total PFAS	<0.001–237	ND	ND
Min. PFOA	0.01	2	0.8
Max. PFOA	123.6	50,000	2,531
Median PFOA	2.7	83	38
Min. PFOS	0.003	0.4	0.4
Max. PFOS	162	460,000	5,500
Median PFOS	2.7	8,722	680.5
United States			
Total PFAS	<0.2–135	ND	ND
Min. PFOA	0.5	58	23.6
Max. PFOA	33	50,000	2,531
Min. PFOS	3.1	9,700	483
Max. PFOS	126	373,000	1,409

NOTE: ND = no data.
DATA SOURCE: Created using data from Tables 1, 2, and 3 in Brusseau et al. 2020.

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quality assurance and quality control protocols; these differences challenge comparison of results across studies. As a result, caution should be exercised before using data from prior work to establish concentrations considered impacted versus unimpacted at agricultural facilities.

FATE AND TRANSPORT OF PFAS IN THE ENVIRONMENT

Once in the landscape, the behavior of PFAS in the soil and their transport outcomes depend on prevailing soil and PFAS properties, as well as topography, climate, and land management. These factors affect PFAS sorption to soils and air–water interfaces, leaching, runoff, wet and dry deposition, uptake by plants, and bioaccumulation. These effects on environmental media and plant and animal life influence what NRCS terms the *resource base*— that is, the condition of soil, water, air, plants, and animals, which NRCS often refers to as SWAPA.

Abiotic and Microbially Mediated PFAS Transformation

Though the carbon–fluorine bond is extremely difficult to break, most polyfluoroalkyl substances are susceptible to biotransformation via oxidation and microbial degradation. Microbial degradation of PFAS is considered a co-metabolic process (Wackett 2025). A few studies have claimed degradation with specific PFAAs as the sole carbon source; however, only partial defluorination was observed and other evidence within the studies was not consistent (e.g., presence of fluoride but no loss of parent compound; Chetverikov and Loginov 2019; Harris et al. 2022; Smorada et al. 2024).

The PFAS that break down into terminal PFAAs are known as precursors. Though intermediate PFAS transformation products may also persist in the environment for some time, precursor degradation ultimately yields PFAAs, including PFOA and PFOS (Box 2-2; Figure 2-4).

For FT-derived precursors, degradation typically ends in the formation of a suite of PFCAs, with the dominant PFCA corresponding to the length of the precursor's perfluorinated carbon tail (Liu and Mejia Avendaño 2013; Figure 2-4A). For example, degradation of 8:2 fluorotelomer alcohol (8:2 FTOH) primarily yields PFOA as the major end product but also includes other shorter-chain PFCA products. In contrast, ECF-derived precursors ultimately degrade to PFSAs of the same perfluoroalkyl chain length originally present in the precursor (Mejia Avendaño and Liu 2015; Zhang et al. 2017; Figure 2-4B).

The half-lives of precursors and their intermediates in soils vary widely, often spanning several orders of magnitude (Guelfo et al. 2021). Degradation occurs significantly faster under aerobic conditions than in anaerobic settings. While environmental factors such as soil properties, climate, and vegetation do influence microbial degradation rates, the PFAS class itself is often the most important determinant of degradation half-life under a given set of conditions. Generally, FT-derived precursors and some ECF-derived compounds fall on the shorter end of the half-life spectrum because of the relatively easily attacked non-fluorinated linkages, such as the $–CH_2CH_2–$ group found

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BOX 2-2
PFAS and Persistence

For many legacy PFAS, such as PFOA and PFOS, no environmentally relevant degradation pathways are known under ambient conditions. These compounds persist indefinitely once released. Some PFAS, specifically polyfluoroalkyl substances, can undergo a degree of transformation in the environment, but their intermediate and terminal products are themselves PFAS. Stated differently, parent compounds may not be persistent in their original form, but their transformation products remain fluorinated and resistant to mineralization, and they ultimately transform into fully recalcitrant PFAS such as perfluoroalkyl acids (PFAAs). Thus, even when the parent molecule is not inherently a "forever chemical," transformation processes yield formation of PFAS that are.

Polyfluoroalkyl substances that contain a trifluoromethyl (CF_3) group and are capable of environmental transformation can form PFAAs. In some cases, such as molecules with a single CF_3 group attached to a partially fluorinated or non-fluorinated structure, transformation may yield ultrashort-chain PFAAs such as trifluoroacetate (TFA). In this sense, PFAS have redefined the understanding of molecular persistence in environmental systems. Even when parent PFAS are not persistent in their initial form, they gain persistence through transformation into fully stable, recalcitrant endpoints.

in many FT-derived PFAS. Among fluorotelomers, for example, fluorotelomer alcohols degrade relatively quickly, with aerobic half-lives ranging from a few hours to less than 1 month. In contrast, fluorotelomer sulfonates degrade more slowly, with aerobic half-lives ranging from several months to a few years. For ECF-derived PFAS, certain intermediates—such as ethylfluorosulfonyloxyacetic acid (EtFOSAA) and methylfluorosulfonyloxyacetic acid (MeFOSAA)—can persist in soils for well over a year under laboratory conditions and for multiple years under field conditions. These persistent intermediates can lead to continued, in situ production of PFOS, contributing to long-term environmental contamination (see Figure 2-2).

The unfavorable thermodynamics of breaking the carbon–fluorine bond also leads to natural abiotic processes being limited for transforming PFAS. Soil minerals can react with natural constituents to form reactive oxygen species, such as hydroxyl radicals, that can then degrade other constituents. Potential abiotic processes include hydrolysis, hydroxylation, decarboxylation, and oxidation–reduction, all of which will be PFAS-dependent and only lead to a partial transformation result similar to biotransformation processes (Fang et al. 2025). These processes under natural soil conditions are slow and considered insignificant for PFAS mineralization. Considerable attention has been given to the role of biological enzymes and the use of added enzymes to promote PFAS degradation (Amin et al. 2025; Harris et al. 2025; Mekureyaw et al. 2025) or covalent binding of PFAS to organic matter, known as humification (Munir et al. 2025).

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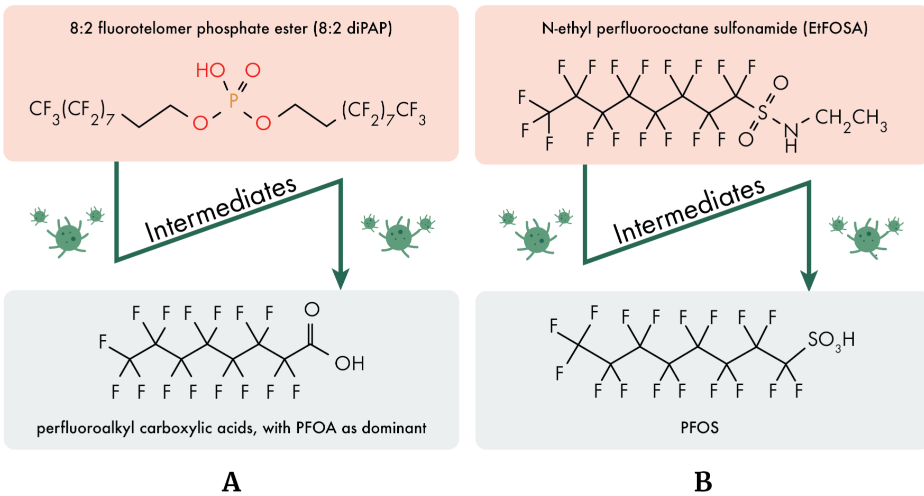

FIGURE 2-4 Depiction of microbially mediated transformation for two representative precursors, (A) fluorotelomerization example of 8:2 fluorotelomer phosphate diester (diPAP) transformation to PFCAs with PFOA as dominant and (B) electrochemical fluorination example of N-ethyl perfluorooctane sulfonamide (EtFOSA, sulfluramid) transformation to PFOS.
NOTE: Precursors of PFAAs may go through many intermediate steps, pathways, and rates before ultimately transforming into terminal microbial metabolites.
SOURCE: Original from Linda S. Lee, modified with permission.

Nevertheless, to date, only lab-scale studies have shown partial degradation similar to trends in biotransformation or humification. Applications at the field scale are likely to be made difficult by stability under environmental conditions, enzyme specificity, limited substrate range, and a lack of understanding of the enzymatic pathways.

Sorption

Sorption of PFAS by soils occurs through several mechanisms, including hydrophobic and electrostatic interactions, as well as hydrogen and covalent bonding (Higgins and Luthy 2006; Figure 2-5). Hydrophobic interactions take place between the perfluorocarbon tails of PFAS and soil organic matter (SOM), with increasing ionic strength increasing sorption. Electrostatic interactions, which are affected by pH, occur directly between the polar functional groups of PFAS and the charged components of soil, such as SOM or metal oxides (e.g., iron or aluminum oxides), or indirectly through cation bridging with divalent cations (Mejia-Avendaña et al. 2020; Mei et al. 2021; Kookana et al. 2023). Sorption to metal oxides can also occur via ligand exchange of hydroxyl groups, for example, the carboxylate head of PFCAs (Du et al. 2014). PFAA affinity to soil proteins has been attributed to electrostatic interactions between anionic PFAAs and positively charged amino and amide groups in proteins (F. Li et al. 2019). Hydrogen

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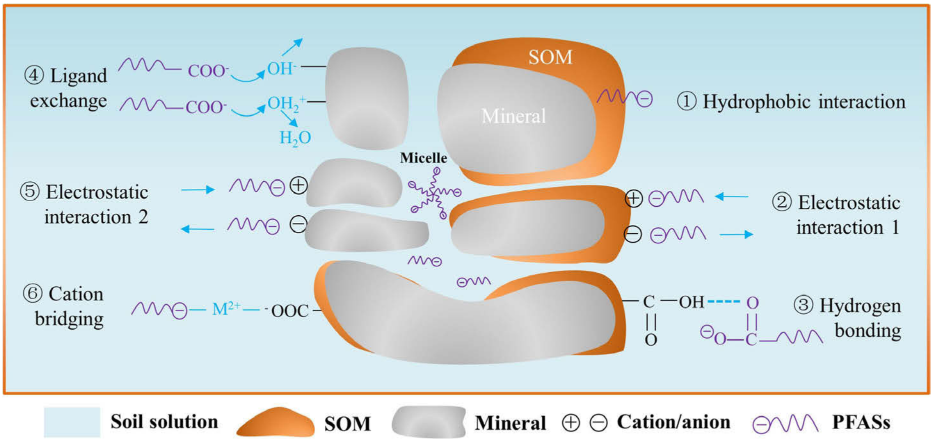

FIGURE 2-5 Possible sorption behaviors of PFAS in soil environments, an example of anionic perfluoroalkyl acids (PFAAs).
NOTE: SOM = soil organic matter.
SOURCE: Mei et al. 2021. CC BY-ND 4.0.

bonding of PFAAs with soil functional groups and covalent bonding with SOM have also been demonstrated in lab-scale spectroscopic studies (Zhu et al. 2021). In addition, PFAS can self-assemble into micelles, hemi-micelles, and versicular structures (Krafft 2025; Yan et al. 2025), which affects their interaction with soil surfaces and air–water interfaces (AWI), including potential entrapment in soil aggregates.

Perfluorocarbon chain length and the type of polar functional group are the main PFAS structural properties that influence sorption. Most sorption data to date are for PFAAs. Sorption is generally stronger as the chain length increases for PFAS with the same functional group (e.g., PFCAs or PFSAs) because the longer the chain, the more hydrophobic the PFAS (Sharifan et al. 2021). Different functional groups have different sorption behavior; for example, among the PFAAs, PFSAs exhibit stronger sorption than PFCAs of the same chain length. Zwitterionic and cationic PFAS may bind to greater magnitudes than PFAAs because of the dominance of negative charge sites on soils.

The charge state of a PFAS also affects the extent of sorption. Most PFAS, especially PFCAs and PFSAs, have relatively low acid dissociation constants (pK_a values below 1.6 and 0.3, respectively) (Burns et al. 2008; Goss 2008; Rayne and Forest 2010; Vierke et al. 2013; Murillo-Gelvez et al. 2023), which means they exist as negatively charged anions under most environmental conditions (i.e., pH 4–9). Exceptions include FASAs, which have a pK_a of ~6 and may exist in neutral or anionic form at environmentally relevant pH. In contrast, zwitterionic and cationic PFAS—many of which have been used historically in AFFF—exhibit different sorption behavior because of their positive or mixed charges and may bind more strongly to soil surfaces. Although soil organic carbon has traditionally been viewed as the primary driver of sorption for

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hydrophobic chemicals, it alone often does not accurately predict PFAS sorption to many soil types and within soil profiles because of the charge of the polar functional group (Li et al. 2018; Kookana et al. 2023; Evich et al. 2025).

In addition, PFAS with polar functional groups are surfactants and therefore tend to accumulate at interfaces, especially the AWI in the vadose (unsaturated) zone (Brusseau 2018; Sharifan et al. 2021), akin to how soap suds collect at the AWI. The extent of this interfacial sorption (K_{aw}) increases with PFAS chain length (thus molar volume), as longer-chain PFAS have higher affinity for the AWI (Brusseau 2023; Endo et al. 2023). Decreasing soil particle size and moisture content both lead to higher interfacial surface area and thus more air–water interfacial partitioning of PFAS; interfacial partitioning also increases with increasing ionic strength of the porewater (Lyu and Brusseau 2020). Thus, the magnitude of sorption at the AWI is determined by soil properties, moisture content, and the PFAS AWI sorption coefficient. PFAS concentration can also affect sorption in the vadose zone because of both PFAS self-assembly mechanisms (micelle formation) and competitive sorption (Silva et al. 2021). Fate and transport models with PFAS-specific considerations for sorption to soil and the AWI are increasingly being used to understand and predict PFAS fate and transport (see Box 4-1 in Chapter 4), including in agricultural scenarios (Guo et al. 2022; Silva et al. 2022; Brusseau and Guo 2023; Smith et al. 2024; Liao et al. 2025; Doria-Manzur et al. 2026).

Plant Uptake

Many PFAS can move within plants through both passive and active transport mechanisms, allowing them to translocate from one part of the plant to another. The extent and pathway of PFAS uptake depend on several key factors, including the chemical structure of the PFAS (especially functional group and alkyl chain length), the initial concentration and profile of PFAS in environmental media (such as soil or water), plant type, and the chemical characteristics of the media—notably organic carbon content, surface charge, and pH (Ghisi et al. 2019; Costello and Lee 2024). Measured transfer factors of PFAS from soil to plant are also affected by the presence of precursors that can transform during the growing season. The PFAAs generated through precursor degradation are not captured in the soil concentration but are equally subject to plant uptake. In field studies, Simones et al. (2024) found PFOS precursor presence to be significantly associated with increasing PFOS transfer factors. Likewise, in a forage greenhouse study, Openiyi et al. (2025) attributed high transfer factors to measured precursor transformation. In addition, it is well established that uptake and accumulation of PFAS are distinctly higher in the vegetative parts of plants (leaves) than in storage organs (fruits, grains, tubers) (Stahl et al. 2009; Blaine et al. 2014; Wen et al. 2014; Wang et al. 2020; Lesmeister et al. 2021).

PFAS typically accumulate passively in root tissues, primarily via diffusion from high-concentration zones in the surrounding environment. This diffusion is strongly influenced by PFAS sorption to soil particles, which affects bioavailable concentrations in porewater, and by soil moisture content, which mediates PFAS mobility and access

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to the root surface. Once at the root surface, PFAS accumulation is further influenced by the protein and lipid content of root tissues, which may enhance or inhibit binding. Root density and architecture affect the root's contact area with soil and soil porewater where PFAS reside, as well how much of the soil is explored by the roots, thus affecting the extent of PFAS accumulation. However, molecular size and structure play a critical role in whether a PFAS can penetrate the root barrier. Some larger or more complex PFAS molecules may be restricted from entering root tissues or prevented from translocating further into the rest of the plant. PFAS interaction with the roots is defined by the *root concentration factor*—the ratio of PFAS concentration in the root to that in the surrounding media—and will be PFAS, plant, and media dependent. Additionally, in one greenhouse study, mixtures of PFAS were also noted to affect uptake, with PFOA uptake increasing when present in a mixture of PFAAs (Zhang et al. 2022).

Once PFAS have entered the root, translocation to above-ground plant parts (such as stems, leaves, and reproductive tissues) can occur and is often quantified by a *translocation factor*—the ratio of PFAS concentration in the above-ground tissues to that found in the root. This process happens primarily for PFAAs and is driven by transpiration-induced flow through the xylem, the vascular system that transports water and nutrients upward from the roots. Shorter-chain PFAS, which are less likely to sorb to soil particles, remain more freely dissolved in porewater and thus are more readily available for uptake and translocation through transpiration (Krippner et al. 2015; Wang et al. 2020; Costello and Lee 2024). Consequently, as chain length increases, both overall plant uptake and movement into above-ground tissues tend to decrease.

Nonetheless, some long-chain PFAS, including PFOS, have been detected in the leaves, stems, and seeds of grasses and other plants. For PFAS to reach reproductive tissues such as seeds (e.g., grains, beans, or corn kernels), they must be transferred from the xylem to the phloem, which transports nutrients throughout the plant. This xylem-to-phloem offloading may occur via nonselective substrate transporters, allowing certain PFAS to move into reproductive tissues (Yao et al. 2020; Gill et al. 2021). For example, Lazo and Lee (2024) observed primarily short-chain perfluorobutanoic acid (PFBA) and perfluoropentanoic acid (PFPeA) and did not observe PFSAs in the bean of soybean plants although PFOS soil concentrations were several hundred ppb (μg/kg). This result indicates that PFCAs, which mimic fatty acids, are likely to be inadvertently transported into the phloem, whereas the PFSAs are not. Trends from greenhouse and field studies to date show that levels of long-chain PFAS are half to three orders of magnitude lower in storage organs (fruits, grains, tubers) than in plant vegetative parts (Stahl et al. 2009; Blaine et al. 2014; Wen et al. 2014; Krippner et al. 2015; Wang et al. 2020; Lesmeister et al. 2021; Lazo and Lee 2024; Ortiz and Mallory 2025).

Transport Via Water and Air

PFAS present in soil can be transported through the environment via water by vertical leaching into deeper soil layers and groundwater and by surface runoff during precipitation and snowmelt events. The extent to which PFAS are transported by these

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processes is strongly influenced by their sorption to soil surfaces as well as their accumulation at the AWI within the vadose (unsaturated) zone. The degree of PFAS leaching is determined by a combination of climatic and hydrologic conditions, soil hydraulic and chemical properties, and PFAS sorption, which is discussed above. Environmental factors—such as rainfall intensity and duration and snowmelt, as well as irrigation rates—play a particularly critical role in mobilizing PFAS via leaching and runoff (Borthakur et al. 2021c). These effects can be amplified by the release and downward transport of soil colloids during infiltration events, which may carry sorbed PFAS deeper into the soil profile (Borthakur et al. 2021a). Additionally, natural weathering and seasonal drainage cycles can remobilize PFAS that had previously been bound to soil particles (Borthakur et al. 2021b).

As discussed above, short-chain PFAS sorb less than longer-chain PFAS, leading to their higher propensity to be in soil porewater. Short-chain PFAS are thus more available for plant uptake or leach more readily than long-chain PFAS. These characteristics create an inverse relationship between soil depth and the long-chain PFAS concentration. Specifically, long-chain PFAS tend to accumulate in surface soils, while short-chain PFAS migrate deeper or are more likely to be absorbed by vegetation (Alvarez-Ruiz et al. 2024; Peter et al. 2025). Time since application and the balance of rainfall events leading to leaching versus to runoff control what PFAS may remain in surface soils and thus be subject to runoff. The persistence of long-chain PFAS in surface soils makes them more susceptible to overland transport via runoff, particularly during high-intensity or frequent precipitation events (Peter et al. 2025). However, any PFAS present in surface soils are subject to runoff. Therefore, short-chain PFAS are also frequently found in runoff; they have been observed often in urban water systems (Kali et al. 2025; Saleh et al. 2025; Zhang et al. 2025). Often attached to suspended solids, PFAS can be carried into nearby surface water bodies. PFAS-laden runoff that enters streams or closed or semi-closed aquatic systems, such as ponds and lakes, can increase exposure of animals that use those water bodies as drinking sources (e.g., livestock) or habitat (e.g., fish) (see section “Bioaccumulation” below). In tile-drained agricultural fields (perforated corrugated piping placed approximately 1 meter below the surface), vertical PFAS transport to groundwater is short-circuited and diverted to the agricultural ditch network, which flows into larger flowing surface water bodies (Gottschall et al. 2017; Peter and Lee 2025).

PFAS enter the atmosphere through manufacturing emissions, landfill waste combustion, volatilization, and wind-blown particles from PFAS-contaminated lands and through aerosols produced during the use of AFFFs or spraying PFAS-containing pesticides, as well as from water bodies including lakes, the ocean, and aeration basins (Faust 2023; Kourtchev et al. 2023; Lin et al. 2024; Pandamkulangara Kizhakkethil et al. 2024). Once in the atmosphere, precursor PFAS such as FTOHs can undergo oxidative transformation to the terminal PFAAs (Ellis et al. 2004; Wallington et al. 2006; D’eon et al. 2006; Nielsen et al. 2007; Faust 2023). Airborne PFAS undergo wet/dry deposition through rain events and particle settling. For example, PFAS concentrations up to 200 μg/kg have been reported in agricultural soils near a fluorochemical manufacturing plant

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(Liu et al. 2019). Additionally, airborne PFAS (whether sorbed to particles or present as aerosols) can be transported via air currents for several months and well beyond initial emission locations (Kourtchev et al. 2024), thus contributing to background levels of PFAS in terrestrial and aquatic ecosystems.

The myriad of PFAS uses coupled to long-range atmospheric transport has led to an increasing frequency of PFAS detections in rainwater, in some instances above prevailing regulatory limits or guidelines (Shimizu et al. 2021; Cousins et al. 2022; Pfotenhauer et al. 2022). Natural precipitation has been shown to contribute to PFAS accumulation in North American and Asian topsoils (Scott et al. 2006; Chen et al. 2019; Gewurtz et al. 2019). A study by Shimizu et al. (2021) showed that the annual flux contribution of PFAS was over an order of magnitude greater via wet versus dry deposition. Shimizu et al. (2021) suggested that PFAS incorporation into natural precipitation may be localized, yet PFAS have been found at both poles of the globe (Del Vento et al. 2012; Xie et al. 2015).

Bioaccumulation

Because PFAS are hydrophobic, lipophobic, and proteinophilic, as well as environmentally persistent, they tend to accumulate in biota, including human and animal tissues (Savoca and Pace 2021; De Silva et al. 2021). As with their stronger sorption to soils, longer-chain PFAS have a higher bioaccumulation propensity and take longer to be eliminated from the body (body $t_{1/2}$). PFAS affinity for proteins has made some PFAS highly bioaccumulative, particularly as perfluorocarbon chain length increases. PFAS accumulation has been found in muscle tissue, liver, kidneys, and breast milk of humans and animals globally (Custer et al. 2014; Death et al. 2021; Wood et al. 2021; Coy et al. 2022; Khan et al. 2023; Witt et al. 2024). PFAS have even been found in brains (Khalid et al. 2025), most likely transported through phospholipids. PFAS have been found in the blood samples of nearly all human beings (Jian et al. 2018; Kuo et al. 2023) and are frequently detected in wildlife, domesticated animal products (milk, meat, eggs, fish) (Göckener et al. 2020; Lasters et al. 2022), and a variety of foods. Some PFAS, such as PFOS, tend to bioaccumulate effectively in animal tissue, even when feed or forage contain low PFAS concentrations, resulting in livestock animal products (e.g., milk and meat) with high levels of PFAS (Fitzgerald et al. 2025). Likewise, relatively low PFAS concentrations in water can lead to elevated concentrations in humans and other biota.

PFAS that bioaccumulate in one species can transfer to another through food webs. New Mexico issued a health advisory in January 2025 to hunters and anyone consuming game from Holloman Lake after samples of waterfowl and rodent tissue collected from the habitat were found to contain the highest PFAS levels ever recorded in wild animals (Witt et al. 2024; Daniel B. Stephens & Associates, Inc. 2025; New Mexico Department of Health 2025). Stormwater runoff and treated sewage from nearby Holloman Air Force Base were found to outflow into the lake, potentially contributing to this problem. In a

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separate investigation, a freshwater food web in a North Carolina/South Carolina river likely contaminated by municipal and agricultural sources identified high concentrations of several PFAS in biofilm, aquatic insects, and fish, suggesting that insects may bioaccumulate PFAS from feeding on biofilm, and fish may do the same by feeding on insects (Penland et al. 2020). However, bioaccumulation of PFAS varied by type of PFAS, and organisms were likely exposed via water in addition to diet. Within tributaries of the Hudson River in New York, elevated levels of PFAS have been measured in benthic macroinvertebrates, even though concentrations of PFAS in surrounding surface water and sediment were not exceedingly high; these results indicate bioaccumulation in the macroinvertebrates, with implications for the fish that feed on them (Brase et al. 2022). PFAS bioaccumulation has also been reported in feeding experiments involving crickets (McDermett et al. 2022), earthworms (Rich et al. 2015), and toads (East et al. 2025). In studies conducted in Europe, PFAS have been found in honeybees (Müller et al. 2025) and honey (Surma et al. 2016).

Biomagnification

Bioaccumulation of PFAS through food webs often leads to biomagnification. Biomagnification results when ingested compounds accumulate and become more concentrated in the animal's tissues because elimination rates are slower than accumulation rates (Death et al. 2021; Fremlin et al. 2023; George et al. 2023; Khan et al. 2023; Miranda et al. 2023; Adeogun et al. 2024). Biomagnification is affected by both PFAS properties and ecological factors such as habitat (e.g., temperature) and organism characteristics (e.g., size, age, and sex; Burkhard 2021; Cara et al. 2022; Adeogun et al. 2024). Trophic magnification factors (TMFs) are used to describe quantitatively the increase in concentration with increasingly higher trophic levels (Death et al. 2021; Adeogun et al. 2024; Kelly et al. 2024; Ricolfi et al. 2025). TMFs are higher for longer-chain PFAS and tend to be higher for PFSAs compared to PFCAs with a similar chain length (Adeogun et al. 2024). For PFAS-contaminated areas, similar to the legacy chemicals mercury and polychlorinated biphenyls, fish consumption recommendations include restricting the amount of higher-trophic-level fish consumed per unit time (ECOS 2025). Of particular concern in the livestock industry are dairy and meat products. The high affinity of PFAS for proteins (Martin et al. 2013; Ng and Hungerbühler 2013), which are high in meat and milk, leads to bioaccumulation and subsequent biomagnification. Livestock consume large amounts of plant material (e.g., typically 25 pounds or more per day for cows), which can lead to unacceptable PFAS levels in meat and milk even for low PFAS-containing feed. There are currently no formal maximum contaminant levels for PFAS in milk and meat, but Maine has set action levels when PFOS exceed 210 parts per trillion (ng/kg) in milk (Maine Center for Disease Control and Prevention 2017) and 3.4 ppb (µg/kg) in meat (Maine Center for Disease Control and Prevention 2020), based on potential risk to children. Another concern due to biomagnification is PFAS levels in higher-trophic-level fish in surface water bodies receiving PFAS-contaminated runoff or deposition. For example, Hoskins

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et al. (2023) observed PFOS at several hundred ppb (μg/kg) in largemouth bass collected in a pond receiving runoff from nearby farms that had received biosolids over time.

ENTRY AND CYCLING OF PFAS IN AGRICULTURAL SYSTEMS

Like all contaminants, PFAS can enter an agricultural system through a point or a nonpoint source. An example of point-source PFAS contamination is the release by military installations of AFFF into groundwater that is eventually used by farmers for livestock watering or crop irrigation.[4] Documented cases of such contamination include Highland Dairy near Cannon Air Force Base in New Mexico (Amec Foster Wheller Programs, Inc. 2018; NASEM 2022; State of New Mexico 2022) and Venetucci Farm near Peterson Air Force Base in Colorado (Aerostar SES LLC 2017; Gaulke 2020). Nonpoint-source contamination can enter via any number of routes (Figure 2-6). PFAS from off-site emissions from any unknown source(s) may be introduced via fate and transport processes, including atmospheric transport (e.g., wind-born particulate deposition, precipitation), impacted groundwater, land-applied wastewater effluent, and impacted surface water. Products applied to agricultural fields may also introduce PFAS impacts. Organic soil amendments (e.g., biosolids, manure, compost; Box 2-3) are increasingly scrutinized as a source of introduction to agricultural operations. PFAS have also been detected in pesticides, but there is debate about whether the container or formulation is the source of the PFAS as well as which PFAS occur and at what levels, even within a single pesticidal formulation (PEER 2020). Additionally, fluorinated pesticides can degrade to ultra short-chain PFAS trifluoroacetate (TFA) (Ellis and Mabury 2000; EFSA 2014). Other potential sources include synthetic fertilizers, commercial livestock feed (Choi et al. 2023), and animal bedding (Fernandes et al. 2019), which can include paper and paper industry residuals that may contain PFAS (Choi et al. 2019). Lastly, PFAS-impacted water sources can affect aquaculture fish, and studies have identified PFAS in commercial fish feed used in freshwater aquaculture (X. Li et al. 2019; Rushing et al. 2023).

Once PFAS are introduced to agricultural facilities, there is the potential for on-farm cycling (Figures 2-6 and 2-7). Animal manure represents one potential source of PFAS cycling at facilities following exposure of livestock to PFAS via contaminated feed or drinking water. A recent study identified PFAS in 17 of 21 manure samples from European dairy cow, pig, and poultry (Munoz et al. 2022). The management of as much as 1.4 billion tons (wet weight) of animal manure generated in the United States each year is already a significant challenge (Pagliari et al. 2020). High manure volumes, low value, and high disposal costs sometimes lead to over application of manure on site (Pagliari et al. 2020; Lim et al. 2023). If PFAS are present in the manure, PFAS will be distributed in the field and potentially be taken up by plants, leach into groundwater, and leave the field through runoff. This movement into plants and water can then lead

[4] This groundwater is also often a source of drinking water for farmers, other rural residents, and municipalities.

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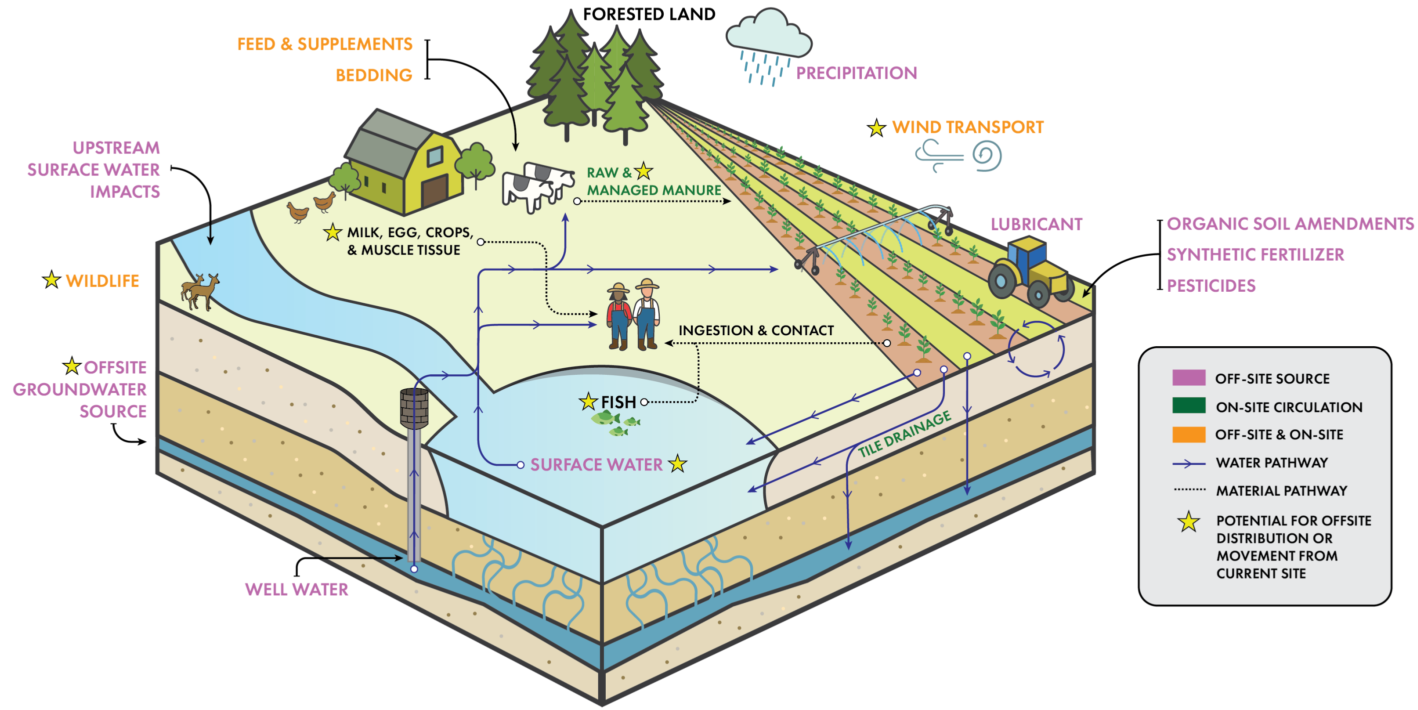

FIGURE 2-6 Conceptual model of the entry and cycling of PFAS on agricultural land.

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BOX 2-3
Organic Soil Amendments

Organic soil amendments are natural materials added to soil to improve its physical, chemical, and biological properties. They can increase the amount of available organic material in soils; improve the structure, water retention, and nutrient availability of soils; and support beneficial soil microbes[a] (Siedt et al. 2021). Organic soil amendments are primarily derived from plant, animal, or microbial sources and are used to enhance soil quality, structure, and health (Larney and Angers 2012). Common types include animal manure, biochar, biosolids, compost, and crop residues (Urra et al. 2019; Sakhiya et al. 2020; Malone et al. 2023).

Animal manure is everything that would be considered animal waste, both solid and liquid, in addition to any animal bedding materials (Urra et al. 2019). In U.S. agricultural systems, manure is primarily from pigs, cows, and poultry (Lim et al. 2023). Manure may be applied raw or after undergoing a management process, such as composting or heat treatment (Lim et al. 2023).

Biosolids are nutrient-rich organic materials produced from the treatment of sewage. Solid waste is separated from liquid waste and then stabilized and treated to reduce pathogens and contaminants (Lu et al. 2012; Poornima et al. 2022; Elgarahy et al. 2024). They are often used as soil amendments in agriculture because of their high content of essential plant nutrients and organic matter and their affordability. In the United States, biosolids cannot be applied to land unless heavy metal and pathogen levels are under specified thresholds (Lu et al. 2012). However, there are currently no thresholds for PFAS in biosolids at the federal level.

Biochar, a stable, carbon-rich material made by pyrolyzing organic matter under low-oxygen conditions, helps build long-lasting soil organic carbon. Its high surface area enhances water and nutrient retention, improving soil health and plant nutrient availability (Weber and Quicker 2018; Gao et al. 2019). Made from materials such as wood and crop residues, its properties vary with feedstock and pyrolysis conditions, influencing its effects on soil (Joseph et al. 2021).

Additional examples of organic soil amendments are compost, crop residue, and green manure (Urra et al. 2019). Compost can come from aerobic and anaerobic sources, and it can be made from a variety of organic materials, including biosolids from municipal wastewater (Urra et al. 2019) and manures. Crop residues are the parts of the plant that remain in the fields after harvest (Lal 2005). Green manure refers to plants that are incorporated into soil while plants are green or soon after they mature (Goss et al. 2013).

[a] See *Role of Organic Matter*, https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/role-of-organic-matter.

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to further livestock exposure to PFAS via feed and water. Land application of biosolids or compost that is contaminated with PFAS can cause similar movement of PFAS within an agricultural facility, including into on-site water sources that may be used for irrigation or livestock feed and water.

Furthermore, manure is not always economical to distribute as a fertilizer, so the U.S. Department of Agriculture (USDA) recommends management practices such as the separation of liquids and solids, composting manure, and using manure to generate biogas through anaerobic digestion to raise its value (Lim et al. 2023). The latter may be coupled with the use of digestate as fertilizer, separation of digestate fibers for use in products such as bedding, or both. However, little is known about the impact of these strategies on PFAS composition and concentrations. Studies with municipal biosolids have shown that treatments such as digestion and composting can cause transformation of polyfluoroalkyl substances (i.e., precursors) to terminal, PFAA daughter products (Thompson et al. 2023; Alukkal et al. 2024a,b). Temperature, pH, and oxygen content will affect the rates of PFAS degradation, with aerobic digestion promoting faster degradation of precursors to intermediates to terminal PFAAs than anaerobic digestion (Alukkal et al. 2024a,b). For municipal solids treated in storage nitrification–denitrification reactors, most quantifiable PFAS increased in concentration from both breakdown of known precursors and reduced analytical matrix effects (Alukkal et al. 2024b). Therefore, while PFAS-specific data for manure are still limited, on-site applications of liquid or solid manure fractions or compost or use of digestate fiber as bedding may also promote on-site PFAS cycling.

Another example of on-farm PFAS cycling is plant uptake of PFAS from impacted soils followed by re-release during plant senescence. When the plant decomposes, PFAS reenters the soil and can eventually be taken up by subsequent living plants or leached into groundwater. Plants may be consumed by humans or animals, and groundwater may be used as a source of irrigation for crops or forage or for human and livestock consumption.

PFAS can also migrate off farm via water, soil, or farm products. PFAS from agricultural facilities that drain into groundwater, tile drainage, and surface water can migrate off site. Similarly, wildlife may consume PFAS-impacted water or forage from affected agricultural facilities and migrate off site. PFAS-impacted particulates from farm activities can undergo off-site atmospheric transport. Although not a primary focus of this report, it is also important to consider that PFAS-impacted agricultural facilities have implications for U.S. consumers, who may consume produce, meat, eggs, and dairy that have been contaminated with PFAS; a recent study detected PFAS in fresh and canned vegetables and milk purchased from grocery stores (Yang et al. 2023). Lastly, it is possible to transfer PFAS impacts between agricultural facilities via sale of agricultural products. For example, sale of PFAS-impacted feed may transfer impacts to livestock of another facility. Although some of these considerations (e.g., consumer exposure) are beyond the direct purview of USDA, off-farm considerations facilitate a comprehensive understanding of the problems associated with PFAS at U.S. agricultural facilities.

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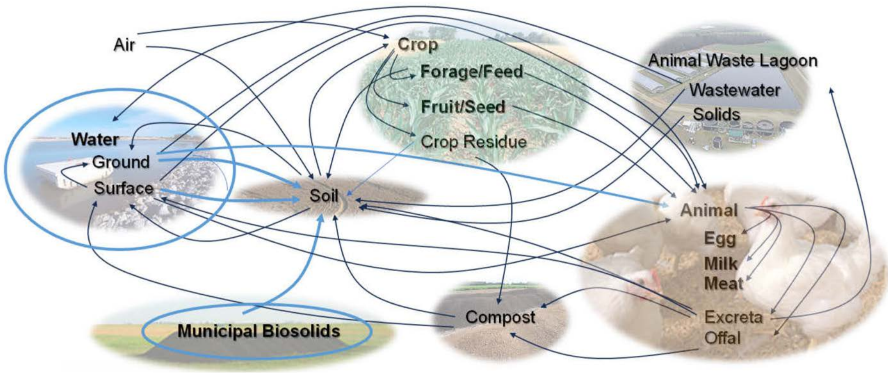

FIGURE 2-7 Potential introduction and on-farm cycling of PFAS through different media.
SOURCE: Photo courtesy of U.S. Department of Agriculture–Agricultural Research Service.

SCOPE OF THE CHALLENGE

As discussed above, the scope of the PFAS challenge in U.S. agriculture is not well characterized (see section "Occurrence of PFAS in U.S. Soils"). However, geospatial data on PFAS sources[5] and detections compiled by EPA show that the footprint of PFAS on the landscape is large (Figure 2-8). Assuming PFAS contamination on agricultural lands is widespread, the severity of the problem is still difficult to assess. Data from various sources collected by EPA indicate where detection has occurred, but most data points do not convey the amount of one or more PFAS detected or the degree to which the detected PFAS present harm to human, livestock, or environmental health. Maximum contaminant levels in drinking water have been set for some PFAS,[6] but no such threshold currently exists on a federal level for soil, groundwater, surface water, livestock, milk, or food in general.

As discussed in Chapter 1, there is no easy way to treat PFAS-impacted media. With no readily available, affordable way to remediate, the question then for NRCS is how can the agency best use its capabilities to address on-farm PFAS contamination and mitigation? The next chapter reviews the relevant programs within NRCS's remit, the conservation practices it supports, and the intersection of both programs and practices with PFAS. Chapter 4 then explores how decisions could be made, given limited information and, presumably, constrained financial resources.

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[5] Sources include drinking water samples, industry and wastewater treatment facility discharge reports, gaseous emissions from large emitting facilities, groundwater and surface water, sediment, and fish tissue analysis, military installations, PFAS spill sites or release events, Superfund sites with PFAS detections, and PFAS manufacturing facilities.

[6] In 2024, EPA established maximum contaminant levels (MCLs) for six PFAS in drinking water under the Safe Water Drinking Act (EPA 2024b). In May 2025, EPA announced its intention to rescind the MCLs for all but PFOS and PFOA (EPA 2025).

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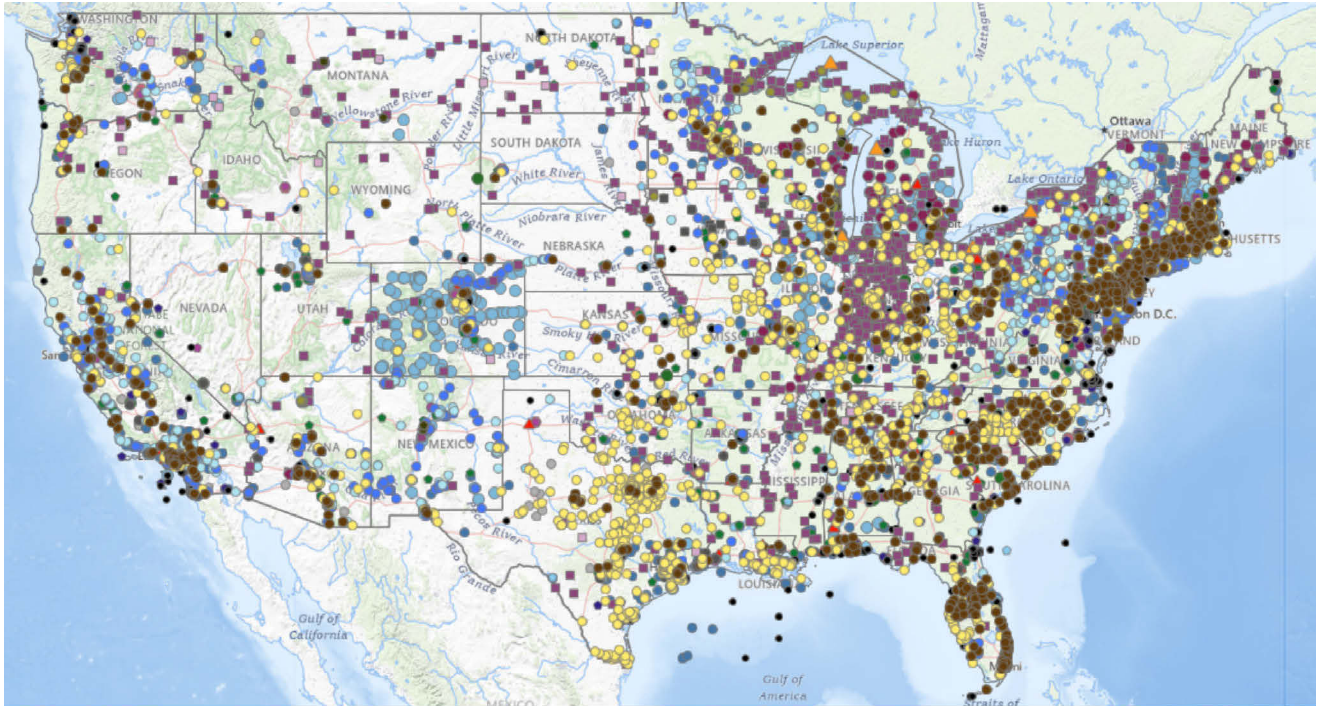

FIGURE 2-8 PFAS detected in drinking water, environmental media, reported discharges and greenhouse gas emissions, as well as locations of military installations, PFAS spills or release events, Superfund sites with PFAS detections, and PFAS manufacturing facilities in the contiguous United States.

NOTE: Sites with no detection of PFAS are not displayed. MRL = minimum reporting level.

SOURCE: Generated with data from EPA PFAS Analytics Tools, https://echo.epa.gov/trends/pfas-tools (accessed September 25, 2025).

continued

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FIGURE 2-8 Continued

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3

Federal Conservation Support and PFAS in Agricultural Systems

The Farm Production and Conservation (FPAC) agencies within the U.S. Department of Agriculture (USDA) administer more than 20 conservation programs. This chapter briefly describes these agencies, their customers, and the goals of the conservation programs. It then reviews the components involved in the creation of a conservation plan for a customer, including the resource concern to be targeted and the practices that could be used to address it. After describing the conservation programs included in the committee's statement of task, the chapter explores how these programs and the practices they support intersect with per- and polyfluoroalkyl substances (PFAS) contamination and mitigation.

CONSERVATION AGENCIES, CUSTOMERS, AND GOALS

Federal assistance for conservation on private lands began in 1935 with the establishment of the Soil Conservation Service at USDA. The agency was led by Hugh Hammond Bennett, often recognized as the "father of soil conservation" (Helms 2009). USDA's role in conservation assistance grew out of the urgent needs created by the Dust Bowl and economic crisis of the 1930s, and this role continues today.[1] The Soil Conservation Service was renamed the Natural Resources Conservation Service (NRCS) in 1994 as part of a larger reorganization effort at USDA (Christensen 2020).[2]

[1] USDA (2025). "90 Years of Helping People Help the Land: The History of NRCS," https://storymaps.arcgis.com/stories/a3a0db06ef774ea6958c870f86c73365.

[2] More detailed summaries of the evolution of federal conservation support in the United States can be found in Braden and Uchtmann (1982), Steiner (1988), and Christensen (2020).

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NRCS and the Farm Service Agency (FSA) are the two agencies within the FPAC mission area that deal directly with conservation efforts on privately owned land.[3] NRCS is the lead agency for providing customers with technical and financial assistance to voluntarily plan and implement conservation practices and systems of practices on their lands, with the goals of natural resource sustainability, environmental improvement, and sound agricultural production. FSA's role in conservation is financial rather than technical. Since 1985, the agency has administered the Conservation Reserve Program, which pays landowners to remove highly erodible and sensitive lands from agricultural production.

The customer base for FPAC conservation assistance is nationwide and extensive. It includes, but is not limited to

- farmers, ranchers, and forest stewards who operate U.S. farms, ranches, and woodlots, predominantly on private lands but also on leased or otherwise accessible public lands;
- for-profit businesses and individuals who support farmers, ranchers, and forest stewards;
- nonprofit organizations and foundations whose conservation objectives align with FPAC;
- urban, suburban, and developing lands landowners, land users, and communities who pursue conservation objectives; and
- units of government at all levels with responsibilities for natural resource use and management, some of which also serve as sponsors for project-based conservation (USDA–FPAC 2022).

Without question, the largest segment of the broad and diverse customer base for FPAC conservation programs is the farmers, ranchers, and forest stewards who own or control the hundreds of millions of acres of agricultural land in the United States (USDA 2020b).[4] Because of the scope and magnitude of this group's natural resource impact, their expressed needs through program signups, and the legislative authorities and focus of FPAC's conservation programs, the overwhelming share of conservation assistance resources are used in direct assistance to farmers, ranchers, and forest stewards. These operators and owners are the decision-makers with the greatest geographic scope and impact through their use and management of the nation's working lands.

The goal of FPAC's conservation support is the science-based use and management of land consistent with its capabilities and needs within the limits of economic practicality. For working lands, the objective is agricultural production and conservation as compatible outcomes. For wetlands and other sensitive lands, the objective is restoration and protection of the resource base. Each conservation program offered by

[3] In 2017, the FPAC mission area was created to align agencies that directly support and deliver a wide range of services and programs to predominantly farmers, ranchers, forest stewards, and rural communities throughout the United States. The other agencies in the mission area are the Risk Management Agency and the FPAC Business Center.

[4] See *Land Use*, https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/land-use.

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NRCS and FSA has defined land eligibility criteria determined by statute to support the purpose of the program.

CONSERVATION PLANNING, RESOURCE CONCERNS, AND CONSERVATION PRACTICES

NRCS is recognized as the nation's leader for the processes, standards, and training criteria for conservation planning, dating back to the origins of the integrated science of soil conservation first established in the 1930s by the Soil Conservation Service. A conservation plan is key to managing the natural resources on a farm, ranch, or woodlot for improved environmental performance, enhanced productivity, and operational efficiency; it can transform an operation by giving a customer science-based data and information to improve sustainability and productivity. As the technical authority and guardian of the certification process for conservation planners, NRCS provides a consistent structure for supporting the technical competence of both public- and private-sector planners to perform conservation planning. This certification, carried out in cooperation with qualified organizations, helps to ensure the quality of conservation treatment nationwide to address resource concerns, objectives of the customer, and the wise use of technical and financial resources (Box 3-1).

The conservation plan belongs to and represents the decisions of the customer, based on technical guidance and recommendations from a certified conservation planner. The benefits of having a conservation plan include

- increased overall effectiveness of recommended conservation systems and their individual conservation practices;
- establishment of an implementation schedule for conservation practices that fits the timetable and available financial and labor resources of the landowner or land user;
- possible improvement of the operation's economic bottom line;
- compliance with state and federal environmental regulations;
- improvement of the sustainability of the natural resource base (soil, water, air, plants, and animals);
- adaptation to the changing needs or goals of the landowner or land user because the plan is a living document intended to be adjusted over time as objectives change, technologies improve, and adaptive management is applied to enhance results from lessons learned and outcomes; and
- a potential path toward enhanced ecosystem services delivery and associated monetary value for the landowner or land user.

The planning process begins with a certified conservation planner's visit with the customer to discuss conservation goals, the operation, and the needs or opportunities related to production and natural resource concerns (Figure 3-1). In concert with the customer, NRCS identifies and describes site-specific resource concerns. NRCS defines a *resource concern* as an expected degradation of the soil, water, air, plant, or animal

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BOX 3-1
Conservation Technical Assistance

A conservation plan and subsequent enrollment in conservation programs that involve payments to customers typically begin with technical assistance. Conservation plans are just one form of technical assistance. It can also involve putting technological advances into practice on the land or developing designs for specific structural conservation practices requiring engineering. Broadly, *technical assistance* is a service that helps customers develop skills and knowledge for maintaining natural resources on agricultural and other eligible, non-federal land (Stubbs 2011; Rosenberg and Wallander 2022). There is no cost to the requesting customer for technical assistance from the Natural Resources Conservation Service (NRCS), which can be self-contained or provided as part of participation in a conservation program that includes financial assistance. Indeed, "technical assistance is what makes financial assistance programs feasible and effective; providing the confidence that conservation practices as applied to a specific landscape will perform to their potential and are wise expenditures of public resources" (Helms 2005, 6).

NRCS is the lead federal agency for providing technical assistance, and local staff located throughout the country provide information, technical expertise, and knowledge of location conditions to customers who request assistance (Stubbs 2011). Other entities also offer technical assistance, including conservation agencies, local conservation districts, technical service providers,[a] and cooperative extension agents (Rosenberg and Wallander 2022).

[a] Technical service providers (TSPs) are registered with and certified by NRCS. Like NRCS staff, TSPs can conduct conservation planning, design, and layout; install conservation practices; and monitor approved practices. Customers can be reimbursed by NRCS for the expenses associated with TSPs as part of an existing contract with NRCS, or NRCS can enter into a cooperative agreement directly with a TSP (Stubbs 2011).

resource base to such an extent that the sustainability or intended use of the resource is impaired (USDA–NRCS 2023). There are more than 40 NRCS-identified natural resource concerns that are grouped, respectively, under the categories of soil, water, air, plants, and animals (SWAPA; Table 3-1).[5] Once a resource inventory or assessment is conducted, the results are used in combination with the objectives of the customer to recommend a plan with relevant conservation practices that, particularly when used in a systems approach, improve the productivity and long-term sustainability of the land.

Conservation practices are the structural and/or vegetative measures or management activities that can be implemented by the customer to protect, conserve, and reduce

[5] NRCS also includes energy as a category, but these resource concerns do not intersect with issues around PFAS. Therefore, the committee does not address this category of resource concerns.

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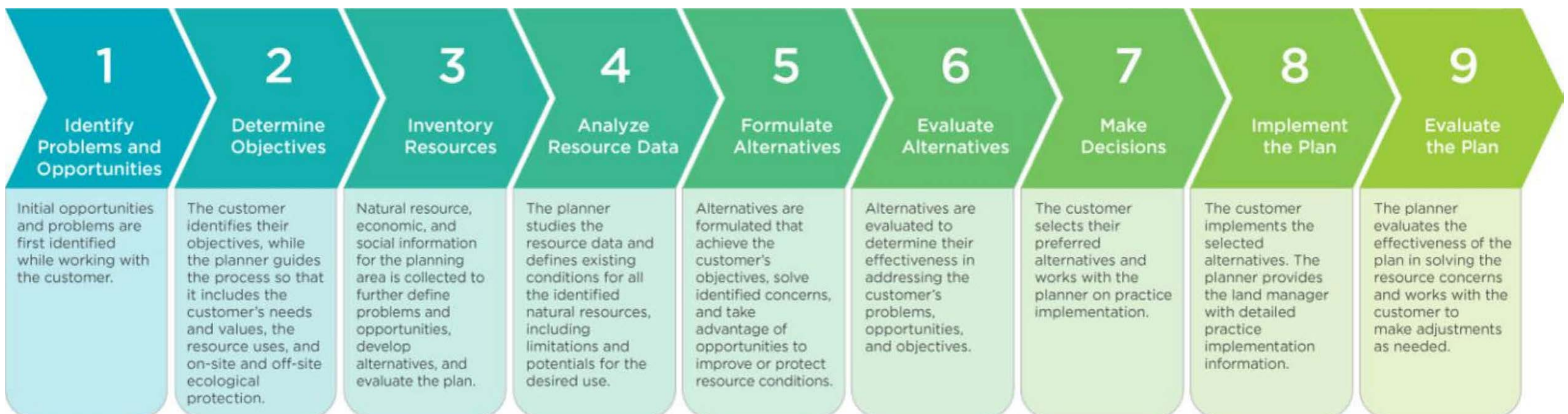

FIGURE 3-1 Natural Resources Conservation Service's Nine-Step Conservation Planning Process.
SOURCE: See *NRCS Conservation Planning*, https://www.nrcs.usda.gov/getting-assistance/conservation-technical-assistance/conservation-planning.

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TABLE 3-1 National Resource Concern List

Resource Concern Category	Specific Concern
Soil Resource Concerns	Sheet and rill erosion Wind erosion Ephemeral gully erosion Classic gully erosion Bank erosion from streams, shorelines, or water conveyance channels Subsidence Compaction Organic matter depletion Concentration of salts or other chemicals Soil organism habitat loss or degradation Aggregate instability
Water Resource Concerns	Ponding and flooding Seasonal high-water table Seeps Drifted snow Surface water depletion Groundwater depletion Naturally available moisture use Inefficient irrigation water use Nutrients transported to surface water Nutrients transported to groundwater Pesticides transported to surface water Pesticides transported to groundwater Pathogens and chemicals from manure, biosolids, or compost applications transported to surface water Pathogens and chemicals from manure, biosolids, or compost applications transported to groundwater Salts transported to surface water Salts transported to groundwater Petroleum, heavy metals, and other pollutants transported to surface water Petroleum, heavy metals, and other pollutants transported to groundwater Sediment transported to surface water Elevated water temperature
Air Resource Concerns	Emissions of particulate matter (PM) and PM precursors Emissions of greenhouse gases Emissions of ozone precursors Objectionable odors Emissions of airborne reactive nitrogen
Plant Resource Concerns	Plant productivity and health Plant structure and composition Plant pest pressure Wildfire hazard from biomass accumulation
Animal Resource Concerns	Terrestrial habitat for wildlife and invertebrates Aquatic habitat for fish and other organisms Feed and forage imbalance Inadequate livestock shelter Inadequate livestock water quantity, quality, and distribution

NOTE: NRCS also includes energy as a category, but these resource concerns do not intersect with issues around PFAS and are therefore not included in the table.
SOURCE: USDA–NRCS 2023.

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the degradation of SWAPA resources. Each conservation practice is supported by a conservation practice standard, which contains details on the purpose of the practice and the conditions where it is applied. A practice standard sets forth the minimum planning criteria that must be met during implementation of the practice to achieve the intended purpose. Standards are adapted and modified at the state level to ensure that practices recommended in a conservation plan meet state and local criteria.[6] Each standard is reviewed and updated if needed by NRCS at least once every 5 years. As of September 2025, NRCS had more than 160 national conservation practice standards.[7]

Nutrient Management (Code 590) is an example of a conservation practice. It is commonly combined with other conservation practices in cropland fields to avoid excess fertilizer inputs, effectively use what fertilizer is applied, and control the off-site negative impacts of fertilizer. The NRCS definition for this practice is to "manage rate, source, placement, and timing of plant nutrients and soil amendments while reducing environmental impacts" (USDA 2019h). Nutrient management stewardship entails applying the right nutrient source at the right rate at the right time and in the right place, often referred to as the 4Rs. Implementation of the 4Rs in a planned approach improves nutrient use efficiency by the plants, minimizes nutrient loss from the field to groundwater, surface water, and the atmosphere, and increases economic returns for the farmer.

Some conservation practices are relevant to concerns about PFAS as they may have potential to cause, exacerbate, mitigate, or reduce contamination. The intersections of PFAS and conservation practices are explored later in this chapter (see section "Conservation Practices Capabilities and Tradeoffs").

CONSERVATION PROGRAMS

If a customer decides to implement conservation practices recommended through a planning process, financial assistance—federal funds reimbursing some of the costs associated with practices—may be available through FPAC's conservation programs. For example, the nutrient management practice (Code 590) is supported with financial assistance at a cost-share rate of 50–90 percent for multiple years, principally through the Agricultural Management Assistance Program, the Environmental Quality Incentives Program (EQIP), and the Regional Conservation Partnership Program. Further enhancements to nutrient management performance above the NRCS conservation practice standard are also supported through financial assistance from the Conservation Stewardship Program (CSP). Together, NRCS and FSA operate more than 20 conservation programs and subprograms (Stubbs 2022). Some NRCS programs focus on working lands—that is, the land stays in production while the customer implements conservation practices to address natural resource concerns that have been identified

[6] This guidance, known as the Field Office Technical Guide, contains technical information about the conservation of soil, water, air, and related plant and animal resources tailored to each county. These guides represent the collective knowledge of technical assistance.

[7] The NRCS website contains the list of national conservation practice standards. See *Conservation Practice Standards*, https://www.nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-standards.

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in a conservation plan. These programs are based on incentives and provide financial assistance to help customers defray the costs of conservation practices, systems of conservation practices, and enhancements to conservation practices. NRCS easement programs pay the customer in exchange for voluntary, permanent land-use restrictions, except where state and tribal laws restrict the use of permanent easements and require a non-permanent easement or contract with a defined maximum duration. NRCS also supports partnerships with non-federal entities to stimulate collaboration, leverage support, foster innovation, and expand the reach and impact of public and private conservation efforts. FSA administers land retirement programs that, as mentioned above, provide payments to landowners for implementing land-use changes that achieve environmental improvements. Unlike easements, retirement programs are not permanent; contracts typically last from 10 to 15 years (GAO 2024).

The committee's statement of task names four conservation programs. Specifically, EQIP and CSP are working lands programs that assist a wide variety of agricultural operations. The Agricultural Conservation Easement Program (ACEP) funds the restoration and protection of wetlands, other sensitive lands, and farmland through contracts and easements. The Conservation Reserve Program (CRP), administered by FSA, can temporarily retire working lands that meet certain criteria from food, feed, and fiber production or place sensitive lands in limited use while producing conservation benefits such as habitat for wildlife. CRP also includes the CRP Grasslands program, which enrolls working grazing or forage production land. The four programs are reviewed below.

Environmental Quality Incentives Program

EQIP is often referred to as NRCS's flagship conservation program because it has broad applicability in helping farmers, ranchers, and forest stewards integrate conservation practices into their use and management of working lands. EQIP provides both technical and financial assistance to these customers to address a wide range of natural resource concerns, such as improving water and air quality, conserving groundwater and surface water, increasing soil health, reducing soil erosion and sedimentation, enhancing or creating wildlife habitat, and mitigating against drought and weather volatility.

Applications for EQIP financial assistance are accepted throughout the year, but specific state deadlines are set for ranking these applications against national, state, and local criteria to provide funding to those that best meet conservation program priorities (USDA–NRCS 2025c). Once an application is ranked and selected by NRCS, the EQIP participant enters a contract with the agency to receive financial assistance toward the cost of implementing the selected conservation practice(s). Payment amounts for conservation practices are reviewed and set each fiscal year through a nationally consistent process that estimates costs incurred and income forgone, if applicable, to implement a practice. Payment rates are usually set at 50 or 75 percent of the NRCS estimated cost for a practice scenario.

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Conservation Stewardship Program

CSP is for agricultural and forest producers who want to take their conservation efforts to a higher level of performance (USDA–NRCS 2025b). The majority of CSP applicants have already applied conservation practices to their land and wish to gain even more conservation benefits from their practices. Through CSP, producers further improve their conservation efforts with conservation activities called enhancements, which give producers ways to go beyond the minimum conservation standards. For example, a producer who may already be planting a single-species, small-grain cover crop as a conservation practice could take this practice a step further by implementing an enhancement for intensive cover cropping. This enhancement activity requires the producer to use a cover crop mix with, at a minimum, three crop species that must be planted with the intention of producing a greater volume of above- and below-ground biomass to maintain or increase soil organic matter (USDA 2019e).

Like conservation practices, enhancements address resource concerns and have criteria that must be met. With help from a certified conservation planner, CSP applicants choose the enhancements that best match their management goals and resource needs for the land they enroll. As of September 2025, there were more than 160 CSP enhancements available nationwide to address resource concerns on agricultural or forest operations.

Producers may also consider bundles of enhancement activities. Each bundle has three or more required enhancements, and for some bundles, the applicant has the option to pick additional enhancements from a select list that addresses specific resource concerns. Bundles group enhancements according to land use—crop, pasture, range, and forest—and receive a higher level of financial assistance to encourage an integrated approach to generate additional conservation benefits. As of September 2025, NRCS offered more than 30 bundles of enhancements through CSP for agricultural or forest producers to consider.[8]

Finally, producers are eligible for supplemental activity payments through CSP. Supplemental activities are advanced grazing management (implementation of at least four enhancements identified by NRCS; USDA 2022a); resource conserving crop rotation (eligible crops determined by the state conservationist, with a minimum 3-year crop rotation; USDA 2021); and improved resource conserving crop rotation, which builds on an existing resource conserving crop rotation by incorporating a perennial crop or grass into the rotation (USDA 2019a).

CSP contracts are for 5 years. Contract payments are based on two components: (1) payments to maintain the existing level of conservation, based on the land uses included in the contract and an NRCS assessment of existing stewardship at the time of enrollment, and (2) payments to implement additional conservation activities. Most CSP participants will be eligible for a $4,000 minimum payment during any year that their total annual contract payment falls below the minimum payment amount.

[8] A list of CSP enhancements and bundles offered in fiscal year 2024 can be found at https://www.nrcs.usda.gov/sites/default/files/2024-01/FY24%20CSP%20Practices%20Enhancements%20and%20Bundles.pdf.

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Existing CSP participants may be eligible to renew their contract for an additional 5-year term during the fifth year of their initial contract. To meet the renewal stewardship threshold, the participant must agree to meet or exceed two additional priority resource concerns or agree to adopt or improve conservation activities to achieve higher levels of conservation for two existing resource concerns.

Agricultural Conservation Easement Program

ACEP provides assistance to customers through two types of easements, one for agricultural land and the other for wetlands (Stubbs 2022). Farm and grass lands are eligible for agricultural land easements, which limit non-agricultural uses on the land. Wetland easements seek to protect, restore, and enhance wetlands that have been damaged previously by agricultural production. NRCS contributes 50–100 percent of the easement value, depending on the type of land enrolled in the program (USDA–NRCS 2025a).

Conservation Reserve Program

CRP is a voluntary program that encourages eligible customers to take highly erodible and other environmentally sensitive land out of crop production and instead plant perennial vegetative cover, such as native grasses, trees, and riparian buffers. The program was enacted in the 1985 Farm Bill and was originally intended to remove agricultural land from production with the dual aims of reducing erosion on highly erodible land and increasing market prices via decreased commodity production (Sullivan et al. 2004). Over time, the program has sought to achieve broader environmental benefits, including wildlife habitat and water quality (Stubbs 2014; Hellerstein 2017).

By enrolling in CRP, customers receive annual rental payments and cost-share assistance to establish eligible practices specified in the customer's conservation plan for long-term, resource-conserving covers. Other incentive payments may also apply. Land enrolled must meet certain eligibility criteria; once enrolled, only specific uses of the land are permitted, depending on the subprogram criteria. Applicants must demonstrate the potential for significant environmental benefits through the implementation of conservation practices. FSA has overall policy and administrative leadership for CRP, while NRCS has technical and conservation planning leadership for determining the suitability of land and covers to achieve program objectives (GAO 2024).

PROGRAMS, PRACTICES, AND PFAS

The committee was asked to characterize the capability of conservation programs, practices, and initiatives to address on-farm PFAS contamination and mitigation. Over the years, conservation programs have been created, adapted, or refocused to treat emerging and critical conservation issues (Christensen 2020). For example, the focus in the 1980s was on addressing highly erodible soil. In the 1990s, the emerging issue was the effects of water quality on surface water and groundwater. There was

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a programmatic emphasis on improving air quality and reducing greenhouse gases in 2000s and, more recently, on increasing soil health and addressing climate and energy concerns. Using the flexibility of the programs to respond to PFAS contamination is in accordance with the ever-adapting nature of federal conservation support.

The goals of FPAC conservation programs and practices generally are congruent with goals to minimize negative impacts from PFAS. As examples, practices intended to reduce soil erosion could also reduce the transport of PFAS; practices intended to increase soil organic matter could also increase PFAS sorption by the soil and reduce plant uptake; and practices intended to protect water quality could also prevent contamination by PFAS. However, there are situations where FPAC conservation programs and practices could unintentionally cause or exacerbate PFAS contamination, either due to the practices themselves or to constraints that exist within the programs.

The discussion below identifies the capabilities of the conservation programs specified in the statement of task to address on-farm PFAS contamination and mitigation, followed by limitations within the programs. How conservation practices may mitigate or exacerbate PFAS concerns in agricultural systems are then reviewed.

Conservation Program Capabilities

The committee examined the capabilities of EQIP, CSP, ACEP, and CRP to respond to PFAS contamination. EQIP, CSP, CRP, and their respective subprograms have the capability to address PFAS concerns, although funding levels likely restrict how widely these programs can be deployed. ACEP is not a viable vehicle to address PFAS contamination because of statute and regulation constraints.

EQIP

Among the many FPAC mission area conservation programs, EQIP presents the greatest opportunity for the widest range of farmers, ranchers, and forest stewards to address PFAS contamination and implement mitigation measures. This capability is because EQIP is a long-standing and proven program with nearly three decades of continuous operation, is available nationwide, and enjoys broad recognition and popularity within the agricultural community. Its widespread demand is demonstrated by the fact that it is consistently oversubscribed each fiscal year (Happ 2025). The program's relatively straightforward processes make it more accessible and easier to navigate than other conservation programs, which is particularly beneficial for producers seeking timely support. EQIP also provides potential access to the full suite of NRCS conservation practice standards, though this access is shaped by national, state, and local priorities; practice suitability; and application ranking criteria in each given geographic area (USDA–NRCS 2022a, 2025c). Financially, EQIP offers significant support by covering 50–90 percent of practice implementation costs, with the majority of participants receiving a 75-percent cost-share (GAO 2017). These payments are transparently determined in advance, using NRCS-established practice scenarios and payment schedules that reflect estimated costs and, when applicable, forgone income.

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Moreover, EQIP can provide cost-sharing for vegetative and management practices over multiple years—up to 5 years in some cases—encouraging long-term conservation outcomes. Finally, EQIP often serves as a gateway to CSP, enabling producers to build upon their conservation efforts and qualify for CSP participation with higher application rankings based on enhanced conservation performance.

Many of the NRCS conservation practices assessed by this committee that are likely to most effectively address on-farm PFAS contamination and mitigation are already widely used by EQIP participants for other conservation purposes (see section "Conservation Practice Capabilities and Tradeoffs" below). Such practices include controlling soil erosion, minimizing nutrient and pesticide runoff to groundwater and surface water, and managing and optimizing use of fertilizer and other soil amendment inputs. However, there are particular opportunities under EQIP that can provide assistance on PFAS issues to customers. Under EQIP, customers can access financial assistance for Conservation Evaluation and Monitoring Activities (CEMAs; USDA–NRCS 2024b). As of 2025, CEMA 209 PFAS Testing in Water and Soil is the only conservation practice or activity specifically created in response to PFAS contamination. The activity provides testing (sample collection and laboratory analysis) to detect and quantify PFAS in water or soil using state-approved or U.S. Environmental Protection Agency (EPA) field sampling techniques and laboratory methods (USDA–NRCS 2022b). This CEMA is cost-shared in a manner similar to conservation practices through EQIP. Its purpose is to provide prescreening information to customers to determine whether PFAS may be present in soil or water at their operation. It is not intended to determine the nature and extent of PFAS contamination applicable to a federal or state cleanup action or to provide a risk-based comparison to soil or water screening level values. Because it is intended only as a prescreening tool, CEMA 209 serves to complement, not replace, PFAS testing offered by state agencies or EPA.

Another opportunity is the Conservation Innovation Grant (CIG) program, a competitive grants subprogram of EQIP. CIG supports the development of new innovative tools, approaches, practices, and technologies to further natural resource conservation objectives on private lands. Authorized in the 2002 Farm Bill, CIG is not a research program. Rather, it can help to advance the application of known research results or innovative approaches proven in the laboratory or in research plots but not yet adopted at field, farm, ranch, or larger scales. The program addresses an issue that has challenged conservation efforts since their initiation in the 1930s—that is, implementing promising research and innovative approaches in the field and bringing them to a stage of readiness for more widespread adoption through practical use and evaluation so they can be refined and incorporated into the nation's conservation delivery infrastructure.

CIG could advance the use of conservation measures and approaches that show promise for PFAS mitigation on agricultural lands but have not yet been adopted by producers on a widespread basis. It also can help introduce innovative conservation measures or approaches proven and adopted in one geographic area to a new geographic area. Additionally, some CIG-funded projects help to advance the introduction of new or improved conservation practices or enhancements, but the program's use is not limited to those conservation measures alone.

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CIG can also evaluate and refine existing conservation practice standards to specify their application for PFAS mitigation purposes. It can assist the development of technical tools and guidance specific to PFAS mitigation. Furthermore, CIG can assess systems of conservation practices and their combined impact on PFAS mitigation or evaluate approaches needed to achieve mitigation success at scale—for example, in locations where multiple farms or ranches have contamination and could benefit from actions involving more than one farming or ranching operation.

The use of CIG to advance PFAS mitigation efforts could employ already well-established processes by NRCS based on its 20 years of program implementation experience. That is, the requests for proposals that initiate CIG competitive processes could establish PFAS mitigation using conservation practices or approaches as a separate priority category for applications and funding. Given program emphasis, and supported by funding, NRCS could design and implement a CIG track for PFAS mitigation to support these objectives (Box 3-2).

CSP

The structure of CSP is more complex than that of EQIP, and the conservation performance bar for entry into CSP is higher, but CSP does offer an excellent opportunity for those farmers, ranchers, and forest stewards with already established conservation practices who wish to do more. A key to successful use of CSP to support the mitigation of PFAS contamination would be the creation of enhancements and bundles of enhancements that can serve this purpose. Just as CIG could be used to further refine practice standards or establish new ones over time, CSP could support the development and field-trial use of existing or new enhancements intended to address PFAS mitigation. Strategically, a category in CSP to support PFAS mitigation could be delineated to take proven research results and use innovative approaches to refine and develop both conservation practices and enhancements to support more effective working lands mitigation.

Conservation practices and enhancements already exist for other conservation purposes that could benefit PFAS mitigation needs. An example of a bundle of enhancements that could have mitigation benefits on PFAS-contaminated cropland that remains in production is Crop Bundle #24—Cropland Soil Health Management System, which serves to address soil, water, and plant resource concerns (USDA 2020a). The foundational conservation practices applicable to this bundle include Nutrient Management (Code 590) (USDA 2019h), Conservation Crop Rotation (Code 328) (USDA 2014), Residue and Tillage Management (Code 329) (USDA 2016), and Cover Crop (Code 340) (USDA 2024a). NRCS has identified seven enhancements to these conservation practices, of which four must be adopted by the CSP participant choosing to implement Crop Bundle #24 through a financial assistance contract. Two of these enhancements are required by NRCS, and two of five other specified enhancements must also be selected

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BOX 3-2
On-Farm Conservation Innovation Trials

The Conservation Innovation Grant subprogram has its own subprogram called On-Farm Conservation Innovation Trials. These trials support adoption and evaluation of innovative conservation approaches (Stubbs 2022). On-farm trial grant awardees provide technical assistance and incentive payments to farmers and ranchers to offset the risks associated with implementation of new conservation practices or enhancements, systems of practices or enhancements, and approaches. Mitigating PFAS issues could be identified as a priority within the On-Farm Conservation Innovation Trials competition, similar to the way soil health has been emphasized in the subprogram's Soil Health Demo Trial.

by the participant.[9] NRCS states "by implementing this combination of enhancements together, a synergy is achieved that should result in more conservation benefits than would be expected from implementing the enhancements individually" (USDA 2020a). Controlling soil erosion, improving soil health, reducing the risk of nutrient losses to surface waters, and minimizing soil compaction are examples of conservation objectives for cropland that should minimize PFAS transport from the cropland to surface waters, although possible unintended consequences should be evaluated (see section "Conservation Practice Capabilities and Tradeoffs"). Specific bundles of enhancements could also be created to align more directly with PFAS mitigation needs.

ACEP

The current Code of Federal Regulations for ACEP[10] does not allow the use of ACEP on land where the purposes of the program would be undermined because of on-site or off-site conditions, such as the risk of hazardous materials. Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), two legacy PFAS (see Box 2-1), are considered hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (EPA 2024). Therefore, any farm or other eligible land at risk of PFOA or PFOS contamination cannot be enrolled in ACEP.[11] Additionally,

[9] The customer must adopt a no-till system enhancement (USDA 2019c) and an enhancement to improve soil health and increase soil organic matter (USDA 2019b). Two of the following enhancements must also be selected: improved nutrient uptake efficiency and reduced risk of nutrient losses (USDA 2023), reduced risk of nutrient loss to surface water with the help of precision agriculture (USDA 2022b), or use of cover crops to reduce soil erosion, minimize soil compaction, or suppress excessive weed pressure and break pest cycles (USDA 2019d, 2019f, 2019g).

[10] See 7 C.F.R. § 1468.20(e)(5) (2024) and 7 C.F.R. § 1468.30 (g)(6) (2024).

[11] See 16 U.S.C. § 3865d Sec 1265D (a)(4) (2023).

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through an easement, the federal government is purchasing certain property rights from the landowner and holding those property rights (or passing them through to a willing land trust or other eligible entity) for a defined time period or into perpetuity. The central limitation of using ACEP as a program to take actions to mitigate PFAS contamination is the easement itself. The federal government does not want to take on the potential risks and responsibilities associated with controlling certain property rights for a wetland, cropland, or rangeland that is known or suspected to be PFAS contaminated.[12] Absent specific federal legislation to create a statutory purpose and intent for ACEP to be used to enroll PFAS-contaminated lands, the risks and liability of knowingly controlling certain property rights for a piece of land that may be contaminated with PFAS, even though the ownership for that land does not lie with the federal government, prevents the use of ACEP for this purpose.

CRP

As shown in Figure 2-6 (in Chapter 2), PFAS can enter agricultural systems from sources other than organic soil amendments. The establishment and maintenance of vegetative conservation covers on highly erodible and environmentally sensitive land should benefit PFAS mitigation efforts if soil PFAS contamination is present, simply by keeping soil in place and filtering the water that flows off the land through vegetative cover.

Under existing statute and regulatory language, PFAS-contaminated agricultural lands that do not meet the traditional CRP definition of highly erodible and environmentally sensitive could still be eligible for enrollment in the program if the Secretary of Agriculture determined that, if the lands were to remain in agricultural production, they would "contribute to the degradation of soil, water, or air quality or pose an on-site or off-site environmental threat to soil, water, or air quality."[13] CRP also has existing pilot subprograms that could be used as models for a subprogram targeted at PFAS. The CLEAR30[14] pilot enrolls acres with certain water quality practices that are expiring from existing CRP contracts into new 30-year contracts, while the Soil Health and Income Protection Program supports the planting of perennial vegetative cover in less-productive farmland of the Prairie Pothole Region under 3–5-year contracts (Stubbs 2022). These pilots, authorized by the 2018 Farm Bill, establish precedence for Congress to specifically authorize a pilot program within CRP to mitigate PFAS contamination on agricultural lands. A congressionally authorized pilot program specific to or inclusive of this purpose would give FSA clear authority to reduce the environmental risk of PFAS contamination on eligible agricultural lands, reduce risks for USDA in CRP administration, and establish clear intent and legislative parameters. This kind of pilot could serve to compensate participants through annual rental payments

[12] See 16 U.S.C. § 3865d Sec 1265D (a)(4) (2023).
[13] See 16 U.S.C. § 3831(b)(5)(A)(i)-(ii) (2021).
[14] CLEAR stands for the Clean Lakes, Estuaries, and Rivers initiative; 30 represents the number of years of the contract.

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for the loss of production from these agricultural lands placed into conserving covers for environmental improvement, thereby providing income protection for an extended timeframe. It could also establish expectations and criteria for monitoring and evaluation to assess the effectiveness of its actions and determine better if it should become a permanent provision of CRP.

Another subprogram of CRP, the Conservation Reserve Enhancement Program (CREP), could be used to mitigate PFAS contamination. Under CREP, FSA enters into partnerships with states, tribal governments, and nongovernment organizations to address specific conservation challenges in a given location. PFAS contamination could be identified as the conservation challenge of concern (USDA–FSA 2025a). The same eligibility criteria to minimize water quality degradation or reduce the on-site and/or off-site threat to water quality if the land remains in production could apply. CREP would bring at least 30 percent in matching funds from the eligible partner to leverage the CREP funds from FSA.

Lastly, FSA makes funds available through cooperative agreements for monitoring, assessment, and evaluation (MAE) of conservation approaches and technologies in conjunction with CRP implementation (USDA 2024b). Such projects are used to measure CRP benefits and build the knowledge base that guides and improves policy and program delivery over time. Specific to PFAS, FSA has made at least one award to university scientists to evaluate the use of a grass–legume mix as a possible phytoremediation strategy under CRP (CEQ 2023; Ilango et al. 2024). The greenhouse study was conducted with soil from an agricultural site in Maine that historically had biosolids applied. FSA's funding of this MAE project through CRP demonstrates the ability of the agency to allocate funds for further studies related to PFAS contamination and mitigation that would improve or enhance the ability of CRP to address this concern on eligible agricultural lands.

Conservation Program Limitations

There are clearly opportunities within the structures of EQIP, CSP, and CRP to address on-farm PFAS contamination and mitigation. However, limitations exist. The first is funding, which applies to all conservation activities, not just those related to PFAS contamination. Applications for EQIP and CSP consistently outstrip available funds (Happ 2025). Even in 2024, when more money was available for conservation programs than the average of the past 15 years, more than 60 percent of applications for EQIP, CSP, and ACEP were not funded (USDA–NRCS 2024a).

As with funding, other general impediments to participation in FPAC conservation programs exist that could thwart producer enrollment for the purpose of responding to the impacts of PFAS contamination on agricultural land. Even if funding is available, producers may have insufficient available capital to implement conservation practices and wait for reimbursement from the program funds, or they may consider the cost-share percentage of EQIP or CSP too low for conservation practice implementation to make operational economic sense. The lengths of agreements or contracts supported by the programs may be inflexible—that is, too long or too short to meet the producer's

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conservation needs and objectives. Producers may also be concerned that program participation could lead to increased scrutiny of farm practices from regulatory agencies.

Enrollment barriers also may discourage participation. For example, CRP is currently capped by existing legislation at 27 million acres nationwide. As of May 2025, less than 2 million acres were available for new enrollment (USDA–FSA 2025b). Were contaminated land to become more easily eligible for the program, either through existing mechanisms or pilot programs, the acreage cap would have to increase or PFAS-contaminated land would have to be prioritized over highly erodible and sensitive land. Furthermore, not all CRP subprograms are available nationwide. Even if more funding or flexibility existed to move PFAS-contaminated land into CRP, questions such as whether there are vegetative conservation covers that can achieve PFAS-mitigation purposes that would not pose undue risk to wildlife health need to be answered (see section "Understanding Plant Characteristics that Affect PFAS Uptake and Accumulation" in Chapter 5).

Conservation Practice Capabilities and Tradeoffs

This section focuses on conservation practices and enhancements supported by FPAC conservation programs that have the potential to mitigate or to cause or exacerbate on-farm PFAS contamination. Evaluating the impacts that a specific conservation practice may have on PFAS contamination on and off the farm requires considering what to prioritize. Minimizing impacts on farmworker health, farm viability, and the food supply are unquestionably top priorities. After that, the question becomes how goals and resource concerns related to soil, groundwater, surface water, and wildlife are valued relative to potential PFAS issues. In many cases, there are clear synergies among goals regarding PFAS contamination, but in other cases, there may be tradeoffs.

In assessing the potential benefits and risks of specific conservation practices, several case-specific factors should be considered. Site characteristics, such as soil type, rainfall or irrigation amounts, and depth to groundwater, will influence how readily PFAS may move through the farm system. The types of PFAS present (e.g., carboxylates versus sulfonates, long-chain versus short-chain, cationic and zwitterionic versus anionic) also will affect their mobility as well as where they pose the greatest risk in the agricultural system. The levels of PFAS present in the system, relative to levels in the surrounding area, should also be considered.

Table 3-2 outlines several ways that NRCS conservation practices and enhancements could mitigate, cause, or exacerbate PFAS contamination on or off the farm and notes where further research is needed (see Chapter 5 for discussion of applied research needs). Practices focused on increasing soil carbon, such as the Soil Carbon Amendment (Code 336) and Nutrient Management (Code 590), have the potential to reduce plant uptake of PFAS and crop contamination by increasing PFAS sorption by the soil and reducing plant availability (see "Sorption" section in Chapter 2). However, as reviewed in Chapter 2, PFAS can be introduced to a farm through off-site materials or inputs (see Figure 2-6). Any conservation practices that involve importing materials onto the farm or that support the addition of organic soil amendments to the farm could directly cause PFAS contamination by inadvertently introducing PFAS-containing materials. While

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TABLE 3-2 Potential Positive and Negative Impacts of Conservation Practices on PFAS Contamination of Agricultural Lands

Purpose of practices and enhancements	Could have these positive impacts related to PFAS	Could have these negative impacts related to PFAS	Example practices with NRCS code
Increase soil carbon	Reduce plant uptake by immobilizing PFAS in soil*	Introduce PFAS onto the farm by importing contaminated materials	Soil Carbon Amendment (Code 336); Nutrient Management (Code 590)
Improve nutrient management	Reduce surface loss of PFAS if a nutrient source with unknown contamination is applied via subsurface injection	Introduce PFAS onto the farm by importing contaminated materials	Nutrient Management (Code 590)
Reduce soil erosion via wind	Reduce on-farm farmworker exposure and off-site transport by decreasing movement of PFAS-containing soil particles with air*	Increase PFAS leaching and transport to groundwater if the practice increases water infiltration	Row Arrangement (Code 557); Residue and Tillage Management, No Till (Code 329); Windbreak/Shelter Belt (Code 380)
Reduce soil erosion via runoff	Reduce off-site transport of PFAS sorbed by soil particles	Increase PFAS leaching and transport to groundwater by increasing water infiltration	Residue and Tillage Management, No Till (Code 329); Anionic Polyacrylamide (PAM) Application (Code 450); Row Arrangement (Code 557); Sediment Basin (Code 350); Water and Sediment Control Basin (Code 638)
Intercept and divert runoff	Reduce PFAS transport by installing an engineered system for PFAS removal*	Increase PFAS transport to surface waters if runoff is directed to surface waters	Diversion (Code 362); Hillside Ditch (Code 423); Irrigation Field Ditch (Code 388)

continued

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TABLE 3-2 Continued

Purpose of practices and enhancements	Could have these positive impacts related to PFAS	Could have these negative impacts related to PFAS	Example practices with NRCS code
Improve surface and subsurface drainage water management	Reduce PFAS transport by installing an engineered system for PFAS removal*	N/A	Drainage Water Management (Code 554); Saturated Buffer (Code 604); Denitrifying Bioreactor (Code 605); Phosphorous Removal System (Code 624)
Collect and store water on the farm	Sorb and capture PFAS in sediments Provide opportunity for the engineered removal of PFAS*	Increase PFAS exposure to wildlife Result in buildup of contaminated sediment on the farm, which would pose a risk if the water-retention structure failed	Sediment Basin (Code 350); Pond (Code 378); Constructed Wetland (Code 656)
Develop new water sources on the farm (e.g., for irrigation, livestock)	Provide new source with lower PFAS than current source	Introduce PFAS onto the farm if water source is contaminated	Spring Development (Code 574); Water Well (Code 642)
Improve irrigation water management and use	Provide opportunity to switch to water with lower PFAS levels Apply less PFAS by increasing water use efficiency if water source is contaminated	Introduce PFAS onto the farm or increase on-farm circulation of PFAS if water source is contaminated	Irrigation Water Management (Code 449); Irrigation and Drainage Tailwater Recovery (Code 447)
Improve wildlife habitat		Increase exposure of wildlife to PFAS via food, water, or both	Leave Standing Grain Unharvested to Benefit Wildlife (E328D); Wildlife Habitat Planting (Code 420); Upland Wildlife Habitat Management (Code 645)

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TABLE 3-2 Continued

Purpose of practices and enhancements	Could have these positive impacts related to PFAS	Could have these negative impacts related to PFAS	Example practices with NRCS code
Convert annual cropland to perennial system	Provide opportunity to retire contaminated land Reduce off-site transport of PFAS-contaminated soil and/or water by reducing runoff, increasing infiltration, and increasing PFAS immobilization in soil	Increase PFAS concentration in harvested crops if switching from a grain crop to perennial forage because bioaccumulation tends to be higher in leafy, vegetative crops than in grain crops* Increase PFAS leaching and transport to groundwater by increasing water infiltration Potential increased exposure of wildlife to PFAS via perennial forage	Stripcropping (Code 585); Conservation Crop Rotation (Code 328); Conservation Cover (Code 327)
Control particulate matter (particle pollution)	Reduce farmworker exposure and off-site transport by reducing airborne PFAS	Introduce PFAS onto the farm by using PFAS-contaminated materials to control dust	Dust Management for Pen Surfaces (Code 375); Dust Control on Unpaved Roads and Surfaces (Code 373); Field Operations Emissions Reduction (Code 376); Cover Crop (Code 340); Conservation Cover (Code 327); Mulching (Code 484)
Decommission an agricultural waste facility	N/A. This practice does not apply to sites with known hazardous substance contamination	Contaminate new areas on or off the farm if the waste has unknown PFAS contamination	Waste Facility Closure (Code 360)
Reduce input of nutrients and pathogens from livestock to surface water	Reduce PFAS contamination of surface water if livestock are contaminated Reduce livestock exposure to PFAS if surface water is contaminated	N/A	Fence (Code 382); Manage Livestock Access to Waterbodies to Reduce Nutrients or Pathogens to Surface Waters (E472A)

NOTES: Potential impacts include those that could occur on- and off-farm. * = More research is needed in this area.

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industrial biosolids have gained the most attention as potential sources of contamination, municipal biosolids, composts, mulches, and other organic amendments are also potential sources (Bolan et al. 2021; Sivaram et al. 2022). The Soil Carbon Amendment practice (Code 336) recognizes this risk by stating, "When feedstocks have higher risk of synthetic organic or heavy metal contaminants, evaluate amendment as appropriate for contaminant and amendment type (e.g., processed municipal waste feedstocks that may contain pesticide residues, polycyclic aromatic hydrocarbons [PAHs], polychlorinated biphenyl's [PCBs], and polyfluoroalkyl substances [PFAS])" (USDA 2022c).

Conservation practices that develop new water sources for livestock and irrigation, such as Spring Development (Code 574) and Water Well (Code 642), could also introduce PFAS contamination to a farm if groundwater is contaminated. Conversely, these practices might be used to develop a new water source with negligible PFAS levels. Likewise, practices to improve irrigation water management and use, such as Irrigation Water Management (Code 449), may provide an opportunity to switch to water sources with lower PFAS levels as well as reduce PFAS application through improved water use efficiency. However, they also pose a potential risk of introducing PFAS onto the farm and, in the case of the Irrigation and Drainage Tailwater Recovery (Code 447) practice, increasing on-farm circulation of PFAS if water is already contaminated.

Where PFAS contamination of soil already exists on a farm, NRCS conservation practices and enhancements could potentially alleviate or exacerbate the situation by altering transport pathways on and off the farm. Practices that reduce soil erosion via air without affecting water infiltration, such as Windbreak/Shelter Belt (Code 380) and Field Operations Emissions Reduction (Code 376), could be important tools for reducing on-farm farmworker exposure and off-farm transport with minimal or no tradeoffs. However, practices that do increase water infiltration to reduce soil erosion via wind or runoff (e.g., Residue and Tillage Management, No Till [Code 329] and Anionic Polyacrylamide Application [Code 450]) could reduce off-site PFAS transport, and in some cases farmworker exposure, but could also facilitate leaching of soil PFAS to groundwater. Conversely, practices that use drainage to control runoff, such as Hillside Ditch (Code 423), may potentially reduce transport to groundwater yet may also increase transport to surface waters. As noted above, the relative likelihood of these various effects depends on characteristics of the specific site and PFAS involved and should be taken into consideration when selecting practices.

Conservation practices that divert and intercept water (e.g., Irrigation Field Ditch [Code 388] and Drainage Water Management [Code 554]) or that collect and store water on the farm (e.g., Sediment Basin [Code 350] and Pond [Code 378]) could provide an important opportunity to capture PFAS using engineered filters and remove them from the system.[15] However, if these practices are not combined with PFAS removal systems, they could increase PFAS transport to surface waters if runoff is directed thus or, if directed into sediment basins or ponds, accumulate contaminated sediments and increase exposure to livestock and wildlife. Wildlife exposure to PFAS could also be exacerbated by implementing practices or enhancements intended to improve wildlife

[15] See Chapter 5 for a discussion of these emerging technologies.

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habitat, such as Leave Standing Grain Unharvested to Benefit Wildlife (E328D), if PFAS accumulate in the part of the plant consumed by wildlife.

Finally, altering cropping patterns, such as bringing abandoned land into production (e.g., Land Clearing [Code 460]) or changing crops, could increase PFAS contamination of food if the land is contaminated. In the latter case, both the Stripcropping (Code 585) and the Conservation Crop Rotation (Code 328) practices involve replacing annual grain crops, which have relatively low rates of PFAS bioaccumulation, with perennial forages, which, as leafy, vegetative crops, have relatively high rates of PFAS bioaccumulation (Stahl et al. 2009; Blaine et al. 2014; Lesmeister et al. 2021; Scearce et al. 2023).

Identifying Existing Conservation Practice Standards Relevant to PFAS

The examples of potentially PFAS-relevant conservation practices highlighted in Table 3-2 were identified by the committee using the NRCS Conservation Practice Physical Effects (CPPE) matrix. The CPPE matrix consists of the National Resource Concerns (listed in Table 3-1) as columns, NRCS's individual conservation practices as rows, and the potential positive or negative impacts of the specific practice on the specific resource concern as the content of the cells. In its review of the CPPE matrix, the committee identified 24 existing resource concerns that are *potentially* relevant to PFAS contamination given what is known today about origin, fate, and transport (Table 3-3).

Soil resource concerns that are relevant for PFAS include various forms of erosion that may transport contaminated soils to adjacent land or water and soil health factors (compaction, organic matter depletion, aggregate stability) or chemical concentrations addressed using practices that require soil disturbance, even if only initially, when new perennial vegetation is established. Water resource concerns fall into two broad categories: (1) managing excess water (ponding or flooding, seasonal water table, seeps) and (2) contaminant transport to groundwater or surface water. Air quality concerns that are relevant for PFAS arise when contaminated soil or plant material (particulate matter) is blown or otherwise dispersed through the air. The final two identified resource concerns relate to farm animals (livestock water sources) and wildlife habitat. Because providing or enhancing wildlife habitat is a common benefit from conservation practices under different programs, including CRP, it is important to consider whether a practice may expose wildlife to PFAS.

The committee chose to highlight nine conservation practices identified as candidates to address a subset of the resource concerns in Table 3-3. These examples are used to illustrate how this set of PFAS-relevant resource concerns can be used to evaluate the entire set of existing practice standards for their relevance to PFAS. These practices were intentionally selected to include a variety of different types of farm operations (such as crops, forage, and animals) and to include practices that are contracted under NRCS programs on a large number of acres today. The committee also reviewed the entire list of conservation practices included in the fiscal year 2025 version of the CPPE matrix and identified 88 existing practices that could be further reviewed individually by NRCS for their relevance to PFAS contamination, transport, or fate (Appendix D).

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TABLE 3-3 PFAS-Relevant Resource Concerns

Resource Concern Category	Specific Concern
Soil Resource Concerns	Sheet and rill erosion
	Wind erosion
	Ephemeral gully erosion
	Subsidence
	Compaction
	Organic matter depletion
	Concentration of salts or other chemicals
	Soil organism habitat loss or degradation
	Aggregate instability
Water Resource Concerns	Ponding and flooding
	Seasonal high-water table
	Seeps
	Nutrients transported to surface water
	Nutrients transported to groundwater
	Pesticides transported to surface water
	Pesticides transported to groundwater
	Pathogens and chemicals from manure, biosolids, or compost applications transported to surface water
	Pathogens and chemicals from manure, biosolids, or compost applications transported to groundwater
	Petroleum, heavy metals, and other pollutants transported to surface water
	Petroleum, heavy metals, and other pollutants transported to groundwater
	Sediment transported to surface water
Air Resource Concerns	Emissions of particulate matter (PM) and PM precursors
Animal Resource Concerns	Terrestrial habitat for wildlife and invertebrates
	Inadequate livestock water quantity, quality, and distribution

NOTE: No existing resource concerns designated for plants were identified as PFAS relevant.
SOURCE: Adapted from USDA–NRCS 2023.

The following subsections briefly address each of the nine example practices with the total acres contracted under each practice in fiscal year 2023, which the most recent fiscal year that data are available from the online NRCS Resource Conservation Act Dashboard.[16] It is important to keep in mind that the resource concerns included in these examples were not developed with PFAS in mind and thus may exclude PFAS-specific concerns or risks discussed in the previous section (see "Conservation Practice Capabilities and Tradeoffs"). In Appendix E, each practice is summarized using a table

[16] See *NRCS Resource Conservation Act Dashboard,* https://publicdashboards.dl.usda.gov/t/FPAC_PUB/views/RCATopPracticesbyLandUseandState/TopPracticesDashboard.

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containing the resource types affected by the implementation of the practice, the specific resource concerns that the practice addresses, the effect of the practice on each concern, and the rationale for its use.

Crop Cover (Code 340)

Adding cover crops to a field in between the harvest of one cash crop and the planting of the next is commonly promoted to improve soil health and reduce nutrient and soil loss from fields to waterways. By having roots in the soil during non-cash crop periods, cover crops can improve soil aggregate stability and help soil be more resistant to compaction from trips over the soil surface with farm equipment. The additional vegetation contributes more biomass to the soil, increasing organic matter, while more vegetated cover of bare soil, as well as plant residue on the soil surface, protects bare soil from erosion and reduces various forms of runoff from fields. By reducing runoff and erosion, cover crops reduce the amount of sediment transported to surface waters. One important thing to keep in mind is that NRCS financial assistance for cover crops excludes a crop planted over winter and harvested to be sold (like other cash crops) and limits financial assistance to adopt cover crops to those with a singular resource conservation purpose. As an example, winter wheat that functionally acts as a cover crop over the winter months is not eligible for financial assistance because the grain is harvested and sold to generate revenue. In 2023, 1,768,655 acres were contracted under the cover crop practice.

The committee determined cover crops to be a PFAS-relevant practice because they reduce erosion and runoff, which should limit off-field surface transport of contaminated soil and water, and enhance soil carbon content, which may result in greater PFAS adsorption and lower availability for plant uptake. However, the end use of the cover crops may be important if they are grazed by livestock or mechanically harvested for forage to be fed to animals. If PFAS are ingested with forage, then animals or their products could become contaminated. Similarly, if wildlife forage on cover crops from contaminated fields, it is possible that these animals will become contaminated. Cover crops may also affect PFAS fate by stimulating microbial activity, via root exudates, and by precursor transformation. There may be additional ways that cover crops could be beneficial or exacerbate the transport of PFAS beyond currently contaminated sites that need to be considered. The species selected and whether or not livestock feed on a cover crop can be important considerations for conservation planning when PFAS are present.

Nutrient Management (Code 590)

Nutrient management is an extremely flexible practice standard that can be implemented in many ways depending on the resource concern(s) being addressed, soil and water conditions, and the crops or animals in each farm operation. This practice could be implemented using reduced fertilizer application rates, eliminating fall fertilizer application and shifting application to after planting, or using soil testing and yield data to implement variable rate nutrient application within a field to match crop needs to

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available nutrients. The 4Rs of nutrient management are often discussed when trying to improve overall nutrient management: choose the right source of nutrients, apply at the correct rate, apply at the right time, and apply in the right place. In 2023, 728,096 acres were contracted under the nutrient management practice.

In practice, synthetic (inorganic) fertilizers or an organic nutrient source—such as animal manure or biosolids—can be used to supply crop nutrients. Organic nutrient sources can address organic matter depletion as a soil resource concern in addition to providing crop nutrition, but if manure or biosolids are used, they should not be contaminated with PFAS. Historical application of contaminated biosolids continues to be an important source of PFAS found in farm soils decades after the biosolids were applied (Pozzebon and Seifert 2023). Because of this, extreme care must be taken when using these materials as a nutrient source so that uncontaminated land remains so and to avoid PFAS runoff into surface water or leaching into groundwater. Depending upon the method of land application, PFAS could be spread or transported in particulates if improperly applied. Testing of any land-applied material from a new or uncertain source is a minimum precaution to avoid introducing or exacerbating on-farm contamination.

Pasture and Hay Planting (Code 512)

Planting a pasture for grazing or hay for baling is a widely utilized practice to establish vegetative cover that reduces multiple forms of erosion and, through root growth, can reduce soil compaction. Establishing a perennial living cover on the soil contributes litter to the soil that enhances organic matter, provides habitat for soil organisms that contribute to soil stability, and reduces wind erosion to address air resource concerns. Plant species selection can also improve wildlife and invertebrate habitat in pastures. In 2023, 324,989 acres were contracted under the pasture and hay planting practice.

Hay planting or pasture establishment that requires soil disturbance through tillage or less intensive soil disturbance will expose PFAS-contaminated soil to water and wind erosion. Care must be taken to prevent pollutant transport into surface water, groundwater, or airborne particulates when implementing this practice on contaminated sites. Selection of nutrients used when establishing or maintaining pasture and forage crops must be done to avoid PFAS contamination through fertilizer or soil amendment(s) application. Irrigation water source, if applicable, could also lead to contamination of soil or forages through this practice.

Grazing Management (Code 528)

This practice is alternatively referred to as prescribed grazing or rotational grazing and can potentially be implemented in different ways depending on site specifics and producer resource concerns. Grazing management is used to achieve production and conservation objectives. Production goals are addressed through increased quality and vigor of forages while also achieving erosion reduction and moderate improvements in soil health (i.e., reducing compaction, improving aggregate stability, increasing

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organic matter). In 2023, 2,392,161 acres were contracted under the grazing management practice.

If grazing animals are introduced where none were present before or excluded from water sources by new fencing to facilitate pasture rotation, the water and feed sources in the newly grazed or segregated areas must be uncontaminated to avoid livestock contamination. As with water sources, any organic fertilizer or soil amendments used to manage pasture productivity should be uncontaminated to protect grazing animals from new PFAS exposure.

Soil Carbon Amendment (Code 336)

This is a relatively new and as-yet not widely contracted practice standard (9,614 acres in 2023), but the committee included it here because of active interest in the practice for multiple potential benefits both on- and off-farm and its potential use on cropland, pastureland, range, or forest. Enthusiasm for soil carbon amendments to improve soil health has prompted great interest in its potential benefits to address PFAS in soils. Carbon amendments in this context refer to high carbon material such as biochar and wood ash rather than manure or biosolids. Early research is underway to evaluate whether and what carbon sources might provide PFAS sorption benefits in contaminated soils. As with any other land-applied material introduced on a farm operation, the PFAS contamination status of the carbon source itself should be verified to avoid introducing contamination or somehow facilitating mobilization of already present PFAS. Potential concerns of using carbon amendments on PFAS-impacted lands include future release of PFAS that have sorbed to the high carbon amendments. Secondly, mobilization of PFAS-laden carbon particles may occur, leading to particles entering groundwater or surface water via tile drainage. For this reason, quantifying desorption behavior of PFAS sorbed to carbon amendments taken from field-amended soils and PFAS quantification with depth post-harvest over time were identified as a research gap to be addressed.

Tree/Shrub Establishment (Code 612)

This popular practice can serve many different conservation purposes. With regards to PFAS, careful selection of species to address wildlife food and habitat resource concerns needs to consider whether the site is contaminated and whether the species established will expose wildlife to PFAS through plant uptake. If planted in previously contaminated soils, careful site preparation will be necessary to avoid water or wind transport of PFAS-laden soil particles or particulates when establishing new stands, especially in riparian areas. Any woody plant stock introduced should be certified PFAS-free to avoid new contamination of the site when implementing this standard. In 2023, 475,782 acres were contracted under the tree/shrub establishment practice.

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Upland Wildlife Habitat Management (Code 645)

Wildlife habitat management, by establishing, improving, or diversifying vegetative land cover, can address soil, water, and air resource concerns through reduced erosion. In 2023, 3,945,826 acres were engaged in this practice. As the name of the standard suggests, animal resource concerns are also addressed if substantial improvement to habitat occurs. As with other practices discussed, care needs to be taken so that soil disturbance or exposure on already contaminated sites does not transport PFAS in soil or water to nearby areas. Any habitat plantings on PFAS-contaminated lands that provide food or could be a wildlife food source should be evaluated to determine whether their consumption will result in unhealthy animal exposure to PFAS.

Water and Sediment Control Basin (Code 638)

This standard is primarily used to address erosion or excess water problems on the farm. It involves building an earthen basin to collect excess runoff from farm fields to reduce or eliminate ponding on farmland that can damage crops or hinder their development. In addition, the basin allows water to slowly infiltrate soil or be discharged in a slow, controlled manner while sediment settles in the basin, collecting it instead of transporting it with stormwater runoff. Land area engaged in this practice in 2023 was 53,443 acres.

Soil disturbance, as with some previously discussed practices, and soil movement to create an embankment (or ridge with trench to intercept runoff on a grade) when constructing a water and sediment control basin (WASCOB) could result in contaminated soil or water transport if PFAS is already present when the standard is implemented. If water stored even temporarily in a WASCOB carries soluble forms of PFAS that are not bound to soil particles captured as sediment in the basin, then this practice could possibly facilitate movement of PFAS off site. Furthermore, if trapped sediment is contaminated and this sediment is periodically removed to maintain the functionality of a WASCOB, then transport of contaminated sediment to an uncontaminated location is a concern and should be avoided.

Watering Facility (Code 614)

Livestock watering facilities can address multiple resource concerns in addition to providing health and production benefits to livestock themselves. Keeping stock out of streams by installing a watering facility reduces streambank erosion and deposition of nutrients and manure-borne pathogens into waterways. Water testing to determine that a candidate water source, whether groundwater or surface water, is not contaminated with PFAS is important to ensure that financial assistance for this standard does not lead to domesticated or wild animals becoming contaminated.

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Considerations for Evaluating Efficacy, Cost-Effectiveness, and Adoption Potential of Practices to Address PFAS

A basis for establishing the efficacy of a conservation practice in the context of PFAS in agriculture today could be preventing harmful exposure (including through pollutant transport), lowering contamination levels to allow agricultural production or unrestricted wildlife access to a site, or avoiding financial losses to the producers. Scientific discovery (i.e., research) of new or more effective practices, conservation or otherwise, typically requires technological development or refinement before cost-effectiveness can be established. Efficacy is a necessary but not sufficient condition to be considered cost-effective for use in new conservation practice standards or conservation enhancements to address PFAS. The relative cost-effectiveness of different practices or technologies is determined by comparing the cost of different options to achieve the same required effectiveness criterion or criteria (Segerson 2013). The most cost-effective option achieves this criterion at the lowest cost among all the available alternatives. However, cost-effectiveness alone is not enough to be a viable solution; even if a practice or technology is the lowest-cost option, this does not automatically mean that it is commercially viable. If all effective options available today are prohibitively expensive—they cost more to produce or implement than the value of the benefits they generate for society—there may not be any feasible alternatives to consider for inclusion in USDA conservation programs.

Producers' private willingness to pay is determined by the benefit or value received from adopting a practice (Bowman et al. 2025). If the private benefit does not exceed the cost of adopting a practice, then uptake will be very low (Engel et al. 2008). The cost borne by a producer to implement a practice is limited to their own out-of-pocket cost. When the government intervenes in the private market by providing financial assistance to adopt conservation practices, it effectively divides (or "cost-shares") the full cost of the practice between the producer and the government. It is important not to lose sight of the fact that the total cost to society is still the entire cost of adopting or installing the practice equal to whatever portion is paid by the farmer plus the cost-share paid by the government. The logic of financial assistance or subsidies is that by lowering the private cost of practices, the government incentivizes a higher level of adoption than would occur without government intervention (i.e., the producer pays the full cost of adoption). If a producer's willingness to pay to implement a practice or adopt a new technology is greater than or equal to their cost after USDA financial assistance is deducted from the total cost of adoption, then it would be expected that they would apply for government financial assistance (assuming the cost of applying is negligible) and adopt the practice if they are accepted into the program (Baylis et al. 2022). If the cost-share payment is not sufficient to close the gap between a producer's willingness to pay and the cost of implementing the practice, then a producer will not apply for program funds (Engel et al. 2008).

There is not unlimited funding, and these programs receive more applications than they are able to fund in each funding cycle, but there are some ways to prioritize practices to address critical problems. Cost-share rates for a given practice can vary

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based on the specific program (be it EQIP, CSP, or CRP), the state where a practice is supported through a conservation contract, and whether the practice (and possibly location of the farm or ranch) has been designated as a priority. State NRCS offices implement federal conservation programs taking into account the specific agroclimatic conditions in their jurisdiction and can designate priority practices for implementation. Designated practices to address prioritized resource concerns can have a portion of the total financial assistance allocated to the state effectively set aside for the prioritized practice or practices. In addition, it is possible to increase the cost-share amount of the estimated cost of adopting prioritized practices. Special landscape initiatives in certain locations also offer higher cost-sharing rates than standard conservation contracts to prioritize satisfying the objectives of the initiative.

From a producer's perspective, once a desirable practice has been identified but the producer is unwilling or unable to afford it, conservation financial assistance can close the gap between willingness or ability to pay and the full cost of adoption. Financial assistance for farmers to install or implement new practices to address resource concerns through the conservation planning process while receiving technical assistance can play a vital role in increasing adoption of practices that have public benefits for decades (Prokopy et al. 2019). Conservation programs could play the same role in addressing PFAS concerns once effective practices are determined that are not cost-prohibitive.

OPPORTUNITIES TO ADDRESS PFAS CONCERNS THROUGH CONSERVATION SUPPORT

Successful use of conservation practices, programs, and initiatives for the mitigation of PFAS contamination will require the identification of PFAS contamination, a determination by NRCS of which conservation practices can be effective, how these practices can be applied in a conservation systems approach to achieve multiple conservation outcomes, including PFAS mitigation, and eligibility under conservation programs to address the issue. Because natural resources are integrated, PFAS cannot be addressed unilaterally but must be considered in the context of soil erosion control and soil health, water movement and management, crop types and cropping systems, and other factors based on the operation type and field conditions. Therefore, addressing PFAS mitigation on a farm, ranch, or forest setting will first require a conservation plan developed by a trained and skilled conservationist in concert with the customer—that is, the decision-maker for the property under his or her control.

Resource Concern Possibilities

Conservation plans are created to address specific resource concerns, and at present, a plan that would directly address PFAS issues would presumably seek to address one of the following concerns[17]:

[17] Personal communication, B. Reck, National Environmental Engineer, Natural Resources Conservation Service, U.S. Department of Agriculture. Presentation to the committee, April 3, 2025. https://www.nationalacademies.org/projects/DELS-BANR-24-03/event/44748.

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- Pathogens and chemicals from manure, biosolids, or compost applications transported to surface water.
- Pathogens and chemicals from manure, biosolids, or compost applications transported to groundwater.

Although PFAS can fall under the umbrella of chemicals, it could be added explicitly to the name of the resource concern to help conservation planners maintain awareness when working with customers. Other resource concerns could be interpreted to apply to PFAS, such as those dealing with petroleum, heavy metals, and other pollutants transported to water.

Alternatively, NRCS could develop and treat PFAS contamination as a distinct resource concern. To become a standalone resource concern, there needs to be an emerging issue that will require conservation efforts to resolve the concern. The ubiquitous nature of PFAS and the many ways in which it can enter the agricultural field, pasture, or forest could warrant PFAS being designated as a standalone resource concern, much like the transport of nutrients to surface water or groundwater are standalone resource concerns. The principal rationale to support this approach is that PFAS contamination could be directly evaluated by NRCS for the effect of each conservation practice on this concern and would not be dependent on surrogate evaluations through the results for related resource concerns. Designating PFAS as a resource concern would help to ensure it receives proper consideration in the conservation planning process and that the most effective conservation practice solutions are planned for the specific site to mitigate PFAS contamination.

There would be pros and cons to elevating PFAS to an explicit resource concern. On the pro side, this move would clearly call out PFAS as an issue that NRCS needs to tackle and provide clear planning guidance to field staff. It would also create the opportunity to examine current and new practices to address the issue and think through the relative ability of the practices to address on-farm PFAS contamination. Customers, as well as state and other federal agencies, would have guidance on how NRCS is addressing the PFAS issue. This guidance could help other natural resource agencies formulate their own plans of action. Furthermore, as reviewed in Chapter 2, PFAS enters and moves in the agricultural system in many different ways, and binning PFAS contamination within an existing resource concern might not achieve the desired planning and practice results. Finally, making PFAS its own resource concern may make it easier for NRCS field staff and TSPs to address the problem if the technical guidance is specific to PFAS.

NRCS would also want to consider the cons of this approach, which would include the fact that it creates another resource concern that needs to go through the NRCS vetting process. This process could slow down addressing the issue, whereas binning within an existing resource concern could cover most of the planning and practice needs. Calling out PFAS as a standalone resource concern could bring unwanted attention to producers and other customers affected by the issue or make producers less inclined to work with NRCS because of concerns of being singled out, though there is precedent in

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the planning process for dealing with sensitive issues.[18] Finally, as the fate and transport of PFAS in the environment is not uniform, addressing PFAS as a specific resource concern in the conservation planning process is challenged by the variety of behaviors that could occur in response to conservation practices.

Conservation Practices Possibilities

Regarding conservation practices, there are a few approaches available to NRCS that it could explore to increase the capabilities of these practices (as well as enhancements and bundles) to address on-farm PFAS contamination and mitigation. As discussed in the review of the programs within this chapter, subprograms that allow for innovation could spur experimentation with new practice standards that are aimed specifically at addressing PFAS concerns. For example, a new practice standard could be developed to help conservation planners identify the best crops to which a producer could switch if plant uptake of PFAS from soil or water sources was found to be a problem. Experimentation could also be used to improve existing standards. Filter Strips (Code 393), for instance, could be a useful practice for keeping PFAS from entering water bodies. Experiments could help identify the best vegetation to plant in a given environment to meet this objective.

NRCS could also make concerns about PFAS more explicit in the existing practices standards. At the time this report was written, only one practice standard, Soil Carbon Amendment (Code 336), flagged PFAS specifically as an issue (see section "Conservation Practice Capabilities and Tradeoffs" above). Many conservation practice standards address contamination issues or provide guidance on how to avoid contamination issues that could be caused by implementing a practice. Nutrients, sediments, and pesticides are often mentioned explicitly in conservation practices that address soil or water resource concerns. PFAS could be added to draw extra attention to potential problems when creating a conservation plan. These additions could be made as part of the 5-year review process of conservation practice standards.

Conservation Program Possibilities

Three of the four NRCS programs the committee was asked to examine have the capability to address on-farm PFAS contamination and mitigation. Table 3-4 summarizes the capabilities of each program. EQIP has high potential for widespread use in support of USDA's efforts to help farmers, ranchers, and forest stewards address mitigation of PFAS contamination on the working lands of farms and ranches and in private

[18] When working with customers, NRCS conservation planners must assess potential adverse effects of proposed conservation practices and systems on cultural resources and endangered, threatened, and at-risk species. They should work to avoid, minimize, or resolve these effects and, in the case of endangered, threatened, or at-risk species, integrate benefits whenever possible, consistent with laws, regulations, and agency policies. See *Cultural Resources*, https://www.nrcs.usda.gov/our-agency/cultural-resources, and *Special Environmental Concerns: Endangered & Threatened Species*, https://www.nrcs.usda.gov/sites/default/files/2023-06/Endangered_And_Threatened_Species.pdf.

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forests. EQIP's CIG subprogram could be a valuable tool to fill the gap between proven research results and transitioning those results into practical applications on working lands through revised practice standards and enhancements; new practice standards and enhancements; and innovative technologies, technical tools, and approaches. CSP has medium potential for assistance through its offer of enhancements or bundles of enhancements that can improve the performance of conservation practices, especially if these enhancements and bundles were assembled specifically to address PFAS contamination. There is also high potential for the use of CRP to address mitigation on PFAS-contaminated cropland and grazing lands because CRP offers long-term contracts for conservation purposes on environmentally sensitive lands and PFAS contamination satisfies one of the land eligibility criteria: contributing to the degradation of water quality or posing an on-site or off-site environmental threat to water quality if the land remains in food, feed, or fiber production. The committee sees pathways to exercise CRP for mitigation purposes through its current provisions, including CREP, as well as the potential for Congress to authorize a PFAS-specific pilot program, which could include monitoring and evaluation to assess the effectiveness of pilot program efforts. In addition, the annual rental payments through enrollment in CRP would compensate participants for the loss of agricultural production on working lands. In all uses of CRP for this purpose, care would need to be taken with CRP's use of conservation covers to ensure the vegetation used does not create contaminated food sources for wildlife detrimental to their health. FSA also can fund MAE projects through CRP to support studies by subject matter experts related to PFAS contamination and mitigation that would improve or enhance the ability of CRP to address this concern on eligible agricultural lands through program policy and delivery changes.

Using ACEP for PFAS mitigation has no potential given the current statute and program rule that underpin this program, which prohibits the enrollment of lands where the purposes of ACEP would be undermined, such as by the suspected or confirmed presence of hazardous materials. While ACEP offers long-term participant obligations for conservation purposes, the easements and long-term agreements create substantive risk for the government, especially with easements where the government is purchasing certain property rights from the landowner for conservation purposes. Statutory direction is needed if NRCS were to use ACEP easements for PFAS-contaminated lands given the potential liabilities associated with the federal government (or another entity through USDA) controlling certain property rights for lands containing or suspected of containing a hazardous substance such as PFOA or PFOS.

Conclusion 3-1: There are opportunities within the statutory, policy, and operational frameworks of EQIP, CSP, and CRP to help address on-farm PFAS contamination and mitigation. For example, PFAS could be identified as a priority for funding through existing program features and procedures. Pilot initiatives could be pursued within programs to target the avoidance or mitigation of PFAS contamination on agricultural lands.

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TABLE 3-4 NRCS Conservation Programs and Their Potential to Mitigate PFAS Concerns on Agricultural Lands Based on Current Program Legislation and Regulation

Conservation Program	**Primary Target Participant**	**Fund Obligation Vehicle**	**Key Potential PFAS Mitigation Mechanisms**	**Not Applicable**	**Medium Potential**	**High Potential**
EQIP	Individual	Contracts	Conservation practices and activities on working lands			
CIG[a]	Entity	Agreements	Trials of innovative practices, technologies, tools, and approaches for working lands			
CSP	Individual	Contracts	Enhancements, enhancement bundles, and conservation practices for working lands			
CRP	Individual	Contracts	Vegetative conservation covers on PFAS-contaminated sensitive lands through regular CRP, a legislatively authorized pilot program, and/or through CREP with a partner entity, plus MAE studies			
ACEP	Individual or Entity	Easements and Agreements	Restoration of wetlands and supporting practices and protection of cropland and grassland to limit non-agricultural use			

[a] CIG is a subprogram of EQIP.

NOTE: ACEP = Agricultural Conservation Easement Program; CIG = Conservation Innovation Grant; CREP = Conservation Reserve Enhancement Program; CRP = Conservation Reserve Program; CSP = Conservation Stewardship Program; EQIP = Environmental Quality Incentives Program; MAE = monitoring, assessment and evaluation.

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Conclusion 3-2: PFAS could be addressed in a conservation plan through existing resource concerns, such as those pertaining to the transport of pathogens and chemicals to water, or through the creation of a standalone resource concern, much as nutrient transport to surface water and groundwater are standalone resource concerns. There are pros and cons to either approach.

Conclusion 3-3: There are opportunities for NRCS to increase the capabilities of conservation practices to address on-farm PFAS contamination and mitigation. These include:

- *Supporting on-farm conservation field trials, such as through EQIP's Conservation Innovation Grant subprogram, on the basis of proven research to improve existing conservation practice standards or develop new standards that address PFAS concerns.*
- *Including PFAS as an explicit contaminant of concern in existing conservation practice standards whose purpose and the conditions where the practice applies have relevance to PFAS contamination, mitigation, or both.*

Tackling PFAS across the varied agricultural landscapes NRCS works within will be a difficult task. Creating opportunities within conservation programs and practices and perhaps creating new practices or modifying resource concerns to address PFAS would provide local staff with some of the information needed to make educated decisions. The next step, addressed in Chapter 4, is to fit these programs and practices into a larger framework that helps guide staff, who might have only cursory knowledge of an issue, to start customers down the decision-making process towards informed choices on the appropriate practice(s) to mitigate or reduce a PFAS issue.

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4

Decision-Making Under Uncertainty

The lack of data regarding the magnitude of per- and polyfluoroalkyl substances (PFAS) contamination on agricultural land, combined with uncertainties about what different potential PFAS sources may contribute to farm contamination, poses a challenge to advising farmers on how to manage PFAS risks. Concomitantly, there are issues around the unknowns on the fate, transport, and toxicity of different PFAS, and there is no federal agency consensus on the definition of PFAS, including in the context of agriculture. This chapter describes considerations the Farm Production and Conservation (FPAC) agencies may take into account with regard to a working definition of PFAS. It also summarizes how data on the proximity of farmland to potential PFAS sources along with PFAS measurements from previous studies could be leveraged to identify at-risk agricultural land and to advise farmers accordingly. Finally, it describes a framework that could be used by FPAC agencies to make decisions about PFAS in the face of uncertainty.

IDENTIFYING PFAS OF CONCERN ON AGRICULTURAL LAND

As discussed in Chapter 2, PFAS have circulated so widely around the globe that detection of one or more of these substances is likely even on farmland distant from major PFAS sources. However, much is unknown about the fate, transport, and toxicity of many PFAS. In addition to evaluating the risk that conservation practices could lessen or exacerbate PFAS contamination in soil and water on or off the farm, the Natural Resources Conservation Service (NRCS) needs to identify a way to determine if all PFAS that may be present are of equal concern. However, crafting a working agricultural definition of PFAS for the purpose of reducing complexity for on-farm guidance is difficult. No single definition of PFAS has been agreed to, whether based on chemical structure, existing regulations, or chemical behavior and properties. Below,

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the committee reviews approaches that could be considered for defining PFAS in an agricultural context.

While there is agreement that what makes PFAS different from other synthetic compounds is the presence of one or more perfluorocarbons bound to a polar functional group, there is not a single, internationally accepted definition of PFAS. Slight variations exist among different federal agencies and international organizations regarding which chemical structures fall under a general class definition for PFAS. Commonly referenced definitions are based on structure and include Buck et al. (2011), the Organization for Economic Co-operation and Development (OECD 2021), one published by the Environmental Protection Agency (EPA) in 2022, and a second EPA definition published in Gaines et al. (2023) (Table 4-1). Additionally, the 2021 National Defense Authorization Act (NDAA) contained a PFAS definition that was used to coordinate federal activities related to PFAS.[1] Notably, under the fiscal year 2023 NDAA, a report on PFAS use within the U.S. Department of Defense (DoD) was issued that utilized the OECD definition of PFAS (DoD 2023). In some cases, there are curated lists of compounds that have been identified as meeting these PFAS published definitions. For example, the structures in Gaines et al. (2023) and EPA (2022) are in the EPA Comptox lists "PFAS Structures in DSSTox (Update August 2022)"[2] and "Chemical Contaminant Candidate List 5,"[3] respectively. Although specific numbers of compounds that would be defined as PFAS under these definitions vary, in some cases (e.g., Gaines et al. 2023), there are currently more than 14,000 compounds with structures known to meet the relevant criteria.

Even though thousands of PFAS can be captured within the above definitions, few can be analyzed. Analytical standards are available for only a small subset of PFAS (less than 100), and there is no standard sample preparation or analytical method that includes all PFAS for which standards are available or all media relevant to agricultural systems (e.g., water, soil, sediment, plants, pesticides, fertilizers). However, EPA Method 1633A is one of the most widely applied standard methods for PFAS analysis (EPA 2024a). This method is applicable to the analysis of 40 PFAS in aqueous, soil, biosolids, sediment, and tissue samples. Additionally, EPA Method 1633A provides the flexibility to add additional PFAS without EPA approval and as standards become available, provided all quality control criteria can be met (EPA 2024a).

Therefore, a working PFAS definition based on chemical structure could be created for agriculture by narrowing down a broad list of chemicals that meet a structural definition of PFAS in Table 4-1 to those substances that can be successfully analyzed using a method such as EPA Method 1633A. This method alone would not be sufficient because, for example, the primary PFAS precursors in biosolids, such as the fluorotelomer phosphate diesters (diPAPs) of varying chain length, are not on the EPA Method 1633A list. However, they can be included and analyzed with this method. Utilizing

[1] William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Public Law No. 116–283, tit. III, § 300f (2021).

[2] See https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCTV5.

[3] See https://comptox.epa.gov/dashboard/chemical-lists/CCL5PFAS.

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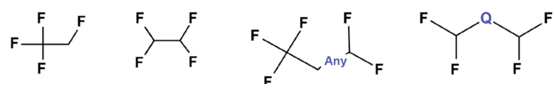
TABLE 4-1 Commonly Referenced Definitions of Per- and Polyfluoroalkyl Substances (PFAS)

Reference	**Definition**
Buck et al. (2011)	"highly fluorinated aliphatic substances that contain 1 or more C atoms on which all the H substituents (present in the non-fluorinated analogues from which they are notionally derived) have been replaced by F atoms, in such a manner that they contain the perfluoroalkyl moiety C_nF_{2n+1}–"
2021 National Defense Authorization Act	"…(A) man-made chemicals of which all of the carbon atoms are fully fluorinated carbon atoms; and (B) man-made chemicals containing a mix of fully fluorinated carbon atoms, partially fluorinated carbon atoms, and non-fluorinated carbon atoms."
OECD (2021)	"PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e., with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."
EPA (2022)	Chemicals that have at least one of the following structures: R-(CF_2)-CF(R')R", R-CF_2OCF_2-R', or $CF_3C(CF_3)$RR'
Gaines et al. (2023)	Must contain at least 30% fluorine (not counting hydrogen) and a set of "substructural features" as shown below: 

analysis to guide a working definition of PFAS in this manner would require scheduled reviews (e.g., annual or similar) of the availability of new standards and the ability of laboratories to successfully analyze those standards using an established method.

Another approach to establishing a working definition of PFAS in agriculture could be to focus on PFAS that are already the subject of regulation, either at the federal level (such as under the Safe Water Drinking Act[4] or the Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA][5]) or at the state level. In 2024, EPA established maximum contaminant levels (MCLs) for six PFAS in drinking water under the Safe Water Drinking Act (EPA 2024b);[6] however, in May 2025, EPA announced its intention to rescind the MCLs for all but perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA; EPA 2025). Management of superfund sites subject to CERCLA relies on EPA Regional Screening Levels (RSLs), which are default screening levels for human exposure to contaminated residential and commercial–industrial soil, air, and drinking water that are based on toxicity information (i.e.,

[4] 42 U.S.C. §300f et seq.
[5] 42 U.S.C. §9601 et seq.
[6] The other PFAS in the 2024 rule were PFNA, PFHxS, HFPO-DA (GenX chemicals), and mixtures of two or more of the following: PFNA, PFHxS, HFPO-DA, and PFBS.

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reference doses) combined with default exposure assumptions.[7] At the time this report was published, there were more than 35 PFAS with screening levels for residential and industrial soil, tap water, and soil to groundwater pathways. As noted, RSLs are for residential and industrial exposure, so they are not specific to agricultural scenarios. Lastly, some states have developed regulatory criteria for PFAS in media including soil, water, and air. These criteria vary widely and are subject to change, but compilations are maintained by organizations such as the Interstate Technology & Regulatory Council (ITRC).[8] Similar to analytical considerations, use of available MCLs and RSLs to guide an agricultural working definition of PFAS would require routine reviews for available reference doses (and associated RSLs when relevant).

As a result of the complications surrounding analysis and toxicity assessments of individual PFAS, some agencies and regulatory bodies are implementing limits on "total PFAS" concentrations. For example, the fiscal year 2020 NDAA prohibited DoD from procuring aqueous film-forming foam (AFFF) with greater than 1 part per billion (µg/kg) of PFAS.[9] Total PFAS analysis does not elucidate which PFAS are present. It provides the total fluorine concentration associated with PFAS in a sample. Challenges include analysis and data interpretation. For example, combustion ion chromatography is often used as a method of total PFAS analysis, but sensitivity is low, and there is not a perfect method of sample preparation to ensure that analytical results represent total PFAS. Results may include non-PFAS sources of organic fluorine, including fluorinated pharmaceuticals, and when samples are prepared by extraction, it can lead to exclusion of highly soluble PFAS that are not well retained by the extraction approach (e.g., trifluoroacetic acid). Another example of analysis increasingly being used is the total oxidizable precursor (TOP) assay. The TOP assay converts PFAS precursors and some intermediate compounds to perfluoroalkyl acids (PFAAs), which can be more easily detected with targeted methods (Rehnstam et al. 2023; Lange et al. 2024; Dauchy 2025). Limitations of the TOP assay are that it is less likely to identify compounds such as fluorinated pharmaceuticals and there are challenges with data interpretation because some PFAS oxidize into more than one terminal PFAA. Moreover, oxidation consistency is affected by PFAS, matrix type, temperature control, reaction time, and proper analysis of ultra short-chain PFAAs. Regardless of these additional assays that may help to address estimation of total PFAS, regulatory or guidance criteria to inform total PFAS levels that require further action are lacking. Nevertheless, as more sensitive methods of total PFAS analysis (e.g., Hahm et al. 2024) become more commercially available, guidance on use of total PFAS as a screening or regulatory criteria may be developed. In that scenario, using total PFAS as a working definition (at least at the screening level) may be a practical and cost-effective method to help screen agricultural facilities for problematic PFAS impacts.

[7] See https://www.epa.gov/risk/regional-screening-levels-rsls.

[8] State-level standard and guidance values for PFAS in groundwater, drinking water, surface water, residential soil, and air are available by the ITRC under "PFAS Environmental Media Values Table Excel file," found at https://pfas-1.itrcweb.org/fact-sheets/ (accessed September 2, 2025).

[9] National Defense Authorization Act for Fiscal Year 2020, Public Law No. 116–92, tit. III, § 322b (2019).

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Another option for identifying a subset of PFAS that merits the most concern in agriculture (and thus its use as a working definition) is through approaches such as those used in the European Union Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). Specifically, REACH identifies and defines substances of concern using persistence (P), bioaccumulation (B), and toxicity (T). More recently there have also been considerations for mobility (M) (Table 4-2) (Strempel et al. 2012; Hale et al. 2020; ECHA 2023, 2024). Designations used include PBT, PMT, PvB, and vMvT.[10] Within REACH, these designations would be used to identify substances of very high concern that would be subject to restrictions such as reduced production volumes. However, in other settings, these factors could be used to identify chemicals within a family such as PFAS that merit the closest scrutiny when detected in environmental media. Compound-specific data are needed to evaluate P, B, T, and M categories, and experimental values are available for some PFAS. Compilations of experimental and calculated values needed to evaluate persistence, bioaccumulation, and mobility are provided for the majority of PFAS by EPA.[11] The Open (Quantitative) Structure-activity/property Relationship Application (OPERA)[12] is the primary tool used to generate calculated values. In the absence of toxicity data, these approaches could be proactively used to identify PB, PM, vPvB, or vPvM PFAS. There is also increasing focus on the use of high-throughput screening methods to facilitate faster data collection, particularly for toxicity (NASEM 2017; Escher et al. 2023).

Approaches such as RSLs and assessments using REACH criteria focus on a single compound at a time and neglect the impacts of mixtures. It is well-established that PFAS in the environment primarily occur as mixtures. In some cases, this may lead to synergistic toxicological effects where the impacts of mixture exposure on human or environmental health exceed the sum of impacts of individual exposures. The approach used for regulation in the context of contaminant mixtures will depend on the type of toxicity data available (e.g., whole mixture or individual compound data) and the toxicological effect (EPA 2000). As noted above, the original EPA MCLs for PFAS included six compounds. Four PFAS (GenX, perfluorobutanesulfonic acid [PFBS], perfluorononanoic acid [PFNA], and perfluorohexane sulfonate [PFHxS]) were to be regulated using a hazard index (HI), which is appropriate for contaminant mixtures that have similar toxicological effects (EPA 2000). Specifically, the original MCLs proposed that detected concentrations of GenX, PFBS, PFNA, and PFHxS in drinking water would each be divided by a compound-specific, health-based limit in water to yield a hazard quotient. The sum of the hazard quotients (i.e., the HI) should not exceed 1. Although EPA has announced it intends to rescind the HI (EPA 2025), the original 2024 regulation demonstrates a PFAS-specific example of a common approach for regulating contaminant mixtures. Approaches for regulating PFAS mixtures is an emerging area that may change as PFAS toxicity research evolves.

[10] Persistent, bioaccumulative, and toxic; persistent, mobile, and toxic; persistent and very bioaccumulative; very mobile and very toxic.

[11] See https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCT and https://comptox.epa.gov/dashboard/chemical-lists/PFASDEV1.

[12] See https://ntp.niehs.nih.gov/whatwestudy/niceatm/comptox/ct-opera/opera.

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TABLE 4-2 Definitions of Persistence, Bioaccumulation, Toxicity, and Mobility by the European Union Registration, Evaluation, Authorization and Restriction of Chemicals

Characteristic	Definition
Persistent (P)	Meets 1 of the following: • Degradation $t_{1/2}$ in marine water >60 days • Degradation $t_{1/2}$ in fresh or estuarine water >40 days • Degradation $t_{1/2}$ in marine sediment >180 days • Degradation $t_{1/2}$ in fresh or estuarine water sediment >120 days • Degradation $t_{1/2}$ in soil >120 days.
Very Persistent (vP)	Meets 1 of the following: • Degradation $t_{1/2}$ in marine, fresh or estuarine water >60 days • Degradation $t_{1/2}$ in marine, fresh or estuarine water sediment >180 days • Degradation $t_{1/2}$ in soil >180 days.
Bioaccumulative (B)	BCF ≥2000
Very Bioaccumulative (vB)	BCF ≥5000
Toxicity	Meets any of the following: • Long-term no-observed effect concentration (NOEC) or effect concentration 10% (EC10) for marine or freshwater organisms <0.01 mg/L • Substance meets the criteria for classification as carcinogenic (category 1A or 1B), germ cell mutagenic (category 1A or 1B), or toxic for reproduction (category 1A, 1B or 2) according to Regulation EC No 1272/2008 • Other evidence of chronic toxicity, as identified by the substance meeting the criteria for classification: specific target organ toxicity after repeated exposure (STOT RE category 1 or 2) according to Regulation EC No 1272/2008 • Substance meets the criteria for classification as endocrine disruptor (category 1) for human health or the environment according to Regulation EC No 1272/2008
Mobility	Log organic-carbon water partition coefficient (K_{oc}) <3.0
Very Mobile	Log organic-carbon water partition coefficient (K_{oc}) <2.0

NOTES: Degradation half-life ($t_{1/2}$) is the time for half of the parent compound to be degraded. BCF = bioconcentration factor
DATA SOURCE: ECHA 2024, European Chemicals Agency, http://echa.europa.eu/.

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In summary, a working definition of PFAS for agriculture may need to consider structural features, the ability to detect a specific PFAS, and thresholds for deciding when detected concentrations merit further investigation. Currently, one of the most pressing challenges is the lack of consistent regulatory criteria for PFAS in agricultural soils (e.g., RSLs), including considerations for occurrence of PFAS mixtures. Because of the variation in regulations at the state level, federal guidance on thresholds in agricultural lands would be beneficial to assist conservation planners and others in contextualizing PFAS occurrence at agricultural facilities. Notably, all of these considerations (structure, analysis, regulatory criteria, or the exceedance of a set threshold for some combination of persistence, bioaccumulation, toxicity, and mobility) are evolving areas of study and will require review and revision as the science advances.

IDENTIFYING AGRICULTURAL LANDS AT RISK FROM PFAS IN THE ABSENCE OF SITE-SPECIFIC DATA

Most agricultural lands have not been screened for PFAS. Monitoring PFAS occurrence at field sites including agricultural facilities can be expensive and time consuming, which can limit application to large regions. Additionally, although NRCS has an activity to assist with sampling costs for agricultural facilities interested in analyzing samples,[13] routine and large-scale monitoring of PFAS at agricultural facilities is outside of NRCS's scope. However, an understanding of PFAS occurrence may be useful for decision-making when considering implementation of conservation practices or support for agricultural facilities through the FPAC programs within the U.S. Department of Agriculture (USDA).

Because of the difficulty of site-specific modeling, along with the high costs of PFAS testing, new methods for estimating PFAS contamination risks based on available information about PFAS source locations could be helpful to inform decision-making about agricultural land. Recently developed databases and modeling methods provide a foundation for such alternative approaches. An increasing number of studies have demonstrated that data-driven approaches are useful for predicting the likelihood of PFAS occurrence (e.g., Guelfo et al. 2018; George and Dixit 2021; Hu et al. 2021; Li and MacDonald Gibson 2023; Moghadasi et al. 2023). These approaches couple existing datasets with statistical and/or machine-learning approaches to develop predictive models of PFAS occurrence.

Databases on PFAS Sources

Some federal and state agencies have compiled data on PFAS source locations and locations where PFAS have been measured previously that may be useful to inform risk management decisions. Table 4-3 lists selected examples. Data such as PFAS sources and soil and hydrogeologic characteristics are used as predictors for the likelihood of

[13] See discussion of Conservation Evaluation and Monitoring Activity 209 in section "Conservation Program Capabilities" in Chapter 2.

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PFAS impacts. PFAS occurrence data are typically used to train and validate predictive models. In addition to geospatial data, data-driven approaches may incorporate PFAS fate and transport properties such as soil–water partitioning coefficients, particularly when models are focused on prediction of specific PFAS concentrations as opposed to the simple presence or absence of PFAS. Data from fate and transport models are increasingly being integrated with machine-learning models (Boxes 4-1 and 4-2).

Among the most comprehensive datasets is the EPA PFAS Analytical Tools database.[14] This database allows users to visualize and download locations of a wide variety of facility types where PFAS have been manufactured, used, or unintentionally released to the environment. Examples include PFAS manufacturing companies, federal facilities that use or handle PFAS (e.g., Air Force bases that used AFFF), industrial facilities using PFAS, Superfund sites, and others. The database also includes data from previous PFAS testing in groundwater and surface waters.

PFAS Risk Screening Models

Recently, multiple research teams have leveraged public data sources (such as those in Table 4-3) to build and test computational models that predict the probability of PFAS occurrence in groundwater. Such models could also be useful for identifying areas where soil is at risk because soil serves as a major PFAS reservoir and source for groundwater contamination. Less extensive efforts have been made in predicting PFAS in soil. In both cases, models have been built and tested at a variety of scales, from local to state, regional, and national.

Predicting PFAS in Groundwater

Studies using data-driven approaches to predict PFAS occurrence have largely focused on groundwater. As an example of a local model, Li and MacDonald Gibson (2023) used public data sources (such as those in Table 4-3) along with data on PFOA measurements from 12,226 groundwater samples collected by the Minnesota Department of Health in the East Metro area of Minneapolis/St. Paul. The authors trained machine-learning Bayesian network models to predict the probability of PFOA occurrence above a state health-based action level for drinking water. This area of Minnesota is affected by PFAS released by the 3M Cottage Grove Facility, which has produced PFAS since the 1940s. Li and MacDonald Gibson (2023) found that the models were 82–89 percent effective in distinguishing locations where groundwater had PFOA concentrations above the state action level. In a separate study, the authors used a similar modeling approach to predict the occurrence of four short-chain PFAS above Minnesota's corresponding health risk limits (Li and MacDonald Gibson 2022). Models were more accurate for these short-chain PFAS than for the previously described PFOA models. Following a similar approach, one could create maps that predict the chance

[14] See https://echo.epa.gov/trends/pfas-tools.

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TABLE 4-3 Representative Datasets[a] Used in Data-Driven Approaches for Predicting PFAS Occurrence in the Environment

Data type	Data description	Reference
Potential PFAS Sources	Industry sources manufacturing 25,000 pounds of PFAS	Chemical data reporting under the Toxic Substances Control Act[b] (also accessible in U.S. Environment Protection Agency [EPA] PFAS Analytic Tools[c])
	Those importing 25,000 pounds of PFAS	
	Facilities within industrial sectors that *may* be associated with PFAS use (e.g., paper manufacturing, petroleum manufacturing, textile mills)	EPA Enforcement and Compliance History Online (ECHO) database[d]; also accessible in EPA PFAS Analytic Tools
		EPA Facility Registry Service[e]
	State-level data on sites of land application of organic soil amendments or sites of permits for land application of biosolids	Examples: Minnesota Pollution Control Agency;[f] North Carolina Department of Environmental Quality;[g] Maine Department of Environmental Protection PFAS Investigation Map[h]
PFAS spills/releases	Federal facilities with known or suspected PFAS releases (e.g., U.S. Department of Defense [DoD] sites)	Compiled by EPA in the PFAS Analytic Tools
	Agricultural facilities within one mile of a known or suspected DoD PFAS release	Annual reports posted to DoD web page,[i] also accessible as part of the federal facilities in the EPA PFAS Analytic Tools
	Superfund sites with known PFAS detections	EPA search Superfund site information tool,[j] also accessible in EPA PFAS Analytic Tools
	Spill responses	National spill response center database,[k] also accessible in EPA PFAS Analytic Tools
	Accidental spills/one-time releases and those part of normal facility operations	EPA toxic release inventory data and tools,[l] also accessible in EPA PFAS Analytic Tools
	Point-source discharges	National pollution discharge elimination system data; available multiple locations including ECHO database and PFAS Analytic Tools
PFAS monitoring data	PFAS in public water systems serving >10,000 and a subset of those serving 3,300–10,000 people	EPA unregulated contaminant monitoring rule (UCMR) web page,[m] also accessible in EPA PFAS Analytics Tools
	Public water systems	Collected by a subset of states and compiled by EPA in the PFAS Analytics Tools
	Ambient PFAS data in water, soil, sediment, and biota collected by researchers and other stakeholders	Water quality portal,[n] also accessible in EPA PFAS Analytic Tools

continued

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TABLE 4-3 Continued

Data type	Data description	Reference
Hydrogeologic data	Surface water drainage basins	United States Geological Survey hydrologic units in the watershed boundary database[o]
	Depth to groundwater	National Groundwater Monitoring Network[p]
Soil data	PFAS attenuation in soils	Natural Resources Conservation Service Web Soil Survey[q]
	PFAS movement classes	

[a] In some cases, national datasets were assembled by EPA from multiple, smaller (e.g., state-level) regional datasets and only represent regions where such data collection was implemented.

[b] See *How to Access the TSCA Inventory*, https://www.epa.gov/tsca-inventory/how-access-tsca-inventory#alternate#access.

[c] See *PFAS Analytic Tools*, https://echo.epa.gov/trends/pfas-tools.

[d] The ECHO database integrates federal records (including the Facility Registry Service) with environmental compliance data. See https://echo.epa.gov/.

[e] See *Facility Registry Service*, https://www.epa.gov/frs.

[f] See *Land Application Sites in Minnesota*, https://gisdata.mn.gov/dataset/env-land-application-sites.

[g] See *Division of Water Resources (DWR) Non Discharge Land Application Field Permits*, https://data-ncdenr.opendata.arcgis.com/datasets/4e16c0959f234a0eaf79ee4c3282fe8b_0/explore?location=35.090606%2C-79.681950%2C8.01&showTable=true.

[h] See *Maine Department of Environmental Protection PFAS Investigation Map*, https://experience.arcgis.com/experience/462392f57317486eb1c8d7eb6d0fea3d?id=468a9f7ddcd54309bc1ae8ba173965c7.

[i] See *PFAS Task Force Reports and Briefings*, https://www.acq.osd.mil/eie/eer/ecc/pfas/tf/reports.html.

[j] See *Search Superfund Site Information*, https://cumulis.epa.gov/supercpad/CurSites/srchsites.cfm.

[k] See National Response Center website, https://nrc.uscg.mil.

[l] See *Toxic Release Inventory Toolbox*, https://www.epa.gov/toxics-release-inventory-tri-program/tri-toolbox.

[m] See *Occurrence Data from the Unregulated Contaminant Monitoring Rule*, https://www.epa.gov/dwucmr/occurrence-data-unregulated-contaminant-monitoring-rule.

[n] See National Water Quality Monitoring Council WQX 3.0 Beta website, https://www.waterqualitydata.us/beta/.

[o] See *Watershed Boundary Dataset*, https://www.usgs.gov/national-hydrography/watershed-boundary-dataset.

[p] See National Groundwater Monitoring Network website, https://www.drought.gov/data-maps-tools/national-groundwater-monitoring-network.

[q] The Web Soil Survey does not have PFAS data present in its database. However, if a landowner suspects a PFAS issue on site or on adjacent sites, utilizing the Web Soil Survey tools related to PFAS may lead the user to more closely examine specific soil types to further identify the presence/absence/downward transport of PFAS.

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BOX 4-1
Modeling PFAS Fate and Transport

An increasing number of studies are using models that incorporate PFAS-specific considerations to model PFAS fate and transport. Specifically, these models allow incorporation of transport parameters standard for modeling organic contaminants (e.g., sorption to soil) as well as those that are more unique to PFAS (e.g., air–water interface [AWI] sorption). Two examples are HYDRUS-1D and PFAS-LEACH. The earliest versions of HYDRUS-1D were developed in the 1990s by researchers at the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA; Simunek et al. 1998). HYDRUS-1D solves the Richards equation for unsaturated flow and couples it with advection–dispersion–reaction equations for solute transport, where reactions include processes such as chemical and biological transformation, sorption, plant uptake, and volatilization. Sorption models include equilibrium and rate-limited, and the latter has been found particularly relevant in modeling PFAS fate and transport. Recent versions of HYDRUS-1D have been adapted for use with PFAS by adding considerations for AWI sorption (Silva et al. 2020). HYDRUS-1D has been used to model non-agricultural scenarios, as well as fate and transport of PFAS at farmlands under effluent and biosolids application scenarios (Silva et al. 2022; Liao et al. 2025; Doria-Manzur et al. 2026).

More recently, the U.S. Department of Defense has sponsored efforts to develop PFAS-LEACH, which is a multitiered "decision support platform" to assess PFAS leaching in source zones.[a] The four tiers decrease in complexity from Tier 1 to Tier 4. Tiers 1 and 2 are still under development. Tiers 3 and 4 are both Excel-based tools. Tier 3 relies on mathematical solutions to transport equations to estimate how PFAS leach through the unsaturated zone (Guo et al. 2022). Unsaturated zone leaching can be coupled with groundwater dilution to support estimation of PFAS concentrations in receptor wells and development of site-specific soil screening levels (SSLs) for PFAS (Smith et al. 2024), both of which are key for regulatory decision-making. Tier 4 is an algebraic model that revises the Environmental Protection Agency's (EPA's) method of calculating dilution and attenuation factors (DAFs; Brusseau and Guo 2023). EPA DAFs are used in calculating SSLs by modeling how contaminant concentrations are reduced between the source zone and a receptor well. The revised DAF model incorporates the impact of AWI sorption.

Whereas HYDRUS-1D and PFAS-LEACH focus primarily on contaminant leaching in the unsaturated zone, other models that originated in USDA–ARS laboratories focus on surface processes such as runoff, erosion, and sediment transport. The Soil and Water Assessment Tool (SWAT) was first published in 1998 as a tool to predict how land and water management choices (e.g., water use, nonpoint-source loading, and pesticide use) affect water quantity and quality at the watershed scale to support conservation planning and long-term scenario assessment (Arnold et al. 1998). The Agricultural Policy/Environmental eXtender (APEX) model, published in 2009, also simulates surface processes

continued

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BOX 4-1 Continued

but at the facility scale (Gassman et al. 2009). APEX simulates the impacts of different management practices, including nutrient management, tillage, crop selection, and conservation practices, on factors such as water flow, sediment transport, and pollutant transport at the facility to small watershed scale. Although neither SWAT nor APEX has been widely applied to understand PFAS in agricultural systems, both tools already incorporate pollutant transport and thus are well-poised for adaptation to include PFAS-specific considerations.

[a] See PFAS-LEACH, https://github.com/GuoSFPLab/PFAS-LEACH-Tier-3-4?tab=readme-ov-file.

BOX 4-2
Predicting Where PFAS Will Occur: From Mechanistic Models to Machine Learning

Managing PFAS risks on agricultural lands is challenging in part because it is difficult to know where these chemicals will occur. Therefore, predictive models are a fundamental tool in understanding the likelihood of PFAS occurrence in scenarios where PFAS data are not available. Traditional (i.e., mechanistic) models, such as the HYDRUS-1D and PFAS-LEACH models, simulate how chemicals move, accumulate, and degrade using known physical, chemical, and biological processes. These models work well when key parameters describing the behavior of PFAS (e.g., potential to sorb to soil and to transform chemically or biologically) are known. However, for the majority of PFAS, the parameters needed to implement mechanistic models are uncertain or unavailable, making fully mechanistic prediction challenging.

Statistical regression approaches offer an alternative method of predicting PFAS occurrence across geographic areas (e.g., Wood et al. 2025). For example, in linear regression, the expected value of a continuous outcome is modeled as a linear combination of independent variables (e.g., concentration = a_0 + a_1•distance to source + a_2•soil carbon + …) while also accounting for correlations between observations in close spatial proximity to one another. In logistic regression, the log-odds of exceeding a threshold are modeled as a linear function of the predictors. For PFAS, however, because the properties of most compounds are uncertain or unavailable, parameters (e.g., a_1 and a_2 in the above equation) do not need to be known a priori but instead are estimated based on fitting a model to an existing dataset, in which PFAS of interest have been measured in soil or groundwater at known spatial locations.

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While statistical models are a form of machine learning, in that parameters are "learned" from data, more recent machine-learning models offer a complementary approach. Rather than assuming relationships between PFAS occurrence and potential predictor variables are linear or quasi-linear, these models learn complex, often non-linear patterns from data. A typical PFAS training dataset is similar to those used for regression modeling; it links measured PFAS at sampling locations to predictors such as distance to known or potential sources, soil properties (e.g., organic carbon, texture, mineralogy, and pH), hydrogeology, land use and land cover, and climate. After training, the model can estimate PFAS presence or concentration at unsampled locations.

Machine-learning models can handle two kinds of prediction problems: classification and regression. Classification, like logistic regression, asks a yes–no or exceedance question, such as "Will PFAS exceed a health-based threshold at this location?" The model returns a probability or a class label. Regression, as in statistical regression models with continue outcome variables, asks for a continuous value, such as "What concentration should we expect at this location?" The model returns a number. Some machine-learning methods are designed for only one of these problem types, whereas many have versions that handle either type.

Decision trees and random forests, support-vector methods, neural networks, and gradient-boosting frameworks can all be configured either for classification (to estimate exceedance probability) or for regression (to predict concentration). Bayesian networks are most often used to estimate probabilities and support "what-if" reasoning, but with appropriate specification they can also predict continuous outcomes.

The above approaches come with different assumptions and tradeoffs. For example, logistic regression assumes a linear relationship on the log-odds scale and can be sensitive to strongly correlated predictors. Bayesian networks explicitly encode probabilistic relationships among variables and can incorporate correlated predictors and expert knowledge. Neural networks can capture complex, nonlinear patterns but are less transparent and typically require more data. All of these approaches require careful validation.

A recent review (Rahman et al. 2025) summarized 32 peer-reviewed studies using machine learning for PFAS prediction, source identification, and remediation assessment. Many studies reported high performance, although results depended strongly on data quality, coverage of source types, and appropriate validation, especially when models were applied beyond the conditions represented in the training data.

Overall, mechanistic and machine-learning approaches can be complementary. Machine learning can rapidly screen large areas—whether the task is classification or regression—to guide targeted sampling and management, while mechanistic understanding helps assess whether relationship observed in machine-learning models may be causal. Furthermore, some machine-learning techniques, such as Bayesian networks, may be useful for guiding further development of mechanistic models by uncovering key drivers of PFAS occurrence. The combination of these modeling approaches offers power for creating data-generated, evidence-based maps to help guide soil conservationists and agricultural producers in deciding whether testing for PFAS may be necessary.

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(or probability) of occurrence of (in this case, four short-chain) PFAS in groundwater (e.g., Figure 4-1).

Bayesian network and other machine-learning approaches also have been used to develop models and maps for predicting PFAS in groundwater in other areas (see Box 4-2), including southeastern North Carolina (Roostaei et al. 2021), Michigan (Fernandez et al. 2023), and Colorado (Barton et al. 2025). George and Dixit (2021) used data including co-contaminant occurrence, proximity of facilities that likely used AFFF, and hydrologic data to build machine-learning models using linear and random forest regression to predict PFAS occurrence in California groundwater. The random forest model combining all predictors (270 total) was able to predict where the sum of PFOA and PFOS would exceed 70 ng/L (.07 µg/L) in groundwater with an area under the curve (AUC) of 0.90. Hu et al. (2021) used data including PFAS sources, hydrogeologic data, and meteorological data to build machine-learning models using logistics and random forest regression to predict concentrations of five commonly occurring PFAS in New Hampshire groundwater. The random forest model using 20 predictors was able to predict individual PFAS concentrations achieving AUCs of 0.74 (PFOS) to 0.86 (perfluoroheptanoic acid [PFHpA]) and the sum of five PFAS achieving an AUC of 0.81. These and other studies that use machine-learning approaches to evaluate environmental occurrence of PFAS were also included in recent reviews that provide more in-depth treatment of this topic (Rahman et al. 2025; Torres-Martínez et al. 2025).

Recently, researchers have used previous PFAS monitoring data to build prediction tools and maps of nationwide risks to groundwater. Tokranov et al. (2024) published a model and associated map for predicting the detection of any PFAS from among 24 analytes. The model was trained on thousands of water samples collected through multiple national sampling campaigns conducted by EPA, the U.S. Geological Survey, and the state of Wisconsin. They used a machine-learning approach known as XGBoost, which essentially involves constructing and linking hundreds of decision trees. The model predicts the probability of PFAS detection in groundwater at depths used for drinking water at a scale of 1 km by 1 km across the United States (Figure 4-2); its accuracy is comparable to that of previously referenced local and regional models.

In another study, private well samples were collected from four case study communities in different U.S. regions (West, northern Midwest, central Midwest, and South; Wood et al. 2025). At these sites, the research team found that proximity to known PFAS production facilities was the most important predictor of the total concentration of 25 measured PFAS, considering all source types represented in the EPA PFAS Analytic Tools database. Their statistical model estimated that a well located 0.5 km from a production facility could be expected to have a nine-fold higher total PFAS concentration than a well located 1 km away. Superfund sites, sites where PFAS were known to have been spilled, and federal facilities also were statistically significantly associated with the concentration of total PFAS. Wood and colleagues are using these results to create nationwide maps of PFAS risks in private wells that can serve as additional risk screening tools.

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FIGURE 4-1 Risks of the occurrence of four short-chain PFAS in groundwater in the Minneapolis/St. Paul East Metro area at concentrations above the state's health advisory concentration.
NOTE: A: Perfluorobutanoic acid (PFBA); B: Perfluorobutanesulfonic acid (PFBS); C: Perfluorohexanoic acid (PFHxA); D: Perfluorohexane sulfonate (PFHxS).
SOURCE: Li and MacDonald Gibson 2022. CC BY 4.0.

Predicting PFAS in Soil

Limited studies have applied data-driven approaches to predict PFAS concentrations in soil. Moghadasi et al. (2023) used PFAS soil-monitoring data and PFAS point sources to build a machine-learning model using random forest regression to predict PFAS occurrence in European soils. The random forest model—built only on point sources and existing PFAS soil data (divided into training and validation sets)—was able to predict PFAS concentrations in soil with an R^2 of 60 percent. Predicted soil concentrations were coupled with soil bulk density, water content, and PFAS sorption coefficients (K_d) to predict PFAS concentrations in pore water. Soil concentrations of 5,000 ng/kg were predicted to lead to pore water concentrations of 2–5 ng/L (.002–.005 µg/L), which exceeds European regulatory criteria for drinking water. Despite limited applications, results of this study demonstrate that data-driven approaches utilized to generate predictive models of PFAS in groundwater can be applied to soil, which is key for agricultural scenarios.

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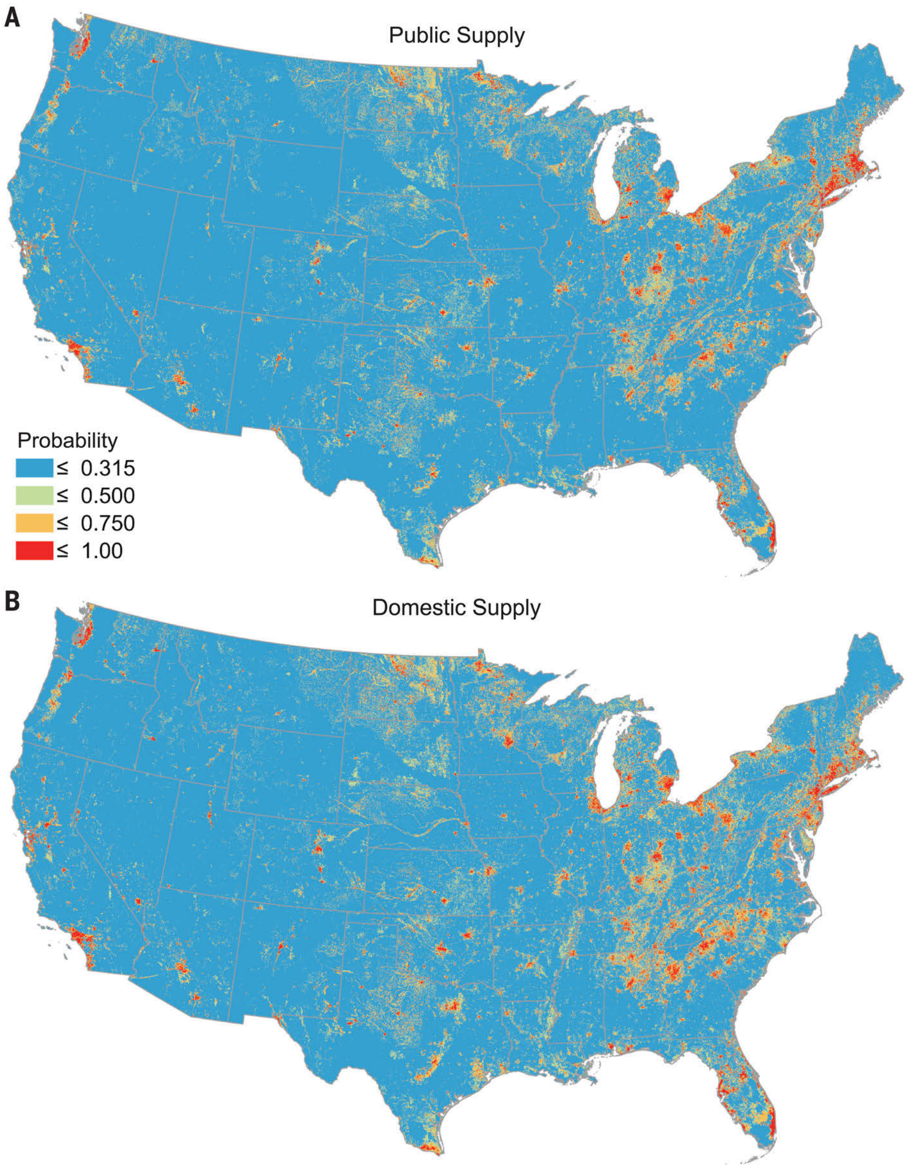

FIGURE 4-2 Probability of detection of any PFAS in groundwater at depths used for drinking water.
NOTE: (A) Public supply wells represent those used by community water systems (serving at least 15 service connections or 25 people year-round). (B) Domestic supply wells represent those used by one or a few households (fewer than 15).
SOURCE: Tokranov et al. 2024.

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Challenges with Predictive Models

Data-driven approaches show exceptional promise as a practical tool for understanding PFAS occurrence over large regions, but key challenges in widespread application remain. First, data availability may vary from region to region, particularly PFAS monitoring data and data on certain types of PFAS releases such as biosolids and effluent application sites and historical spills and releases that pre-date tracking in regulatory databases. There are also issues associated with data consistency. This is particularly applicable to PFAS and water-quality monitoring data. Data preprocessing may be needed to handle factors such as varied detection limits and treatment of locations with data at multiple time points. Lastly, there is not a standard machine-learning approach for development of predictive models of PFAS occurrence. Despite these challenges, the studies to date demonstrate that development of large, regional models of PFAS occurrence in scenarios relevant to agricultural facilities (e.g., soil and groundwater) are currently feasible to develop with existing datasets.

INITIAL FRAMEWORK FOR DECISION-MAKING

Chapter 2 reviewed what is known about the occurrence, fate, and transport of PFAS in agricultural lands. Chapter 3 described the conservation planning process and how conservation practices, programs, and initiatives could influence PFAS introduction and movement on agricultural lands. In the sections above, the committee discussed different approaches for defining PFAS, in general and in agriculture, and how predictive maps may be tools to identify agricultural lands that could potentially have PFAS problems. Although there is a great deal more to learn about the fate and transport of different PFAS in agricultural systems, the committee drew upon the material reviewed up to this point to inform a decision-making framework that the FPAC agencies could potentially use to guide their efforts to respond to PFAS contamination on agricultural land.

The framework illustrated in Figure 4-3 is connected to the nine-step conservation planning process described in Chapter 3 (see Figure 3-1). The figure below depicts the same planning process as an iterative effort with three phases, with the conservation planner able to move back and forth between steps and phases. The depiction is intentionally cyclical rather than linear to reflect how experienced planners move in and out of steps as new information surfaces. It also accommodates two possible realities: PFAS could be the explicit focus of a planning conversation, or it could be a background consideration while another resource concern drives the plan. The committee added a grid to the original NRCS image to describe in each phase certain considerations that might be made, resources that are available, and resources that are needed for the FPAC agencies to move forward in the face of uncertainty and lack of consensus information about PFAS contamination on agricultural land.

Phase 1 is the opportunity to identify the degree to which PFAS is a concern. If testing has not been carried out, it could be conducted at this time if the customer elects to do so. As outlined above (see section “PFAS Risk Screening Models”), planners could

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make use of existing datasets and soil and hydrogeologic characteristics to determine whether PFAS are likely to be a problem for the specific site and resource in question (e.g., soil, water, air). Ideally, NRCS would work with other agencies that could build models specific to agricultural land, and the agency or others could add relevant features (such as distances from known sources, prior application of organic soil amendments, and soil and climate characteristics) from public sources and then use the resulting curated data to train and test predictive models. NRCS has already made at start by adding information about potential PFAS movement and attenuation in soils to the Web Soil Survey (Box 4-3).

If testing takes place, the process would benefit from a suitable standard operating procedure to collect representative samples, one that considers the targets of interest (e.g., PFAS concentrations), field topography, size, prior management, purpose of the measurement, and cost. A common approach is to collect several grab samples within each grid, combine them into a composite for that grid, and then analyze or subsample those grid composites to create one overall composite. However samples are collected, the test results remain with the customer and may or may not be disclosed back into planning. Whether or not testing occurs, as planners move into Phase 2, they can formulate and compare alternatives with PFAS risk explicitly kept in mind—avoiding new PFAS inputs (such as certain organic soil amendment sources) and avoiding practices that could mobilize or spread existing contamination—while weighing these considerations alongside the original resource concern (if PFAS is not the primary issue). Table 3-2 presents examples of how conservation practices may have positive or negative impacts with regards to PFAS contamination that conservation planners may want to keep in mind when recommending practices.

Phase 3 focuses on implementation with built-in evaluation. Practices could move forward with clear documentation of how PFAS was considered. If monitoring information, observations, or outcomes raise concerns about PFAS risk or unintended consequences, the process loops back to Phase 2 to adjust practices. The emphasis is on adaptive management—for example, switching water or soil amendment sources or revising practice selections—to avoid causing or exacerbating a PFAS problem. Innovative trials (as described in Chapter 3 with regard to the Conservation Innovation Grants under the Environmental Quality Incentives Program) and monitoring and evaluation (also described in Chapter 3 as part of the Conservation Reserve Program) could be implemented in this phase.

Overall, this framework is a planning aid rather than a prescriptive algorithm. It respects producer choice, the voluntary nature of programs, and current constraints such as the absence of uniform federal thresholds and the confidentiality of test results. Its purpose is to help field staff fold PFAS awareness into the work they already do—whether PFAS is the central issue or simply a prudent factor to consider—so that conservation activities do not inadvertently create new PFAS risks. Full operationalization of the framework will require additional data and tools development. NRCS could work with other agencies and entities to establish nationwide screening levels for different types of agricultural production facilities, soil types, and climatic systems. Machine-learning models could be trained, similar to those underlying the groundwater

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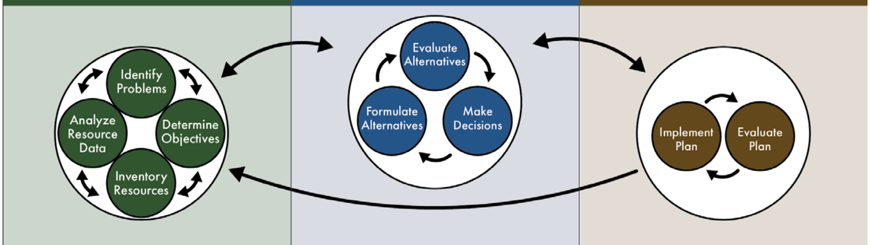
	PHASE 1 Collection & Analysis	**PHASE 2** Decision Support	**PHASE 3** Application & Evaluation



	PHASE 1	PHASE 2	PHASE 3
Considerations	Are PFAS a significant concern at this site? What is the source of irrigation water used on the farm? Has organic material from an off-site source been applied to the land? Is there a source of PFAS proximate to the farm?	What is known about the effects of PFAS on the condition of the soil, water, air, plant, and animal resource bases? For example, are the PFAS present long-chain and likely to stay in soil or short-chain and likely to be taken up by plants? Do the proposed conservation practices have the potential to: • mitigate a PFAS problem? • limit transport of PFAS off-site? • introduce PFAS? • exacerbate a PFAS problem? • transport PFAS off-site?	When implementing the practice, take care not to: • introduce PFAS. • exacerbate a PFAS problem. • transport PFAS off-site. When evaluating, employ adaptive management for new information (e.g., new practices or adjustments to existing practices)
Existing Resources	Prescreening tools (examples provided in Table 4-3) Web Soil Survey information on PFAS behavior in soil PFAS testing (available as a cost-share activity through Conservation Evaluation and Monitoring Activity 209 or from the Environmental Protection Agency or state environmental agencies)	Table 3-2 is an initial resource that could be further developed. It could also be expanded to include the practices listed in Appendix D.	Table 3-2 is an initial resource that could be further developed. It could also be expanded to include the practices listed in Appendix D. Conservation Innovation Grant program to • advance conservation measures and approaches that show promise for PFAS mitigation. • introduce innovative conservation measures or approaches from one geographic area to a new area. • evaluate and refine existing conservation practice standards for PFAS mitigation purposes. • assess systems of conservation practices and their impact on PFAS mitigation. Cooperative agreements to monitor, assess, and evaluate conservation projects related to PFAS on land enrolled in the Conservation Reserve Program.
Needed Resources	Standards (screening and action levels) Inclusion of PFAS as a consideration in Conservation Practice Standards or designation of PFAS as a separate Resource Concern Agricultural working definition of PFAS Predictive modeling of PFAS in soil and water PFAS site index tool to evaluate potential for PFAS loss from fields to water bodies Research on: • fate and transport of various PFAS in different soil types and under different climatic conditions • PFAS sorbents that could be effective under field conditions • plant uptake of PFAS, accounting for different crops (vegetables to trees to forage) and different soils, under field conditions • animal PFAS uptake and elimination to inform relevant conservation practices related to livestock Development of conservation practices standards designed specifically to capture PFAS (e.g., removal structures, bioreactors) PFAS-specific training for NRCS field conservationists	Application of results on fate and transport research to assessment of positive and negative effects of conservation practices. Determination that agricultural land affected by PFAS can be eligible for the Conservation Reserve Program.	New pilot programs in the Conservation Reserve Program to mitigate PFAS contamination. PFAS contamination identified as a conservation challenge of concern under the Conservation Reserve Enhancement Program.

FIGURE 4-3 Framework for conservation planning and practice implementation to address PFAS concerns, accounting for uncertainty.
SOURCE: Based on NRCS, https://www.nrcs.usda.gov/state-offices/tennessee/nine-step-conservation-planning-process.

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BOX 4-3
USDA's Web Soil Survey

The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) Web Soil Survey contains PFAS-related data present in its database. As most PFAS are anionic and thus have some degree of mobility in soils, a suite of soil properties that can lessen or completely retard PFAS movement through soils are coupled within the Web Soil Survey. To date, however, information regarding PFAS attenuation in soils and the PFAS attenuation model has not been created as a field in the Web Soil Survey. If a landowner suspects a PFAS issue on site or on adjacent sites, utilizing the PFAS variables in the Web Soil Survey may help the user to more closely examine specific soil types to further identify the presence, absence, or transport of PFAS to groundwater or surface water (Figure 4-4).

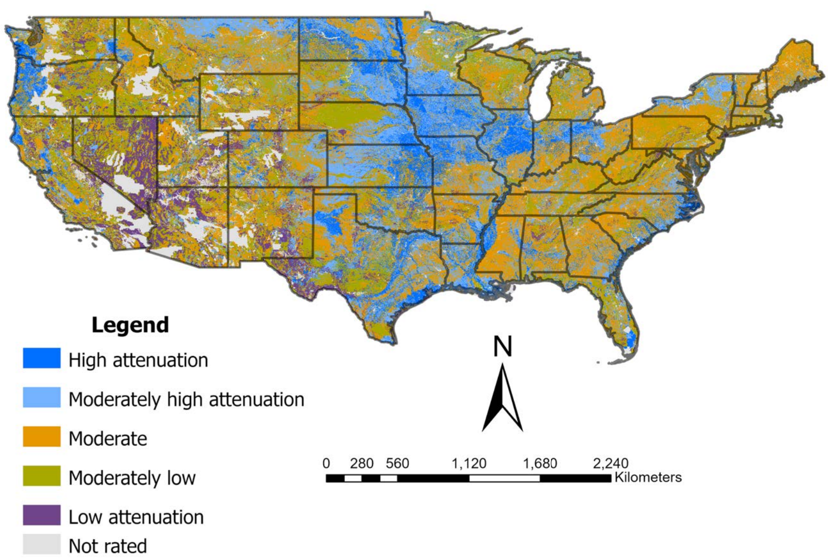

FIGURE 4-4 PFAS attenuation by 30-meter soil map unit.
SOURCE: Data from NRCS Web Soil Survey, https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

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maps, using nationwide data on PFAS in agricultural soils and information in the Web Soil Survey combined with data on proximity to PFAS sources, agricultural land uses, climate, and other features.

Full operationalization of the framework would also be advanced through PFAS-specific training for NRCS field conservationists. NRCS field conservationists are often first points of contact for customers with PFAS concerns. At a minimum, a basic understanding by field conservationists of PFAS issues in agricultural systems, of the local, state, and federal resources available to impacted farmers, and of who to contact to help farmers access these resources would be of assistance to these customers (PFAS and Agricultural Policy Workgroup 2025). On-line training could be provided through USDA's AgLearn centralized learning management system so that NRCS field conservationists across the country have consistent and up-to-date information.

Conclusion 4-1: A working definition of PFAS for agriculture may need to consider structural features of the compounds, the ability to detect a specific PFAS, and thresholds for deciding when detected concentrations merit further investigation. Federal guidance on thresholds of PFAS in agricultural lands would benefit conservation planners in contextualizing PFAS occurrence at agricultural operations.

Conclusion 4-2: Based on existing data-driven efforts to predict PFAS occurrence in groundwater and soil, it is possible to develop large, regional models that could help identify agricultural land at risk of PFAS contamination. NRCS could work with other agencies to build, train, and test such predictive models.

Conclusion 4-3: Even though many knowledge gaps about PFAS exist, there are sufficient opportunities within the conservation planning process, the conservation practice standards, and the conservation programs, as well as sufficient data about PFAS, for the FPAC agencies to create a framework for responding to the impacts of PFAS contamination on agricultural land. The development of federal guidance on PFAS thresholds in agricultural lands and the evaluation of additional data on PFAS in agricultural soils nationwide—which could be used to train predictive models—would enhance the ability of conservation planners to respond to PFAS concerns.

Conclusion 4-4: There is a need for coordinated training of NRCS field conservationists in the basics of PFAS and agriculture and for each NRCS state office to maintain a list of available resources for PFAS-affected farmers and contacts.

Applied research, discussed in the next chapter, could expand the capacity of existing practices and the development of new practices to address PFAS concerns. In cases where decision-makers determine that PFAS risks are unacceptably high, NRCS programs that support farmers in taking land out of production may be necessary.

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5

Applied Research Gaps for PFAS Management in the Context of Conservation

To solve problems related to per- and polyfluoroalkyl substances (PFAS), research is underway on many fronts, including on treatment technologies that safely remove and destroy PFAS and for replacement substances that have equivalent functionality but do not harm human health or the environment. In the context of conservation on the land, applied research needs to focus on minimizing PFAS uptake into plants and animals, in situ sequestration, and removal of PFAS to the greatest extent possible. This chapter reviews four areas of research that could advance the ability of conservation practices to address PFAS contamination on agricultural land: a better understanding of PFAS fate and transport in different types of soils, mechanisms by which to trap or sequester PFAS, an improved understanding of PFAS uptake in plants, and an improved understanding of PFAS uptake in animals.

DISCERNING PFAS FATE AND TRANSPORT IN VARYING SOIL TYPES ACROSS THE UNITED STATES

As described in Chapter 2, no single factor can determine PFAS fate and transport within and through soils (Li et al. 2018; Wang et al. 2023). A multitude of soil factors (e.g., clays/oxides, the amount and type of soil organic matter, pH, the presence of various cations, soil texture, soil–water relationships) affect PFAS fate, transport, and risk to producers, farms, and surrounding ecosystems. Climatic conditions (e.g., precipitation, wind, temperature) also must be considered (Box 5-1).

Furthermore, the fate and transport of the various PFAS types present in soils need further evaluation (e.g., zwitterionic, cationic, or anionic PFAS; short- versus long-chain PFAS). For example, Wang et al. (2023) pointed out that zwitterionic PFAS research is lacking and that soil pH likely changes the zwitterionic PFAS charge, thus affecting sorption. The authors also stated that PFAS sorption changes between mineral

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BOX 5-1
Fate, Transport, and Climate

One of the major differences between greenhouse and field studies of PFAS in soils is the effect of climate. For example, higher temperatures increase plant metabolism and transpiration and thus increase PFAS transport and deposition in plant parts (i.e., leaves). An increase in temperature (from 20 °C to 30 °C) has been shown to increase PFAS concentrations by about 2-fold in wheat, with short-chain PFAS accumulation less sensitive to temperature changes (Zhao et al. 2016). Although the study by Zhao et al. (2016) was performed in the laboratory, it sheds light on the effect of field temperature on plant PFAS uptake.

Additionally, precipitation plays a major role in PFAS fate and transport. To the committee's knowledge, there have been no long-term studies linking PFAS fate and transport to variable precipitation patterns—thus, a knowledge gap exists. Often in pot studies with plants, leaching is kept at a minimum and thus short-chain PFAS have a greater likelihood of contacting roots, unlike what may occur under field settings (Costello and Lee 2024). Lasters et al. (2024) attempted to link PFAS bioavailability in gardens to soil factors but found it nearly impossible to link the two together. The authors suggested that perhaps soil porewater (which was not quantified) may better indicate greater PFAS availability in gardens and thus potentially in field settings. Unlike greenhouse trials, field studies need to identify site-specific PFAS sources, focus on a larger number of PFAS and precursors, keep a close eye on site climatic conditions that affect soil conditions (perhaps via the use of weather stations, dataloggers, and soil moisture and temperature sensors), and assess PFAS risks to water sources (Costello and Lee 2024).

types, and whether sorption dominates on clay surfaces versus within clay interlayers depends on clay type (e.g., kaolinite versus montmorillonite; Zhang et al. 2014). A better understanding of the relationships between various clays and PFAS would help to advance knowledge of PFAS sorption mechanisms affecting fate and transport in soils (Mejia-Avendaño et al. 2020). Moreover, it is understood that short-chain PFAS do not readily sorb to soil phases compared with long-chain PFAS. Therefore, Nasrollahpour et al. (2025) pointed out that further sorption or removal research (e.g., clays, other soil phases, or other materials used for remedial purposes) should focus on short-chain PFAS as they are increasingly used to replace long-chain PFAS. Wang et al. (2023) provided a concise starting point for understanding the factors that affect PFAS sorption in soils exemplified for perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs; Table 5-1). Additional factors to consider in future research are soil texture (Li et al. 2018; Nguyen et al. 2020; Mei et al. 2021; Umeh et al. 2021) and iron and aluminum oxides (Umeh et al. 2021; Campos-Pereira et al. 2023).

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TABLE 5-1 Factors that Impact Sorption of PFCAs and PFSAs on Soil

Factor			Research Finding	
Category	Specification	Effect on Sorption	on the Effect	Reference
PFAS Property	Functional Groups	PFSA > PFCA	Consistent	Gellrich et al. 2012; Zhao et al. 2014; Milinovic et al. 2015; Loganathan and Wilson 2022; Luft et al. 2022; Wang et al. 2022
	Carbon Chain Length	Longer > Shorter Chain Length	Consistent	
Soil Property	Organic Carbon (OC)	Higher > Lower OC	Mixed	Becker et al. 2008; Kwadijk et al. 2010; Pan and You 2010; You et al. 2010; Ahrens et al. 2011; Chen et al. 2012; Milinovic et al. 2015; Luft et al. 2022
	Cation Exchange Capacity (CEC)	Higher > Lower CEC	Mixed	Barzen-Hanson et al. 2017; Xiao et al. 2019; Mejia-Avendaño et al. 2020; Nguyen et al. 2020
	Anion Exchange Capacity (AEC)	Higher > Lower AEC	Mixed	Barzen-Hanson et al. 2017; Li et al. 2019
	Humic Acid (HA)	Lower > Higher HA in Low Soil Content	ND[a]	Zhang et al. 2014
		Higher > Lower HA in High Soil Content		Higgins and Luthy 2006
	Minerals	Positively Charged > Negatively Charged Minerals	ND[a]	Hellsing et al. 2016
		Montmorillonite > Kaolinite		Zhang et al. 2014

continued

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TABLE 5-1 Continued

Factor			Research Finding	
Category	Specification	Effect on Sorption	on the Effect	Reference
Water Quality Property	pH	Lower > Higher pH	Mixed	Higgins and Luthy 2006; Kwadijk et al. 2010; Kwadijk et al. 2013; Martz et al. 2019; Oliver et al. 2019
	Cation	Higher > Lower Divalent Cation Concentration	Consistent	Schwarzenbach et al. 2002; Higgins and Luthy 2006; Kwadijk et al. 2010; You et al. 2010; Chen et al. 2012; Cai et al. 2022
		Higher > Lower Monovalent Cation Concentration	Mixed	Higgins and Luthy 2006; Chen et al. 2013; Cai et al. 2022

[a] ND = No basis to decide because only one study reports.
NOTE: AEC = anion exchange capacity; CEC = cation exchange capacity; HA = humic acid; OC = organic carbon.
SOURCE: Wang et al. 2023.

Although there has been considerable work conducted on PFAS sorption, less is understood about PFAS desorption hysteresis, which greatly impacts the behavior of legacy PFAS (perfluorooctanoic acid [PFOA] and perfluorooctane sulfonic acid [PFOS]). The limited desorption data that are available are inconsistent, which is often driven by desorption results from high-concentration lab-spiked soils that showed little desorption hysteresis (Umeh et al. 2024) versus historically contaminated field soils (Schaefer et al. 2022; Klamerus et al. 2025). For the latter, 50 to almost 80 percent of PFOS in soil resisted desorption after several sequential desorption steps (Schaefer et al. 2022; Klamerus et al. 2025). A benefit to sorption, desorption, and hysteretic studies would be to combine them with modeling approaches to further understand PFAS behavior in the environment. The majority of PFAS modeling has focused on groundwater, while less attention has applied modeling approaches to predict PFAS concentrations in soil, as outlined in Chapter 4. More research is needed in this space.

Better insight is needed into how soil and climatic factors coupled to PFAS characteristics affect PFAS fate and transport across the United States for a more in-depth understanding of PFAS risks across the country. To address these research gaps, a national network of researchers could be created to systematically study PFAS fate and transport with a focus on soils containing varying constituents (e.g., clay types or oxides) within individual U.S. regions (e.g., based on soil survey regions, major land resource areas, and climate). Researchers could use the predictive modeling tools

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reviewed in Chapter 4 to locate potentially affected soils, identify soil characteristics based on the Natural Resources Conservation Service's (NRCS's) Web Soil Survey in context for factors that affect PFAS sorption on soils (Table 5-1), and consider already conducted field studies from which data gaps and future needs can be identified. Results could be used to expand Table 5-1 and could be added to the data fields in the Web Soil Survey for PFAS attenuation in soils and PFAS movement classes (see Box 4-3 in Chapter 4). Research findings then could be directed towards addressing the positive and negative effects of conservation practices when utilizing this newly found information (e.g., expanding upon Table 3-2 in Chapter 3). This same type of national research group approach could be utilized to target other research gaps noted below.

OPPORTUNITIES TO TRAP OR SEQUESTER PFAS

Means by which PFAS can be sorbed and sequestered in soils to reduce their bioavailability are now being studied. The benefits to sequestering PFAS include the potential to reduce plant uptake as well as leaching. Potential disadvantages are that PFAS are held in place, which may hinder success of future removal or destruction strategies. There is also the potential for changes in the PFAS sequestering sorbents over time that may lead to unforeseen release of PFAS. If sorbents are to be used effectively, more research is desperately required given the multitude of compounds in the PFAS family. Additionally, if PFAS is an issue in U.S. waters, finding the means by which PFAS can be removed from such water bodies is of paramount importance. The section below outlines possible approaches in targeting PFAS sorption within soils or waters.

Potential Sorbents for PFAS Sequestration on Agricultural Land

Various sorbents, such as biochars, modified clays, activated carbons, various drinking water treatment residuals (DWTR), nanoparticles, and even wood chips blended with biosolids have been studied for their PFAS-sorption affinities. An overview of recent research focused on this topic is outlined below to provide thoughts for filling research gaps.

Biochars

Several designer sorbents have been tested at the bench scale to target high PFAS sorption capacity; however, scalability in terms of provision and cost at the landscape scale are unlikely. Therefore, much attention has turned toward biochar that can be produced in large volumes. Biochars are created by pyrolyzing organically based feedstocks in an oxygen-depleted or oxygen-devoid environment. Pyrolysis temperatures often range from 350 ^{o}C to 700 ^{o}C, although greater temperatures have been utilized for biochar creation. Biochars have been proven to be useful sorbents for heavy metals and trace organic compounds from waters and soils, and thus a great deal of interest is presently focused on biochar use as a sorbent for PFAS. Biochar is specifically named as a candidate amendment under the Soil Carbon Amendment conservation practice

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PFAS in Agricultural Systems: Guidance for Conservation Programs at USDA

standard (Code 336; USDA 2022) to improve soil health. However, at present, its ability (as well as the ability of other possible sorbents) to sequester PFAS is not part of a practice standard to address contamination.

A recent review of using biochars for mitigating PFAS in agricultural settings highlighted important biochar characteristics for PFAS sorption (Ramos and Ashworth 2024). First, biochar can be effective at sorbing PFAS, but success with respect to short- versus long-chain PFAS depends on feedstock and pyrolysis conditions. For example, Inyang and Dickenson (2017) showed that both softwood (i.e., spruce pyrolyzed at 650 °C) and hardwood (source unknown, gasified at 900 °C) sorbed long-chain PFOA equal to activated carbon, yet only hardwood approached short-chain perfluorobutanoic acid (PFBA) removal as compared to activated carbon (87 percent versus 94 percent sorption, respectively); softwood biochar only sorbed 18 percent of PFBA. Inyang and Dickenson (2017) noted that the PFBA sorption efficiency of biochar appeared to increase within increasing surface area. Liu et al. (2021) compared pyrolysis temperature (500 °C, 700 °C, and 900 °C), hold time (3, 5, and 6 hours), and different feedstocks (corn cob, common reed [*Phragmites australis*], aspen wood chips, and soybean dreg) on biochar PFOA and PFBA removal efficiency; results are presented in Figure 5-1. PFOA removal efficiency for corn cob, reed straw, and aspen chip biochars were around 100 percent, similar to activated carbon, while soybean dreg was inferior. Removal efficiencies for PFBA by corn cob and reed straw biochar were 65 percent and 85 percent as compared to activated carbon (around 15 percent); aspen chip and soybean dreg for PFBA removal were lower than activated carbon. Pyrolysis temperature impacted PFOA and PFBA removal efficiency; increasing temperature to above 700 °C led to 100-percent removal of PFOA, yet PFBA removal efficiency was negligible at 700 °C. Not until pyrolysis temperature reached 900 °C was PFBA removal efficiency elevated to around 80 percent.

Most literature on pyrolysis, including that cited here, determine removal efficiency based on removal of the parent compound targeted. It is possible that shorter-chain PFAS were generated, including ultra short-chain trifluoroacetate (TFA) and perfluoropropanoic acid (PFPrA); a more complete picture is determined using a fluorine mole approach. Pyrolysis hold time also played a role, and as hold times increased from 3 to 5 to 6 hours, so did PFOA removal efficiency (80 to 95 to 96 percent, respectively). It is important to note that hold times are often not described in the biochar literature; however, the optimal hold time for creating biochar to remove PFBA was 5 hours, as efficiency decreased with a hold time of 6 hours. The explanation as to why efficiency decreased could have been due to a reduction in pore size diameter with increasing hold time; in general, pores need to be approximately two to three times the molecular diameter of the PFAS in order to be trapped (Zimmerman et al. 2004).

Second, feedstock and pyrolysis conditions that alter specific surface area and biochar carbon–oxygen ratios play a role in PFAS sorption. A subset of data obtained by Ippolito et al. (2020) targeting biochar properties from feedstocks potentially used for agricultural purposes (wood-based, crop waste, manure/biosolids) was used by Ramos and Ashworth (2024). Ramos and Ashworth (2024) then scoured the literature for information on biochars made from those feedstocks and their ability to sorb

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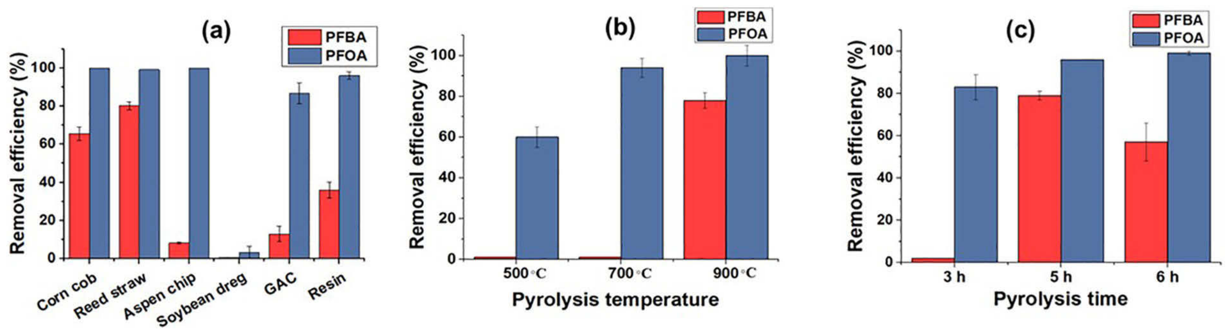

FIGURE 5-1 (a) PFBA and PFOA removal efficiencies exhibited by biochars synthesized with different feedstock materials in comparison with granular activated carbon and anion exchange resin; (b) PFBA and PFOA removal efficiencies exhibited by reed straw–derived biochars synthesized at different pyrolysis temperatures; (c) PFBA and PFOA removal efficiencies exhibited by reed straw–derived biochars pyrolyzed at 900 °C for different durations.

NOTE: Removal efficiency was discerned based on the disappearance of the target perfluoroalkyl acids (PFAAs) after adsorption over 24 hours with an initial concentration of 100 µg/L and an adsorbent dose of 0.2 g/L.

SOURCE: Liu et al. 2021.

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PFAS. A principal components analysis was performed to identify linkages between PFAS removal and biochar feedstock type, pyrolysis temperature, and a variety of characteristics. The authors found that as a function of feedstock type, the greater the specific surface area (SSA) and the greater the carbon–oxygen ratio, the greater PFAS removal. Increases in SSA are most often related to increases in pyrolysis temperature. Increases in the carbon–oxygen ratio are often associated with greater hexane-like carbon structures formed during pyrolysis (via increased temperature) leading to an increased presence of π-electrons that can sorb PFAS, along with an increase in hydrophobic carbonaceous adsorbents (Gagliano et al. 2020). Ramos and Ashworth (2024) did not specifically describe feedstock influence on PFAS sorption, but according to Ippolito et al. (2020), SSA increases from wood to crop to manures/biosolids-based feedstocks. Also noteworthy is that, with a greater carbon–oxygen ratio, biochar has a greater likelihood of having a half-life of more than 1,000 years (Ippolito et al. 2020), increasing its ability to potentially sequester PFAS long-term. Research over time (i.e., over the course of many years) is needed to verify this contention.

Modifications in biochars have been performed to potentially enhance their ability to sorb PFAS. Wu et al. (2022) modified switchgrass, water oak leaves, and biosolids feedstocks with either ferric chloride ($FeCl_3$) or carbon nanotubes prior to pyrolysis and biochar creation. Carbon nanotube modification had little effect on PFAS sorption, yet the authors found that PFOA sorption onto all biochars was approximately doubled when modified with $FeCl_3$ (as compared to no modification). PFOA sorption onto $FeCl_3$-modified biochars followed this order: water oak biochar (102 µmol/g) < switchgrass biochar (112 µmol/g) < biosolids biochar (470 µmol/g). Wu et al. (2022) emphasized that understanding biochar metal content, pore volume, surface area, and surface functional groups present all play important roles in sorbing PFOA via a combination of electrostatic, physical, and hydrophobic interactions. Rodrigo et al. (2022) added magnetite (Fe_3O_4) to Douglas fir biochar, noting that PFOA sorption increased from 9 (unmodified biochar) to over 650 mg/g. Sørmo et al. (2021) created wood-based biochars either without or with increasing molar ratios of steam or carbon dioxide (CO_2) to feedstock carbon. Increasing amounts of biochar were then added to PFAS-contaminated soils containing either relatively low or high soil organic carbon content. At a 5-percent amendment application rate, all biochars almost completely reduced PFAS leachate concentrations (98–100 percent) in the low organic carbon-containing soil; in the high organic carbon-containing soils, PFAS leachate losses were variable (23–100 percent). Increases in PFAS sorption onto biochar was attributed to increasing biochar internal surface areas and porosity associated with treatment modifications. Sørmo et al. (2021) pointed out that although biochar modifications were successful in increasing PFAS sorption, the amount of biochar end product was reduced after modification, which is something to consider when performing steam or CO_2 modification. Others have used varying modifications (e.g., alkali solutions) to increase PFAS sorption (e.g., Zhou et al. 2021). Overall, it is important to note that any post-biochar-creation modification will add cost to the final product and may cause loss of biochar during the process, which must be considered in choosing biochar modifications for PFAS sorption.

Last, a great deal of research has focused on research-grade (lab-modified) biochars for PFAS sorption and remediation. Future work should devote greater attention

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on PFAS sorption from production-scale biochars, potentially suggesting alterations in pyrolysis conditions (e.g., temperature, hold times) if the goal is to increase PFAS-sorption efficiency (i.e., high capacity, fast sorption rates, and limited desorption potential). Perhaps a suite of biochars, based on temperature and hold time, could be created from one feedstock in order to target both short-chain and long-chain PFAS sorption. Attention could also focus on the creation of biochars on-site or near-site from PFAS-contaminated plant materials, keeping in mind the feedstock and pyrolysis conditions, barring concerns on incomplete PFAS combustion in the process and air emissions, to be returned to on-site contaminated soils for PFAS sequestration and reduction in bioavailability. On- or near-site biochar production could potentially reduce overall cost of biochar.

Future work should also focus attention on the use of biochar in a greater number of field settings, as most research has been performed within laboratory-controlled environments. Results from ongoing field studies show variable responses across multiple harvests and years; these results could be due to factors such as sorption–desorption dynamics, mode of application, depth of incorporation, moisture regime, competition from other chemicals in soils for sorptive sites by biochars, and crop species. Depth at which the initial carbon amendment is incorporated will depend on the depth of discing or tilling. However, particles can move during the growing season due to root growth and water movement. Soil type also affects movement; for example, sandy soils and soil profiles with significant preferential flow paths have a higher probability of much greater vertical transport of PFAS-laden particles. Movement deeper into the soil profile can lead, over time, to particle movement to groundwater or to tile drains that are discharged to surface water bodies. As discussed above (see section “Discerning PFAS Fate and Transport in Varying Soil Types Across the United States”), strong desorption of hysteresis of PFAS has been observed for historically contaminated field soils, particularly those contaminated with long-chain PFAS. No such work has been conducted on biochar-amended soils. Therefore, field studies and some supporting bench-scale studies are needed to quantify sorption–desorption hysteresis for varying PFAS alkyl chain length from biochar-amended field soils, assess in-field long-term (e.g., years) effectiveness, evaluate the potential benefits of repeated applications, and account for soil types and properties and climatic conditions.

Quantifying these characteristics applies to any sorbent (including the clays and DWTRs discussed below). However, given the particularly high level of interest in biochars as PFAS sorbents, taking advantage of machine learning and artificial intelligence is warranted to guide the decision-making process in biochar choices and optimization for mitigating PFAS (Nasrollahpour et al. 2025).

Modified Clays

As briefly discussed in Chapter 2, negatively charged clays can attract divalent cations that lead to cation bridging between clays and negatively charged PFAS or directly bind positively charged PFAS (e.g., Munoz et al. 2018; Mejia-Avendaño et al. 2020). Smectitic clays, which have greater surface area for reactivity, are typically

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more attractive for sorbing PFAS compared with kaolinitic clays (although PFAS charge plays an important role). However, this is not always the case, as others have noted kaolinite sorption of PFAS to be greater than smectitic clays (e.g., Zhang et al. 2014; Zhao et al. 2014). Attention has focused on the use of high surface area clays (either by themselves or via some modification) or low surface area clays to alter PFAS fate, transport, and bioavailability.

Hearon et al. (2022) utilized montmorillonite clay (i.e., high surface area clay) by itself or amended with either carnitine or choline (added to increase hydrophobicity). Clay or modified clay was applied at 2 percent to a PFAS-spiked soil (1 μg/g) and a vegetative growth toxicity assay was performed using common duckweed (*Lemna minor*). The two modified clays reduced PFOA and PFOS bioavailability by about 58 percent and 78 percent, respectively, as compared to a control. The unmodified montmorillonite clay was not as effective as the modified clays, yet it still reduced PFOA and PFOS bioavailability by about 45 percent and 70 percent, respectively. Hearon et al. (2022) also focused attention on clay or modified clay (at 2 percent) application to a 1:1 mixture of soil:compost, introducing the soil to a solution containing nutrients and 1 μg/mL PFAS and using the soil to grow cucumber (*Cucumis sativus*). Across all plant parts (e.g., roots, stems, and leaves), the clay, carnitine-modified clay, or choline-modified clay reduced PFOA translocation by 51, 63, and 64 percent, respectively, while reducing PFOS translocation by 50, 70, and 67 percent, respectively. Hearon et al. (2022) suggested that modified clays might not only help with remediation strategies but help reduce PFAS uptake into certain plant components.

Others have focused on the use of kaolinitic clay (i.e., low surface area) to sorb PFAS. For example, using 1 g/L PFOS and 5 g/L clay, Zhang et al. (2014) showed that kaolinite outperformed montmorillonite for sorbing PFOS with 78 μg/g versus 54 μg/g sorbed, respectively. Higher sorption of PFAS to kaolinite was attributed to kaolinite being an electrically neutral mineral with part of it having a hydroxyl surface that may lead to greater PFAS sorptivity. The latter conclusion was also noted later by Ke et al. (2023) in their PFOS sorption studies.

The above findings, however, need to be taken with some caution. First, the ability of inherent soil clays to sorb anionic PFAS may be weak unless cation bridging occurs, or they may be completely ineffective at sorbing hydrophobic PFAS as these clays are hydrophilic due to hydration of cations sorbed on exchange sites of clay particles (Bolan et al. 2021). Thus, modifying clays (external to soil) with a material or surfactant can increase its hydrophobicity, leading to increased hydrophobic PFAS sorption (Guégan 2019) post soil application.

Second, over time, (modified) clays added to soils likely will react with organic matter and competing ions and will be affected by soil pH, ionic strength, and temperature (e.g., Mukhopadhyay et al. 2021), potentially reducing the effectiveness of the modified materials to sorb PFAS (Figure 5-2). Thus, future studies should focus on long-term investigations using (modified) clay mineral mixtures for enhanced sorption and reduction in PFAS fate, transport, and bioavailability, keeping a close eye on on-site climatic and soil conditions. To help guide this area of study, one could start with results presented in Table 5-2 from Mukhopadhyay et al. (2021).

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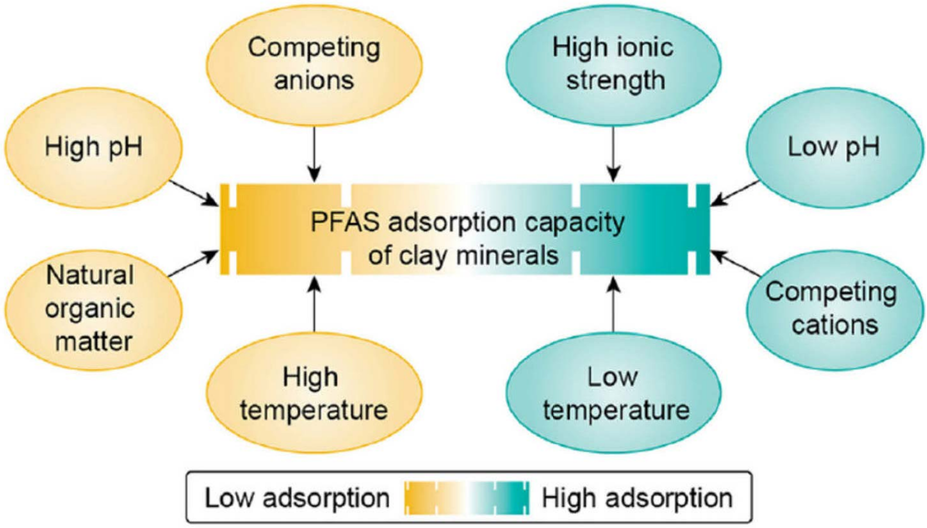

FIGURE 5-2 Factors (pH, temperature, competing ions, natural organic matter, ionic strength) affecting PFAS removal by clay-based adsorbents.
SOURCE: Mukhopadhyay et al. 2021.

Drinking Water Treatment Residuals

Drinking water treatment processes generate a variety of waste products depending on source water, chemicals used for clarification/purification, and other operations utilized (Ippolito et al. 2011). The spent chemicals created post water clarification, DWTRs, typically contain aluminum, iron, or calcium from chemical treatment, in addition to any minerals (e.g., clays, oxides) removed from the source water. Because of the chemical makeup of DWTRs, and the amount generated in the United States on a daily basis (around 2 million tons; Broadbent et al. 2025), they may potentially be a low-cost PFAS sorbent. However, it is important to note that the chemical make-up of DWTRs is heterogenous, a function of suspended sediment in the water column entering the water treatment facility. Hence, the use of DWTRs for sorption of PFAS at a particular location may or may not be optimized via the use of local DWTRs. Resident PFAS on DWTRs, which will vary with water sources and treatment processes, must also be considered. Gravesen et al. (2023) found perfluoroalkyl acid concentrations ranged from 0 µg/kg to 3.3 µg/kg in seven tested DWTRs. Therefore, even though they are inexpensive, more research is needed to determine that DWTRs used as sorbents are optimized to the site of application and are not a source themselves of PFAS.

Zhang et al. (2021) were among the first to report on the use of DWTRs for PFAS sorption. An aluminum-based DWTR, the result of using alum salts in water treatment, was studied for its PFOA and PFOS sorption capabilities from solution. Across a range of solution pH values (3 to 11), aluminum-based DWTRs practically sorbed all PFAS

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TABLE 5-2 Physical and Chemical Properties of Clay-based Adsorbents for PFAS Removal

Clays and clay minerals	Physical properties	Chemical properties	Reference
Natural clays and clay minerals	Surface area: montmorillonite = 67.5 m^2/g, kaolinite = 23.1 m^2/g, hematite = 9.9 m^2/g; Porous structure.	CEC: montmorillonite = 111 cmol/kg, kaolinite = 34 cmol/kg, hematite = 78 cmol/kg; Net negative surface charge due to isomorphous substitution in phyllosilicates; Variable charge under varying pH values in oxides and phyllosilicates; PZC: kaolinite = ~3.6, montmorillonite = 7.2, hematite = 5.9; Exposed -OH groups (e.g., in kaolinite) for H-bonding.	Johnson et al. 2007; Xiao et al. 2011; Zhang et al. 2014
Starch-modified oxidic clays	Increased surface area from 3.98 m^2/g to 8.21 m^2/g after modification; Chemically stable modified product; Intact magenta properties after modification.	Reversal of surface charge from –23mV at pH = 6.5 to slightly positive values at pH = 2–9 after modification; Enhanced surface functional groups such as OH^-, $-COO^-$, and C—O after modification.	Gong et al. 2016
Organoclay minerals	Decreased surface area after modification (e.g., 44 m^2/g of organopalygorskite against 97 m^2/g of pristine palygorskite due to pore blocking by surfactant molecules)	Reversal of surface charge from negative to positive values (e.g., –19.9 mV in pristine palygorskite against 30.6 mV after organic modification of palygorskite); Increased amino ($-NH_2$) functional groups; Increased hydrophobicity due to long-chain alkyl group of surfactants.	Sarkar et al. 2010; Zhou et al. 2010; Sarkar et al. 2011; Sarkar et al. 2012
Clay-polymer composite	Highly porous in nature; Small particle size (e.g., 100–300 µm for PDADMAC-MMT composite).	High positive charge on surface (e.g., –40.3 mV for MMT against 41.0 mV for PDADMAC-MMT at pH 7.6); Enhanced surface functional groups; Presence of hydrophobic moieties due to the inclusion of polymer.	Ray et al. 2019
Magnesium aminoclays (MgAC)	Water dispersible particles; Decreased hydrodynamic diameter (e.g., 508 nm for MgAC coated nZVI against 5130 nm for bare nZVI)	Increased surface positive charge (e.g., 23.5 mV for MgAC coated nZVI against 14.5 mV for bare nZVI); Selective affinity towards hydrophobic PFAS due to enhanced $-NH_2$ functional groups.	Arvaniti et al. 2015

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TABLE 5-2 Continued

Clays and clay minerals	Physical properties	Chemical properties	Reference
Clay-carbon composite	High porous structure; Decreased particle size (e.g., 2.27 nm for MSW-BC-MMT composite against 17.96 nm for MMT); Increased surface area (e.g., 8.72 m^2/g for MSW-BC-MMT composite against 4.33 m^2/g for MSW-BC).	Enhanced hydrophobicity and functional groups (e.g., -OH, $-NH_2$) due to carbonaceous materials (e.g., GO, biochar) and clay minerals.	Ashiq et al. 2019; Premarathna et al. 2019

NOTE: BC = biochar; CAC = cation exchange capacity; MgAC = magnesium aminoclay; MSW = municipal solid waste; MSW-BC = municipal solid waste biochar; nZVI = nano zero valent iron; PDAMAC = poly(diallyldimethylammonium) chloride.
SOURCE: Mukhopadhyay et al. 2021.

instantaneously (pH 3) to approximately 85 percent of PFAS (pH 11) after several hours. At pH 7 (i.e., relevant to soils), aluminum-based DWTRs also sorbed nearly 90 to 95 percent of PFAS after several hours. Zhang et al. (2021) also noted that PFAS sorption was irreversible across all pH levels. It would be important to repeat this study in soils over a broad range of pH values and other characteristics such as those where ions that compete for DWTR binding sites are present in varying concentrations.

Broadbent et al. (2025) mixed one of three different DWTRs (aluminum-, iron-, and calcium-based) into biosolids (50 g DWTR to 1 kg of anaerobically treated biosolids), then applied the mixture to a soil to raise tomatoes (i.e., considered an agricultural setting; 9 g biosolids [containing 0.45 g DWTR]/kg soil) or to a soil to raise ryegrass (i.e., considered a mine land reclamation setting; 130 g biosolids [containing 6.5 g DWTR]/kg soil). Broadbent et al. (2025) found that adding calcium-based DWTRs to biosolids reduced ryegrass PFBA concentrations. They proposed this shift could be due to the increase in soil pH from 6.5 to 7.2 caused by the DWTRs; however, the effective pK_a of PFCAs in an unsaturated system given pH-dependence on surface activity is not well established (Murillo-Gelvez et al. 2023; Patel et al. 2024). Broadbent et al. (2025) also noted that PFAS plant uptake was unaffected by aluminum- or iron-based DWTRs added to biosolids, but this may have been caused by both biosolids and soils containing elevated aluminum and iron content. The latter result suggested that in order to reduce plant PFAS uptake, aluminum- and iron-based DWTRs may be better used in soils containing relatively low amounts of aluminum and iron.

Openiyi et al. (2025a) focused attention on water treatment residuals from using aluminum chlorohydrate to treat wastewater prior to re-injecting it into an aquifer or a biosolids-biochar (1 and 1.5 percent by weight, respectively) to reduce PFAS mobility in soils after biosolids land application (3 percent by weight). Biosolids-biochar showed 41-percent lower total PFAS loss from soil as compared to a control; the wastewater treatment residuals had 31-percent lower total PFAS loss as compared to a control. Both

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amendments reduced PFOS losses by between 62 and 68 percent as compared to a control. The wastewater treatment residuals had higher PFAS loading than other DWTRs, but desorption of resident PFAS was low and the presence of dissolved organic matter in the solution did not affect the ability of the residuals to sorb additional PFAS (Gravesen et al. 2023). The findings of Broadbent et al. (2025) and Openiyi et al. (2025a), which are novel but limited, suggest that further research be performed to fully ascertain the use of DWTRs, singly or in combination with other amendments, for reducing PFAS phytoavailability and leaching loss from PFAS-impacted soils. A research gap could be closed by focusing efforts of combining sorbents (e.g., biochars with biochars, or biochars with DWTR) for reducing PFAS fate and transport to the greatest degree possible. This type of approach could offer a more comprehensive solution in the real world where multiple PFAS are present (Nasrollahpour et al. 2025). Additional applied research in laboratory or greenhouse trials should be performed first, followed by field investigations.

Although no conservation practice standard exists for the use of DWTRs, their use likely would fall under NRCS Nutrient Management (Code 590) conservation practice standard as DWTRs have been proven to reduce phosphorus availability. DWTRs have been proven to sorb excess phosphorus from biosolids when co-applied (Bayley et al. 2008; Ippolito et al. 2009). This approach could be taken to potentially reduce PFAS bioavailability from biosolids, though DWTRs have yet to be fully proven to sorb and reduce PFAS bioavailability. DWTRs have also been used in buffer strips to help capture phosphorus from surface water runoff (Dayton and Basta 2005; Wagner et al. 2008), and thus the potential exists to utilize DWTRs in buffer strips to reduce off-site PFAS transport. Materials similar to DWTRs have been used to capture off-site phosphorus transport in edge-of-field or in-stream containers, and this approach might prove effective at removing PFAS from waters after leaving a site. This type of approach could eventually tie into the creation of a PFAS Site Index, similar to the Phosphorus Site Index used by several U.S. states (Box 5-2). The above concepts should be further explored.

Strategies for Reducing PFAS Discharge to Surface Waters

In addition to using DWTRs to capture PFAS in buffer strips, there are other conservation practices that have been used to trap nutrients that could be experimented with to see if they would also trap PFAS. Two possibilities are reviewed: removal structures and bioreactors.

Removal Structures

To minimize PFAS-contaminated soil and water runoff as well as PFAS discharge from tile drainage, some of the approaches used to capture phosphorus from runoff and tile drainage, originated by Chad Penn at the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA), may be applicable with some modification for capturing PFAS. Penn and Bowen (2018) have detailed several examples of structures

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that can be used to reduce phosphorus entering surface water bodies, including modular boxes, ditch filters, surface confined beds, cartridges, pond filters, blind/surface inlets, bioretention cells, and subsurface tile drain filters.[1] In addition, they have detailed a suite of sorbent options and provided guidance on sorbent selection including a flow chart of things to consider. Lastly, they have included chapters for evaluating sorptive media, which is key in selecting an appropriate sorbent and designing the structure to achieve targeted goals.[2] This work has been developed into a newly established conservation practice standard, Phosphorous Removal System, Code 624 (USDA 2025).

Sorbent selection and design parameters to optimize contaminant capture include sorbent capacity, sorption kinetics, estimated compound mass discharge, and desorption potential. These parameters are needed to determine the residence time and sorbent mass needed in reactors and the frequency at which sorbents will need to be replaced. Other factors to consider include sorbent availability and affordability, as well as ensuring no toxic release from the sorbent of other contaminants (e.g., heavy metals, pH, alkalinity). Additional considerations beyond the design parameters for phosphorus include what

[1] See Chapter 3 in Penn and Bowen (2018).
[2] See Chapters 5 and 6 in Penn and Bowen (2018).

BOX 5-2
PFAS Site Index

Another potential future strategy to follow could be similar to the Phosphorus Site Index (P-index) approach used by several U.S. states. The P-index approach is a tool used by states to evaluate the potential for phosphorus loss from agricultural fields into waterbodies. The state of Maryland's P-index approach[a] is one example of how a PFAS-index approach might be applicable. The Maryland approach evaluates potential phosphorus loss due to site transport characteristics and management practices. Site characteristics include soil test for phosphorus, soil erosion estimates, soil runoff class, leaching potential and/or subsurface drainage, distance to a water body, and priority of the receiving water body. Management characteristics include phosphorus fertilizer application rate and method or organic phosphorus application rate and method. All characteristics are scored, a phosphorus loss rating is determined, and the site of concern is placed into one of four categories regarding the potential for phosphorus movement off site. State-specific threshold models for PFAS could follow a similar approach, considering soil characteristics (e.g., via information found in the Web Soil Survey), other site characteristics, management practices, and specific PFAS present on site.

[a] Maryland Nutrient Management Manual. September 2000. "Section II-C Phosphorous Site Index for Maryland." https://mda.maryland.gov/resource_conservation/pages/nm_manual.aspx.

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specific PFAS need to be captured, as well as PFAS-specific concentrations deemed acceptable for final discharge.

Unlike recommended limits for phosphorus concentrations in flowing waters, which are trying to prevent eutrophication (EPA 1986), considerations of final acceptable PFAS concentrations and masses entering the nearby surface water bodies or agricultural ditch networks should be based on exposure pathways to both terrestrial and aquatic wildlife, as well as free-grazing livestock. Sorbent reactivity, kinetics, and capacity for long- versus short-chain PFAS, as well as affordability and final disposal or regeneration, will need to be considered. Collection or recovery of PFAS-sorbed materials will have an associated cost, so strategically placing sorbents in engineered structures that can be easily connected and disconnected from in-flow water sources and removed or replaced via the use of construction equipment might be a logical approach. Additionally, phosphorus-laden spent media has the potential to be used as a soil amendment in phosphorus-limiting soils or at least in soils where phosphorus levels are not problematic, but PFAS-laden spent media would be considered more in the context of a hazardous waste. Currently, the industry standard for regeneration of PFAS-laden granular activated carbon (e.g., after treating drinking water) is through thermal processes that lead to PFAS volatilization and/or destruction, depending on the temperature (DiStefano et al. 2022). While thermal approaches have been shown to return granular activated carbon to near its virgin state and with similar PFAS-sorption capacities for up to five thermal reactivation steps, literature is currently void on thermal reactivation of biochar.

Research for optimizing absorbent use for PFAS capture in runoff and tile drainage is warranted. Data resulting from some of the current bench- and field-scale efforts on the effectiveness of sorbents tilled into soil for reducing PFAS leaching and plant uptake may be useful as a starting point. However, reactor designs for PFAS in runoff and tile drain discharge will have orders of magnitude higher flow rates compared with water drainage through a soil profile, especially in the case of tile drainage. The latter will be controlled by the amount of the field being drained, diameter of the tile drains, and, of course, weather. The ultimate goal in providing guidance could be the publication of a book similar to the one published by Penn and Bowen (2018) or an updated edition with inclusion of additional chapters targeting PFAS. In addition, parallel to the P-TRAP software created to design phosphorus removal structures (Penn et al. 2021), software specific to PFAS removal could be developed.

Bioreactors

Denitrifying bioreactors have been used to reduce nutrients in runoff and tile drain discharge from agriculture fields prior to flow entering surface waters (Easton 2023). Bioreactors have been found to be more effective at nutrient removal than routing flow into constructed wetlands (Robertson and Merkley 2009). There are a variety of bioreactor designs, but all typically include organic rich materials (e.g., wood chips) to increase microbial activity and hydraulic residence time to allow sufficient time to meet target denitrification goals (Christianson et al. 2021). Guidance on construction and design of

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treatment of tile drain discharge is provided by NRCS conservation practice standard Denitrifying Bioreactor (Code 605; USDA 2020). Other uses of bioreactors are being tried, but practice standards have not yet been developed.

Although efforts to increase the long-term effectiveness of these bioreactors at lower capital and maintenance costs are ongoing (Christianson and Schipper 2016; Christianson et al. 2021), there is potential that similarly designed bioreactors could be optimized to facilitate PFAS degradation. In particular, in-ditch bioreactors, similar to what is used in the construction industry to control soil runoff (referred to as wattles, which resemble large stuffed socks), may have the greatest promise due to lower costs and greater flexibility in both installation options and materials used (Christianson et al. 2017; Payne et al. 2024). These bioditches can be installed parallel to flow or perpendicular to flow, or a hybrid of these two approaches can be used. In many ways, such bioditches are similar to phosphorus (or PFAS) removal structures (discussed above), but these are designed to reduce target constituents by promoting degradation with a carbon food source versus capture via sorption mechanisms. Recent work to optimize denitrification in bioreactors includes biochar, a common sorbent material targeted for contaminant capture including PFAS (see section "Biochars" above). Biochar addition to the bioreactors was found to improve the habitat for microbial growth, enrich the denitrifying bacteria taxa, improve pH buffering, and increase nutrient retention, which all worked together to increase effective denitrification (Andras et al. 2025). Additional bioreactor designs, such as denitrifying walls, were first tested in 1996 in New Zealand (Warneke et al. 2011; Christianson et al. 2021). These walls are in essence permeable reactive barriers used in other applications to capture (when filled with sorbent) or degrade biologically or abiotically targeted contaminants to reduce off-site movement.

Microbial degradation is generally considered a favored, environmentally friendly, and typically low-cost approach to reducing pollutant loads. The biggest challenges facing the implementation of bioreactors to reduce PFAS in runoff and tile drainage are identifying and fostering a microbial community that can degrade PFAS and be maintained in the natural environment and the diversity of PFAS structures (Wackett 2022, 2025). While reduction of PFAS by microbes has been reported from laboratory-scale studies, degradation has been slow and incomplete (Huang and Jaffé 2019; Yu et al. 2020; Y. Huang et al. 2025).

Wackett (2024) posed that PFAS resistance to microbial degradation is due to limited time-of-exposure because PFAS have been manufactured for less than 100 years and microbes need more time to evolve degradation capabilities. So far, microbiologists have been unsuccessful at finding microbial evolution to degrade PFAS at military sites that have been contaminated for over five decades. Repeated exposure of PFAS to microbes in the laboratory to force the evolutionary process forward, which has been successful for some chlorinated organic compounds, has not yielded results for PFAS. There are many other reasons why microbes would not evolve well to degrade PFAS, including fluoride intercellular toxicity and energy requirements to break multiple carbon–fluorine bonds (Harris et al. 2025). Therefore, the timescale feasibility for this evolution, given there are no natural perfluorocarbons, limits any direct applicability in the near future (Walker and Chang 2024; Wackett 2024).

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Addressing this challenge in the near term may be best met by combining biological processes with abiotic processes (Long et al. 2024) that used microbially generated catalysts. These catalysts lead to generation of nano-palladium particles that degrade PFOA with nitrate as the electron acceptor. Of greatest challenge among the PFAS in this regard are the perfluoroalkyl sulfonates such as PFOS, which are also some of the PFAS of greatest concern because of their high potential to bioaccumulate. Nevertheless, design and implementation of bioreactors for treatment of PFAS in runoff and tile drainage that combines both biological and abiotic processes, including enhanced retention, as well as biotically catalyzed abiotic reactions, are ripe for research, even if success is likely a long way off.

UNDERSTANDING PLANT CHARACTERISTICS THAT AFFECT PFAS UPTAKE AND ACCUMULATION

In the context of conservation practices, the selected planting of specific crops or other vegetative cover could address PFAS contamination on agricultural land via plant uptake in one of two ways: (1) by trying to minimize PFAS accumulation in harvested and grazed crops or (2) by trying to maximize plant uptake for phytoremediation. For either approach to be successful, there is an urgent need to better understand the variation in PFAS uptake among agricultural and conservation plants and of the distinct plant characteristics that influence that variation.

To start, quantification of soil-to-plant transfer of PFAS across a broader range of crops and growing conditions than currently exist in the literature is needed (Wang et al. 2020). To be most useful for crop selection decisions, these studies should be conducted in the field under real-world conditions and preferably over multiple years to capture year-to-year variability.

Plant factors already understood to influence PFAS uptake include plant physiological and biochemical characteristics. It is well established that uptake and storage of PFAS are distinctly higher in the vegetative parts of plants (leaves) than in storage organs (fruits, grains, tubers; Stahl et al. 2009; Lechner and Knapp 2011; Blaine et al. 2014; Wen et al. 2014; Wang et al. 2020; Lesmeister et al. 2021; Costello and Lee 2024). These findings are the basis of recommendations by the Maine Department of Conservation, Agriculture, and Forestry and the University of Maine Cooperative Extension for farmers impacted by PFAS (Fitzgerald et al. 2025; Maine PFAS Response Program 2025), which include switching to crops that accumulate lower levels of PFAS (e.g., growing corn and small grains instead of perennial grasses), as well as tuber crops (e.g., potato) over root crops (e.g., carrots).

Transpirational flow is seen as the primary driver of PFAS uptake and storage, with plant parts that receive larger amounts of water accumulating PFAS to a greater extent (Wang et al. 2020), although selective membranes (e.g., Casparian strip) and other transfer barriers in roots and shoots are also thought to play a role (Blaine et al. 2014; Lesmeister et al. 2021). As well, protein and lipid contents (Wen et al. 2016; Xu et al. 2021), root macrostructure (fibrous versus taproot) including root density and surface area (Lesmeister et al. 2021; Xu et al. 2021), and root exudates (Xiang et al. 2020) all have been proposed as mechanisms to explain PFAS uptake difference among plant

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species and cultivars. Further research is needed to investigate the relative importance of these factors.

Differences in PFAS transfer factors among crop species also have been linked to transpiration differences related to the length and seasonality of the vegetative period and the crop's transpirational capacity (Blaine et al. 2014; Ghisi et al. 2019). For instance, in their field study at a highly contaminated site, Liu et al. (2017) observed more than 11-fold higher PFAS concentrations (a sum of 12) in wheat rather than corn; they attributed this difference to differences in the plants' transpirational coefficients (450–600 g water/g dry weight versus 250–300 g water/g dry weight, respectively).

Differences in transpiration rates is one of the hypotheses presented by Simones et al. (2024) to explain their observation over 2 years of higher PFOS uptake by a grass-based perennial forage in aftermath growth harvested in August or September ("second cut" harvested in August or September) than in the initial growth for the season ("first cut" harvested in June). Similar observations were reported by Stahl et al. (2009) and Openiyi et al. (2025b) in greenhouse studies with perennial ryegrass and forage grasses, respectively. Another possible explanation provided by Simones et al. (2024) for this seasonality effect was that root and above-ground structure may have been different between the two growing periods. Perennial forage regrowth is known to have a higher leaf-to-stem/pseudostem ratio (Ball et al. 2001), and leafier plants may exhibit increased PFAS accumulation (Nassazzi et al. 2025) as discussed above. Clearly, more research is warranted.

There is also currently a complete lack of research in PFAS translocation mechanisms from soil into tree fruiting bodies. Gobelius et al. (2017) studied PFAS accumulation in tree species (all nonfruit-bearing) near a firefighting training facility that used aqueous film-forming foams for around 20 years. The relative accumulation of PFAS in tree plant components mirrored that found in annual plant components; birch leaves contained the greatest amount of PFAS (12–97 ng/g wet weight), followed by twigs (5–40 ng/g wet weight), trunk (1–19 ng/g wet weight), and roots (3–6 ng/g wet weight). Spruce tree components followed a somewhat similar order. PFAS (particularly long-chain PFAS) have been shown to bind to proteins as was observed for PFOA and PFOS, which favorably deposited in protein-rich versus lipid-rich root tissues (Wen et al. 2016). However, this concept is unlikely to translate to preferential accumulation in the nuts of nut-bearing trees based on what has been observed for corn kernel and plant seeds. Plant physiology controls whether PFAS in the transpiration stream (xylem) will off-load into the phloem, which appears to be limited. For example, Lazo and Lee (2024) observed no accumulation of PFOS in the bean of six different soybean varieties while PFOS concentrations were high in the other tissues: leaves containing more than stems and stems more than pods. As discussed in Chapter 2, short-chain PFCAs structurally mimic fatty acids, whereas PFOS does not. Therefore, differences in transport from the transpiration stream into the phloem and subsequently into seeds and fruits are likely due to non-specific fatty acid transporters.

Wang et al. (2020) called for increasing the level of genetic understanding of PFAS uptake into various crops. This latter point is currently being tackled by USDA–ARS, which is screening for differences in crop varieties that lead to reduced PFAS uptake into

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edible plant parts, followed by genetic testing.[3] In the area of phytoremediation, results have been mixed, with rates of PFAS uptake having shown that this approach may have promise for some shorter-chain PFAS but is not a viable option for longer-chain legacy compounds (Nason et al. 2024). Researchers are looking into microbe-assisted, chelate-assisted, and genetic-engineering approaches (Naveed et al. 2024), as well as nanotechnology-assisted techniques to enhance plant uptake and phytoremediation efficacy (C. Huang et al. 2025).

Research is also needed to determine and use appropriate vegetative covers that are not detrimental to the health of wildlife when consumed. If uptake of PFAS by vegetative conservation covers causes harmful impacts to wildlife (or grazing livestock), the result would be at odds with conservation practices such as Upland Wildlife Habitat Management (Code 645).

Finally, how crop management affects plant PFAS uptake is a topic that has barely been addressed but is of great importance in the context of conservation practices. Researchers have investigated fertilization (Adu et al. 2025) and intercropping (Scearce et al. 2025) on crop PFAS uptake with mixed effects. No known studies exist on how PFAS uptake is influenced by conservation tillage/no-till, which is known to affect root distribution under certain conditions (Ruis and Blanco-Canqui 2024), crop rotation, crop density, or irrigation. These are major research gaps.

PFAS MITIGATION IN LIVESTOCK

Mitigating PFAS in livestock that are exposed to PFAS-contaminated water or feed is a significant challenge for which research is needed, although some practical guidance has been developed. Animal product consumption tends to be the largest human exposure pathway for PFOS and PFOA (EFSA Panel on Contaminant in the Food Chain 2020). Dairy is of particular concern because whole-plant forages, which comprise a major portion of dairy livestock diets, have relatively high rates of PFAS uptake and therefore PFAS bioaccumulates and biomagnifies in animals and their milk (Hossini et al. 2025). Representative practical guidance from approaches implemented in Maine include the following (Maine PFAS Response Program 2025):

- Take advantage of the fact that PFAS levels in animals will decrease over time once the source of PFAS in the diet is eliminated. The half-life of PFOS in milk and beef tissues is estimated to be between 8 and 12 weeks (Astmann et al. 2025). Switching beef animals to unaffected pastures or “clean feed” during the finishing stage can reduce PFAS levels in subsequent food products.
- Dilute affected feed with “clean feed” to lower PFAS intake for livestock. For hay, mark and keep records of which hay bales come from which fields. For silage, silos or bunkers must be segregated by fields or lots should be adequately mixed during fillings to avoid PFAS “hot spots” when feeding out.

[3] See https://www.ars.usda.gov/pacific-west-area/riverside-ca/agricultural-water-efficiency-and-salinity-research-unit/research/mitigation-and-remediation-of-pfas/.

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- Use soil tests, not forage tests, to assess the potential risk of milk or meat contamination. In the soil–to–forage–to–animal pathway, PFAS concentrations are the lowest in forage, so it is possible to have detectable milk and meat concentrations even if forage is non-detect.

Although guidance is emerging, more research is needed to support continued development of management practices. Livestock studies have focused on a very limited subset of perfluoroalkyl acids (PFAAs), primarily PFOS and PFOA, with an even smaller number including the PFCAs perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnA), and perfluorododecanoic acid (PFDoDA) and the PFSAs perfluorobutanesulfonic acid (PFBS), perfluoropentanesulfonic acid (PFPeS), and perfluoroheptanesulfonic acid (PFHpS) (Lupton et al. 2012; Kowalcyzk et al. 2013; Vestergren et al. 2013; Drew et al. 2021, 2022; Chou et al. 2023; Mikkonen et al. 2023). PFAA elimination from livestock occurs via lactation, urine, and feces, with renal excretion generally considered the primary route of elimination (Mikkonen et al. 2023). For studied PFAS, elimination half-lives in serum increase with increasing chain length (e.g., 9.4, 46.0, and 67.3 days for perfluorohexane sulfonate [PFHxS], PFHpS, and PFOS, respectively) (Drew et al. 2022). Physiologically based pharmacokinetic models have been used to estimate the time for concentrations to decrease to levels below risk-based consumption limits—known as withdrawal intervals—for PFOA, PFHxS, and PFOS in milk (Chou et al. 2023). Based on the affiliated web interface, withdrawal intervals for PFOA, PFHxS, and PFOS following 2 years of exposure to 1 μg/L were <1 day, <1 day, and around 1,875 days, respectively; however, models such as these should be updated to reflect more recent regulatory limits and newly regulated PFAS and validated in real-world scenarios. Research focused on uptake and especially elimination will inform how conservation practices (e.g., Feed Management, Code 592) may be used to mitigate PFAS impacts in livestock.

Research is needed to explore opportunities to interrupt PFAS from cycling on farms and in agrifood systems through animal waste management. Many of the technologies and approaches being explored to separate and destroy PFAS in biosolids could be applied to animal manures, such as foam fractionation (Smith et al. 2023), anaerobic digestion (Li et al. 2021), and mechanochemical degradation, pyrolysis/gasification, and supercritical water oxidation (Berg et al. 2022). If promising, these approaches could be incorporated into or coupled with existing conservation practices that target manure management (e.g., Anaerobic Digestion [Code 366]; Waste Storage Facility [Code 313]; Waste Separation Facility [Code 632]; and Waste Treatment [Code 629]).

Conclusion 5-1: Applied research that advances understanding of PFAS fate and transport in different types of soils, develops better mechanisms by which to trap or sequester PFAS, and minimizes PFAS uptake in plants and animals could improve the ability of conservation practices to address PFAS contamination on agricultural land.

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Conclusion 5-2: A coordinated, national network of researchers focused on the identified areas of applied research would help close information gaps and provide practical knowledge for managing PFAS contamination in U.S. agricultural systems.

Conclusion 5-3: The results of such research and coordination could be used to continually improve existing resources and provide needed resources identified in the suggested framework to advance the ability of the FPAC agencies to respond to the impacts of PFAS contamination on agricultural land.

The issues associated with PFAS in the environment are many. Means by which PFAS contamination can be mitigated still need further research. This chapter took into account the committee's expertise both within and outside the PFAS space, utilizing combined experiences and education to derive potential applied research paths that may be of focus in the future. The described paths include dealing with PFAS in situ (i.e., in soils) by potentially reducing PFAS bioavailability, reducing PFAS from entering waters or reducing PFAS presence within water sources, understanding the complex nature of PFAS within plants and potentially altering cropping systems accordingly, and mitigating PFAS in animals, especially livestock. As the general public's awareness of PFAS is heightened, it will be increasing important to face the challenges in communicating research results in a way that educates but does not exacerbate unfounded concerns or fears (Preisendanz et al. 2024).

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Appendix A

Committee Member Biographical Sketches

Jim Ippolito *(Chair)* is currently the Rattan Lal Endowed Professor of Soil Health and Fertility at The Ohio State University. He was previously a professor at Colorado State University and a research soil scientist with the U.S. Department of Agriculture's Agricultural Research Service. Dr. Ippolito's research expertise lies in the area of soil health and environmental quality in the agricultural sector. He has focused major efforts on biosolids land application, biochar land application, reuse of water treatment byproducts, macronutrient, micronutrient, heavy metals, and the fate and transport of per- and polyfluoroalkyl substances within agroecosystems. Dr. Ippolito is the recipient of the Soil Science Society of America's Soil Science Applied Research Award and the Jackson Soil Chemistry and Mineralogy Award, the U.S. Environmental Protection Agency's National Clean Water Act Recognition Award for outstanding biosolids research, and several other state and federal awards focused on biosolids land application research. He is also a fellow of both the Soil Science Society of America and the American Society of Agronomy. Dr. Ippolito received his B.S. degree in plant sciences with a focus on agronomy from the University of Delaware (1989), his M.S. degree in soil chemistry/fertility from Colorado State University (1992), and his Ph.D. in environmental soil quality/chemistry from Colorado State University (2001).

Thomas W. Christensen serves as the chief operating officer for Ecosystem Services Exchange (ESE), an LLC founded in 2010 that provides technical services and project development and leadership in support of water management, with a strong focus on conservation drainage practices and systems. He joined ESE in February 2020 after retiring from the U.S. Department of Agriculture (USDA) with 40 years of professional experience at the field, state, regional, and national levels in support of public–private partnership efforts to assist farmers, ranchers, and forest stewards with their voluntary conservation needs. Mr. Christensen serves on the board of directors of the Agricultural

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Drainage Management Coalition, a nonprofit organization that supports the improvement of water quality and agronomy by managing agricultural drainage water, and SWRT Solutions, Inc., a small business focused on the use of mechanical chisels for the installation of water retention membranes in sandy soils to improve soil moisture. He worked for three different agencies in USDA, including 37 years with the Natural Resources Conservation Service (NRCS), and held 16 distinct positions in nine separate locations in four states and Washington, D.C. He was the NRCS State Conservationist for Illinois and held eight different national-level senior executive service positions, including serving with NRCS as Associate Chief, Deputy Chief for Programs, Director of Financial Assistance Programs, Director of Conservation Operations, Director of Animal Husbandry and Clean Water Programs, Chief Information Officer, and Regional Conservationist for the 12 central region states, plus with the USDA Farm Production and Conservation Mission Area as Deputy Chief Operating Officer. He is a recipient of a Presidential Meritorious Executive Award for Senior Executives for Public Service. Mr. Christensen has a B.S. in forest management from Rutgers University and an M.S. in renewable natural resources conservation from the University of Connecticut, and he attended Duke University's Public Policy Institute.

Jacqueline MacDonald Gibson is department head and professor in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. Dr. Gibson's research develops quantitative methods for characterizing environmental risks to human health and identifying optimal technical and policy solutions. Her recent work includes projects on characterizing risks from exposure to per- and polyfluoroalkyl substances in private well water in rural areas. She is past-president of the Society for Risk Analysis. She also was recently appointed associate editor of the journal *Environmental Science & Technology*. She earned a dual Ph.D. from the Department of Engineering and Public Policy and the Department of Civil and Environmental Engineering at Carnegie Mellon University, an M.S. from the Department of Civil and Environmental Engineering at the University of Illinois at Urbana–Champaign, and a B.A. in mathematics from Bryn Mawr College.

Benjamin M. Gramig is a research agricultural economist at the U.S. Department of Agriculture's Economic Research Service (2021–present). Previously, he was an associate professor at the University of Illinois at Urbana–Champaign (2017–2021) and Purdue University (2008–2017). Dr. Gramig's research is wide ranging, with a focus on topics at the interface between agricultural production and environmental quality. His active research projects are investigating the impact of conservation practices and federal conservation programs on ambient water quality and working on interdisciplinary teams to leverage economics, agronomy, engineering, and hydrology expertise to address agrienvironmental challenges faced by society. Dr. Gramig is a member of the Agricultural and Applied Economics Association. His past research has been supported by the National Science Foundation, U.S. Department of Energy, and U.S. Department of Agriculture, among others. Dr. Gramig received his doctorate from Michigan State University and his M.S. and B.S. from the University of Kentucky.

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Jennifer L. Guelfo is an associate professor in civil, environmental, and construction engineering at Texas Tech University (TTU). She joined TTU in 2018 following a postdoctoral appointment in the Brown University School of Engineering. In addition to academia, Dr. Guelfo also has a combination of consulting and industry experience, and she uses this background to engage in activities that can inform policy and bridge gaps between research and practice. For the past 15 years, her research has focused on occurrence, fate, transport, and remediation of per- and polyfluoroalkyl substances (PFAS). This experience includes multi-institution, state- and federal-level projects focused on PFAS in biosolids, biosolids-amended soils, and PFAS in agriculture. Dr. Guelfo has received the TTU Ed and Linda Whitacre Faculty Fellowship and the Chancellor's Council Distinguished Research Award, which is the highest honor given by the university to its faculty members for their research efforts. She holds a B.A. in geology from the College of Charleston, an M.S. in environmental science and engineering from the Colorado School of Mines (CSM), and a Ph.D. in hydrologic science and engineering, also from CSM.

Linda S. Lee is a distinguished professor at Purdue University with a joint appointment in the Colleges of Agriculture (Department of Agronomy) and Engineering (School of Sustainability Engineering and Environmental Engineering). She is also the program head of the Ecological Sciences & Engineering Interdisciplinary Graduate Program and College of Agriculture Assistant Dean of Graduate Education and Research. Dr. Lee has established a strong research and teaching program on chemical fate in the environment, analytical tools, and waste and contaminant management strategies with per- and polyfluoroalkyl substances (PFAS) challenges driving her research for the last two decades. She is well published in top-tier environmental journals, and her current research is funded by a diverse portfolio including the Environmental Protection Agency, U.S. Department of Agriculture, Department of Defense, National Science Foundation, Water Research Foundation, and U.S. Geological Survey. Dr. Lee has published more than 180 publications with most being in top-tier environmental journals and served as primary mentor of almost 50 graduate students to date. She is a highly regarded environmental professional for her three decades of notable work in teaching, mentoring, and service, as exemplified by being awarded Purdue Faculty Scholar (2001), fellow by the American Society of Agronomy (ASA) (2003) and the Soil Science Society of America (SSSA) (2004), Purdue Seed for Success Award (multiple years), ASA Environmental Quality Research Award (2021), Purdue Distinguished Professor Award (2022), SSSA Diversity Trailblazer Presidential Award (2023), ASA Mentoring Award (2024), and the Purdue Land Grant Mission Award (2025). Dr. Lee is member of ASA, SSSA, the American Chemical Society, the Society of Environmental Toxicology and Chemistry, and the American Association for the Advancement of Science. She joined Purdue in 1993 with degrees in chemistry, environmental engineering, and soil chemistry and contaminant hydrology from the University of Florida.

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Hui Li is a professor of environmental soil chemistry at Michigan State University. His research program involves analysis, sorption, transformation, bioavailability, and plant uptake of per- and polyfluoroalkyl substances (PFAS), as well as mitigating exposure to PFAS in pharmaceuticals and personal care products and legacy organic contaminants in the environment. Dr. Li's research program focuses on a molecular-level understanding of physicochemical processes at the interface of water and soil, plant uptake of organic contaminants from soil and water, and the development of environmental remediation technology and mitigation management strategies. His research has been sponsored by the U.S. Department of Agriculture, the Environmental Protection Agency (EPA), the National Institutes of Health, National Science Foundation, and Department of Defense's Strategic Environmental Research and Development competitive funding programs. Dr. Li received the Jackson Soil Chemistry and Mineralogy Award from the Soil Science Society of America (SSSA) and the Environmental Quality Research Award from the American Society of Agronomy (ASA). He was elected as a fellow of both SSSA and ASA and serves on the EPA Science Advisory Board and on its Agricultural Science Committee. Dr. Li also received Michigan State University's William J. Beal Outstanding Faculty Award and Research Fellow Award. He earned his Ph.D. in soil chemistry from Purdue University.

Ellen B. Mallory is an extension specialist and professor of sustainable agriculture at the University of Maine. She conducts applied research and educational programming on crop production, soil health and fertility, climate adaptation, and most recently, the transport and mitigation of per- and polyfluoroalkyl substances (PFAS) in agricultural systems. Dr. Mallory's prior research projects documented soil health impacts on soil nitrogen dynamics and potato yield stability, developed biologically based fertility strategies for organic grain and pulse production, and predicted the response of potato–grain production systems to climate change. Her current PFAS research projects investigate the influence of soil and plant factors on PFAS uptake by forage crops and explore management practices to minimize that uptake. Dr. Mallory coordinates the Maine PFAS Agricultural Research Network. From 2008 to 2024, she served as the Maine State Coordinator for the U.S. Department of Agriculture's Sustainable Agriculture Research and Education program. She earned her B.S. in biology from Swarthmore College, two master's degrees in agronomy and land resources from the University of Wisconsin, and her Ph.D. in ecology and environmental sciences with a concentration in sustainable agriculture from the University of Maine.

Timothy Rosen is the Director of Agriculture & Restoration for ShoreRivers, regularly partnering with academic, state, and federal agencies to advance research on agricultural best management practices; managing restoration projects; completing watershed assessments; and working with farmers and landowners to reduce land-based pollution. He joined the staff of ShoreRivers in 2012. He was a 2017 Dairy Sustainability Award winner from the Innovation Center for U.S. Dairy; served on the Chesapeake

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Bay Program's Agricultural Workgroup; and is a member of Delmarva Land and Litter Collaborative, which brings together agricultural industry, farmers, regulatory agencies, academia, and environmental groups in a collaborative and mission-driven manner. He has published research on the efficacy of conservation drainage practices on reducing nutrient pollution from agricultural drainage, has worked on research to optimize cover crop management for water quality purposes, and is a part of the first research efforts to understand how biostimulants impact water quality and crop production. Mr. Rosen majored in biology and minored in environmental studies at Mount St. Mary's University and completed a master's degree in watershed hydrology at Louisiana State University.

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Appendix B

Public Meeting Agendas

Information-gathering sessions include in-person public meetings and webinars held by the committee from February 2025 to April 2025. They are listed in chronological order. The locations of the in-person meetings are provided. Presentations that were made via the Internet at the in-person public meetings are noted.

February 20, 2025

The first public meeting of the Committee on Assistance to the U.S. Department of Agriculture in Building a Framework for Addressing PFAS on Agricultural Land was held in person and virtually.

The Keck Center, 500 Fifth Street, NW
Washington, DC 20001

Open Session Agenda
February 20, 2025
10:00 a.m. – 12:00 p.m.

10:00 **Welcome**
Jim Ippolito, *Committee Chair, The Ohio State University*
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

10:10 **Committee Introductions**

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10:20 **Overview of the National Academies Study Process**
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

10:30 **Remarks by the Study Sponsor, U.S. Department of Agriculture–National Resources Conservation Service (USDA–NRCS)**
Dana Ashford-Kornburger, *USDA–NRCS*

10:40 **Conservation Programs, Planning, and Practice Standards**
Bill Reck, *USDA–NRCS*

11:00 **Presentation on PFAS and Regional Screening Levels**
Linda Gaines, *U.S. Environmental Protection Agency*

11:20 **Committee Discussion with Speakers**

11:45 **Opportunity for Public Comment**

12:00 **Adjourn Open Session**

March 11–12, 2025

The second public meeting of the Committee on Assistance to the U.S. Department of Agriculture in Building a Framework for Addressing PFAS on Agricultural Land was held virtually over 2 days.

Open Session Agenda
March 11, 2025
3:30 p.m. – 5:00 p.m.

3:30 **Welcome**
Jim Ippolito, *Committee Chair, The Ohio State University*

3:35 **Overview of the National Academies Study Process**
Kara Laney, *Study Director, National Academies of Sciences, Engineering, and Medicine*

3:45 **The USDA Agriculture Research Service (ARS) PFAS Research Enterprise, the USDA–ARS and University of Maine PFAS Workshop, and the USDA–ARS and University of Maine Center for Excellence: The ARS Vision for Excellent Science to Address PFAS Issues in Agriculture**
David B. Knaebel, *USDA–ARS*

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4:05 **Farm Practices and PFAS in Food Crop Production Systems**
Clinton Williams, *USDA–ARS*

4:25 **Identifying Microorganisms and Environments that Enhance the Degradation and Reduce the Half-Life of PFAS**
Jude Maul, *USDA–ARS*

4:45 **Committee Discussion with Speakers**

5:00 **Adjourn Day One**

Open Session Agenda
March 12, 2025
1:00 p.m. – 2:30 p.m.

1:00 **Welcome**
Jim Ippolito, *Committee Chair, The Ohio State University*

1:10 **PFAS Fate in Agricultural Systems: Developing Data Useful for Informing Conservation Policy**
Sara Lupton, *USDA–ARS*

1:30 **Finding Solutions to Mitigate the Impacts of PFAS Contamination on Agriculture and Food Systems**
David J. Smith, *USDA–ARS*

1:50 **Committee Discussion with Speakers**

2:30 **Adjourn Meeting**

April 3, 2025

The third public meeting of the Committee on Assistance to the U.S. Department of Agriculture in Building a Framework for Addressing PFAS on Agricultural Land was held in person and virtually.

The Keck Center, 500 Fifth Street, NW
Washington, DC 20001

Open Session Agenda
April 3, 2025
10:00 a.m. – 11:00 a.m.

10:00 **Welcome**
Jim Ippolito, *Committee Chair, The Ohio State University*

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10:05 **Conversation with the Study Sponsor, U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS)**

Follow-up Items from Last Discussion
Bill Reck, *USDA–NRCS*

Conservation Evaluation and Monitoring Activity
Gene Kim, *USDA–NRCS*

NRCS-supported PFAS Science
Charlotte Kirk-Baer, *USDA–NRCS*

PFAS and Hazardous Substances in Agriculture, PFAS Definition
Kale Horton, *USDA-Farm Service Agency (remote)*

National Environmental Policy Act
Barbara (Barbie) Prine, *USDA–NRCS*

11:00 **Adjourn Open Session**

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Appendix C

PFAS Family Tree

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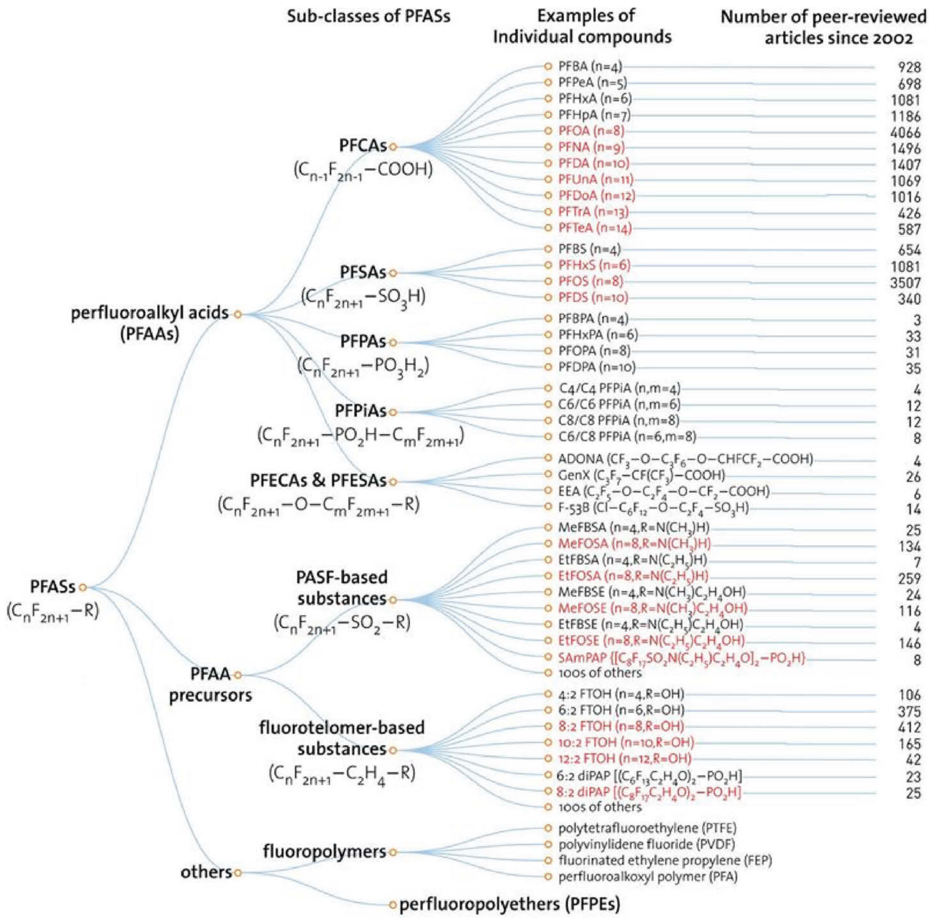

FIGURE C-1 Family tree of PFAS.
NOTE: Family tree includes examples of individual PFAS and the number of peer-reviewed articles on them since 2002. Most articles focused on long-chain PFCAs, PFSAs, and their major precursors. PFAS in red are those that have been restricted under national, regional, or global regulatory or voluntary frameworks.
SOURCE: Reprinted with permission from Wang, Zhanyun, Jamie DeWitt, Christopher P. Higgins, and Ian T. Cousins. "Correction to 'A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)?'" *Environmental Science & Technology* 52 (5): 3325–3325. 2018, American Chemical Society. https://doi.org/10.1021/acs.est.8b00599. Copyright © 2018 American Chemical Society.

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Appendix D

Potentially PFAS-Relevant Conservation Practices

The committee reviewed the entire list of practices included in the fiscal year 2025 version of the Natural Resources Conservation Service's (NRCS's) Conservation Practice Physical Effects matrix and identified 88 existing practices that could be further reviewed individually by NRCS for their relevance to PFAS contamination, transport, or fate.

TABLE D-1 Potentially PFAS-Relevant Conservation Practices

Practice	Practice Code
Amending Soil Properties with Gypsum Products	333
Animal Mortality Facility	316
Aquaculture Ponds	397
Channel Bed Stabilization	584
Composting Facility	317
Conservation Cover	327
Constructed Wetland	656
Contour Buffer Strips	332
Contour Farming	330
Contour Orchard and Other Perennial Crops	331
Cover Crop	340
Critical Area Planting	342
Cross Wind Ridges	588
Cross Wind Trap Strips	589C

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TABLE D-1 Continued

Practice	Practice Code
Dam	402
Deep Tillage	324
Denitrifying Bioreactor	605
Drainage Water Management	554
Early Successional Habitat Development/Management	647
Feed Management	592
Fence	382
Field Border	386
Filter Strip	393
Fishpond Management	399
Forage Harvest Management	511
Grassed Waterway	412
Grazing Management	528
Groundwater Testing	355
Hedgerow Planting	422
Herbaceous Wind Barriers	603
Hillside Ditch	423
Irrigation and Drainage Tailwater Recovery	447
Irrigation Canal or Lateral	320
Irrigation Field Ditch	388
Irrigation Land Leveling	464
Irrigation Reservoir	436
Livestock Pipeline	516
Monitoring Well	353
Nutrient Management	590
Pasture and Hay Planting	512
Phosphorous Removal System	624
Pond	378
Precision Land Forming and Smoothing	462
Prescribed Burning	338
Range Planting	550
Residue and Tillage Management, No Till	329
Residue and Tillage Management, Reduced Till	345
Riparian Forest Buffer	391
Riparian Herbaceous Cover	390
Row Arrangement	557

continued

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TABLE D-1 Continued

Practice	Practice Code
Saline and Sodic Soil Management	610
Saturated Buffer	604
Seasonal Water Management for Wildlife	646
Sediment Basin	350
Silvopasture	381
Sinkhole Treatment	527
Soil Carbon Amendment	336
Spoil Disposal	572
Spring Development	574
Streambank and Shoreline Protection	580
Stripcropping	585
Structure for Water Control	587
Subsurface Drain	606
Surface Drain, Field Ditch	607
Surface Drain, Main or Lateral	608
Surface Roughening	609
Terrace	600
Tree/Shrub Establishment	612
Underground Outlet	620
Upland Wildlife Habitat Management	645
Vegetated Treatment Area	635
Vegetative Barrier	601
Vertical Drain	630
Waste Facility Closure	360
Waste Separation Facility	632
Waste Storage Facility	313
Waste Transfer	634
Waste Treatment Lagoon	359
Water and Sediment Control Basin	638
Water Well	642
Watering Facility	614
Well Decommissioning	351
Wetland Creation	658
Wetland Enhancement	659
Wetland Restoration	657
Wetland Wildlife Habitat Management	644
Wildlife Habitat Planting	420
Windbreak/Shelterbelt Establishment and Renovation	380

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Appendix E

PFAS-Relevant Resource Concerns, Effects, and Rationale for Nine Conservation Practices

Tables E-1 through E-9 contain the resource types affected by the implementation of the practice, the specific resource concerns that the practice addresses, the effect of the practice on each concern, and the rationale for its use for nine conservation practices described in Chapter 3. The information in the tables can be found in the Conservation Practice Physical Effects spreadsheet for fiscal year 2025 at https://www.nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-physical-effects.

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TABLE E-1 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Cover Crop Practice Standard 340

Resource	Resource Concern	Effect	Rationale
Soil	Aggregate Instability	Slight to Moderate Improvement	Live plant roots increase aggregation physically and through exudates.
Soil	Compaction	Slight to Moderate Improvement	Increased biomass and roots improve aggregation, which gives better resistance to compaction.
Soil	Organic Matter Depletion	Slight to Moderate Improvement	More biomass produced will increase organic matter.
Soil	Sheet and Rill Erosion	Moderate to Substantial Improvement	Increased cover during erosive periods will reduce soil detachment by water.
Soil	Wind Erosion	Moderate to Substantial Improvement	Increased cover during erosive periods will reduce soil detachment by wind.
Soil	Ephemeral Gully Erosion	Moderate Improvement	Increased cover during erosive periods will reduce concentrated flow and associated soil detachment.
Water	Sediment Transported to Surface Water	Slight to Moderate Improvement	Vegetation will reduce erosion and transport of sediment.

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TABLE E-2 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Nutrient Management Practice Standard 590

Resource	Resource Concern	**Effect**	**Rationale**
Soil	Organic Matter Depletion	Slight to Moderate Improvement	Use of organic nutrient sources and fertilizers will improve soil organic matter.
Water	Nutrients Transported to Surface Water	Substantial Improvement	Right amount, source, placement, and timing (4Rs) provides nutrients when plants need them most.
Water	Nutrients Transported to Groundwater	Substantial Improvement	Right amount, source, placement, and timing (4Rs) provides nutrients when plants need them most.
Water	Pathogens and Chemicals from Manure, Biosolids, or Compost Applications Transported to Surface Water	Moderate to Substantial Improvement	Proper application of manure, compost, and biosolids should reduce or eliminate pathogens and/or chemicals (if present in source material) from moving into surface water.
Water	Pathogens and Chemicals from Manure, Biosolids, or Compost Applications Transported to Groundwater	Moderate to Substantial Improvement	Proper application of manure, compost, and biosolids should reduce or eliminate pathogens and/or chemicals (if present in source material) from moving into ground water.
Air	Emissions of Particulate Matter (PM) and PM Precursors	Slight to Moderate Improvement	The proper application of nutrients will reduce emissions of particulate matter and ammonia.

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TABLE E-3 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Pasture and Hay Planting Practice Standard 512

Resource	Resource Concern	Effect	Rationale
Soil	Sheet and Rill Erosion	Moderate to Substantial Improvement	Establishment of adapted species increases vegetative cover and reduces erosion potential. During the establishment period, there may be a slight to moderate risk of erosion, depending on seedbed preparation, seeding method, and species planted.
Soil	Wind Erosion	Moderate to Substantial Improvement	Establishment of adapted species increases vegetative cover and reduces erosion potential. During the establishment period, there may be a slight to moderate risk of erosion, depending on seedbed preparation, seeding method, and species planted.
Soil	Ephemeral Gully Erosion	Moderate Improvement	Establishment of adapted species increases vegetative cover and reduces erosion potential. During the establishment period, there may be a slight to moderate risk of erosion, depending on seedbed preparation, seeding method, and species planted.
Soil	Compaction	Slight to Moderate Improvement	There will be enhanced biomass production, root development, litter accumulation, increased biological activity, and/or reduced tillage if associated with change in land use.
Soil	Organic Matter Depletion	Moderate to Substantial Improvement	There will be enhanced biomass production, root development, litter accumulation, increased biological activity, and/or reduced tillage if associated with change in land use.

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TABLE E-3 Continued

Resource	Resource Concern	Effect	Rationale
Soil	Aggregate Instability	Moderate to Substantial Improvement	Perennial living plants and roots provide habitat and food for soil organisms.
Air	Emissions of Particulate Matter (PM) and PM Precursors	Moderate Improvement	Establishing permanent vegetation reduces the potential for generation of particulates by wind erosion.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Moderate to Substantial Improvement	Plant species are selected that are well-adapted and compatible to the site providing habitat for terrestrial wildlife and invertebrates.

TABLE E-4 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Grazing Management Practice Standard 528

Resource	Resource Concern	Effect	Rationale
Soil	Sheet and Rill Erosion	Moderate to Substantial Improvement	Improving the health and vigor of plant communities will maintain and increase vegetative cover and decrease erosion by water.
Soil	Wind Erosion	Moderate to Substantial Improvement	Improving the health and vigor of plant communities will increase vegetative cover and decrease erosion by wind.
Soil	Ephemeral Gully Erosion	Moderate Improvement	Improving the vigor of plant communities will speed vegetative recovery when episodic storms cause erosion.
Soil	Compaction	Moderate Improvement	Soil bulk density decreases on long-term basis because of an increase in vegetative cover, deeper root systems, and increased soil organic material. There may be a moderate increase in bulk density in the short term on intensively managed grazing systems.

continued

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TABLE E-4 Continued

Resource	Resource Concern	Effect	Rationale
Soil	Organic Matter Depletion	Moderate to Substantial Improvement	There will be an increase in vegetative cover, deeper root systems, increased soil organic material and biological activity, and improved nutrient cycling.
Soil	Concentration of Salts or other Chemicals	Slight to Moderate Improvement	Bare ground is covered by increased litter and plant bases. Cover reduces evaporative salt accumulation.
Soil	Aggregate Instability	Moderate Improvement	Improving the health and vigor of plant communities by moving animals will increase vegetative cover, organic matter, and soil biology improving aggregate stability.
Water	Ponding and Flooding	Slight to Moderate Improvement	Runoff will be reduced and infiltration increased due to improved vegetative cover, soil health.
Water	Sediment Transported to Surface Water	Moderate Improvement	Management will result in increased plant vigor and cover, decreasing sediment yields.
Air	Emissions of Particulate Matter (PM) and PM Precursors	Moderate Improvement	Improved vegetative cover reduces the generation of particulates.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Moderate to Substantial Improvement	Improve or maintain quantity and quality of forage for grazing and browsing animals' health and productivity, while improving or maintaining the quantity and quality of food and/or cover available for wildlife.

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TABLE E-5 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Soil Carbon Amendment Practice Standard 336

Resource	Resource Concern	Effect	Rationale
Soil	Organic Matter Depletion	Moderate to Substantial Improvement	Carbon-based amendments are added to the soil, improving organic matter depletion. Amount and placement are controlling factors along with tillage and crop rotation.
Soil	Aggregate Instability	Moderate to Substantial Improvement	Carbon-based amendments improve soil structure. Amount and placement are controlling factors along with tillage and crop rotation.
Water	Sediment Transported to Surface Water	Slight Improvement	Carbon-based amendments improve soil physical, chemical, and biological functions, improving plant establishment and decreasing sediment transport.

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TABLE E-6 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Tree and Shrub Establishment Practice Standard 612

Resource	Resource Concern	Effect	Rationale
Soil	Sheet and Rill Erosion	Substantial Improvement	Vegetation and surface litter reduces erosive water energy.
Soil	Wind Erosion	Substantial Improvement	Tall vegetation creates a wind shadow, reduces erosive wind velocities and provides a stable area, which stops saltating particles.
Soil	Ephemeral Gully Erosion	Moderate to Substantial Improvement	Vegetation, surface litter, and roots reduce erosive energy of concentrated flows.
Soil	Compaction	Slight to Moderate Improvement	Root penetration and organic matter help restore soil structure.
Soil	Organic Matter Depletion	Moderate to Substantial Improvement	Establishment of permanent woody vegetation can lead to increased root and shoot development. Decomposition increases soil organic matter.
Soil	Aggregate Instability	Substantial Improvement	Roots of trees and forages physically hold soils; organic matter inputs improve soil stability.
Water	Sediment Transported to Surface Water	Moderate Improvement	Vegetation provides cover, reduces wind velocities, and increases infiltration.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Substantial Improvement	Plants may be chosen and managed to enhance food value and provide cover and shelter for desired wildlife species.

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TABLE E-7 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Upland Wildlife Habitat Management Practice Standard 645

Resource	Resource Concern	Effect	Rationale
Soil	Sheet and Rill Erosion	Moderate Improvement	Establishment of permanent vegetation reduces erosion by water.
Soil	Wind Erosion	Moderate Improvement	Establishment of permanent vegetation reduces erosion by wind.
Soil	Ephemeral Gully Erosion	Moderate Improvement	Establishment of permanent vegetation reduces erosion by water.
Water	Sediment Transported to Surface Water	Slight to Moderate Improvement	There will be improved vegetative cover with a reduction of runoff and sedimentation.
Air	Emissions of Particulate Matter (PM) and PM Precursors	Slight to Moderate Improvement	Vegetative cover reduces wind erosion and fugitive dust generation.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Substantial Improvement	Not applicable.

TABLE E-8 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Water and Sediment Control Basin Practice Standard 638

Resource	Resource Concern	Effect	Rationale
Soil	Ephemeral Gully Erosion	Slight to Moderate Improvement	Controlled flow will reduce gulley erosion down slope of basin.
Water	Ponding and Flooding	Moderate to Substantial Improvement	Basin will collect storm flows and directly reduce, manage runoff. Slight potential to cause undesirable ponding through incorrect design or application.
Water	Sediment Transported to Surface Water	Moderate to Substantial Improvement	Basin retains sediment and minimizes turbidity.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Slight to Moderate Improvement	Surface runoff retained will provide temporary water to wildlife as sediment is trapped, improving water quality in watershed.

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TABLE E-9 PFAS-Relevant Resource Concerns, Effects, and Rationale for Using Watering Facility Practice Standard 614

Resource	Resource Concern	Effect	Rationale
Soil	Sheet and Rill Erosion	Slight to Moderate Improvement	Increased vegetated cover due to better distribution of water reduces soil erosion.
Soil	Wind Erosion	Slight to Moderate Improvement	Increased vegetated cover due to better distribution of water reduces soil erosion.
Soil	Ephemeral Gully Erosion	Slight to Moderate Improvement	Increased vegetated cover due to better distribution of water reduces soil erosion.
Soil	Classic Gully Erosion	Slight Improvement	Increased grass cover due to better distribution of water will retard flows, decreasing opportunity for classic erosion.
Water	Nutrients Transported to Surface Water	Moderate to Substantial Improvement	When used in place of an in-stream water source, this action decreases manure deposition in stream.
Water	Pathogens and Chemicals from Manure, Biosolids, or Compost Applications Transported to Surface Water	Slight to Moderate Improvement	Improved vegetation due to better distribution of animals will filter and reduce water-borne contaminants. In addition, better distribution of animals results in less concentration of contaminants.
Water	Pathogens and Chemicals from Manure, Biosolids, or Compost Applications Transported to Groundwater	Slight Improvement	The action tends to concentrate animals; however, getting animals out of the stream will keep them cleaner and reduce contact with manure-borne pathogens.
Water	Sediment Transported to Surface Water	Slight to Moderate Improvement	Water development will decrease livestock trampling in wet areas and nearby streams.

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TABLE E-9 Continued

Resource	Resource Concern	Effect	Rationale
Water	Petroleum, Heavy Metals, and Other Pollutants Transported to Surface Water	Slight Improvement	Improved vegetation due to better distribution of water will filter and reduce water-borne contaminants. In addition, better distribution of animals results in less concentration of contaminants.
Animal	Inadequate Livestock Water Quantity, Quality, and Distribution	Substantial Improvement	Facilities supply water at remote locations.
Animal	Terrestrial Habitat for Wildlife and Invertebrates	Slight to Moderate Improvement	Provides dependable water supply to livestock and wildlife in areas where surface water is scarce.

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