

PFAS IN LAND APPLIED BIOSOLIDS - CHALLENGES & MANAGEMENT OPTIONS

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PFAS in Land Applied Biosolids - Challenges & Management Options



PFAS Basics: The what, where, and why of PFAS

A few PFAS Basics to Understand Fate

Fate with land application examples

Plant uptake snapshots and mitigation strategies

Key Take-Aways

PFAS ARE PERVASIVE IN OUR PROCESSES AND PRODUCTS

Used in numerous products & processes due to their unique properties



PFAS BRAND NAMES

- Teflon
- Scotchguard
- Stainmaster
- Stainsafe
- Silverstone
- Polartec
- Texapore
- Gore-Tex



- “nonstick”
- “water-repellent”
- “weather-protective”
- “stain-resistant”
- “fluoro” or “perfluoro”

PFAS WORDS to AVOID

Industries & Infrastructures

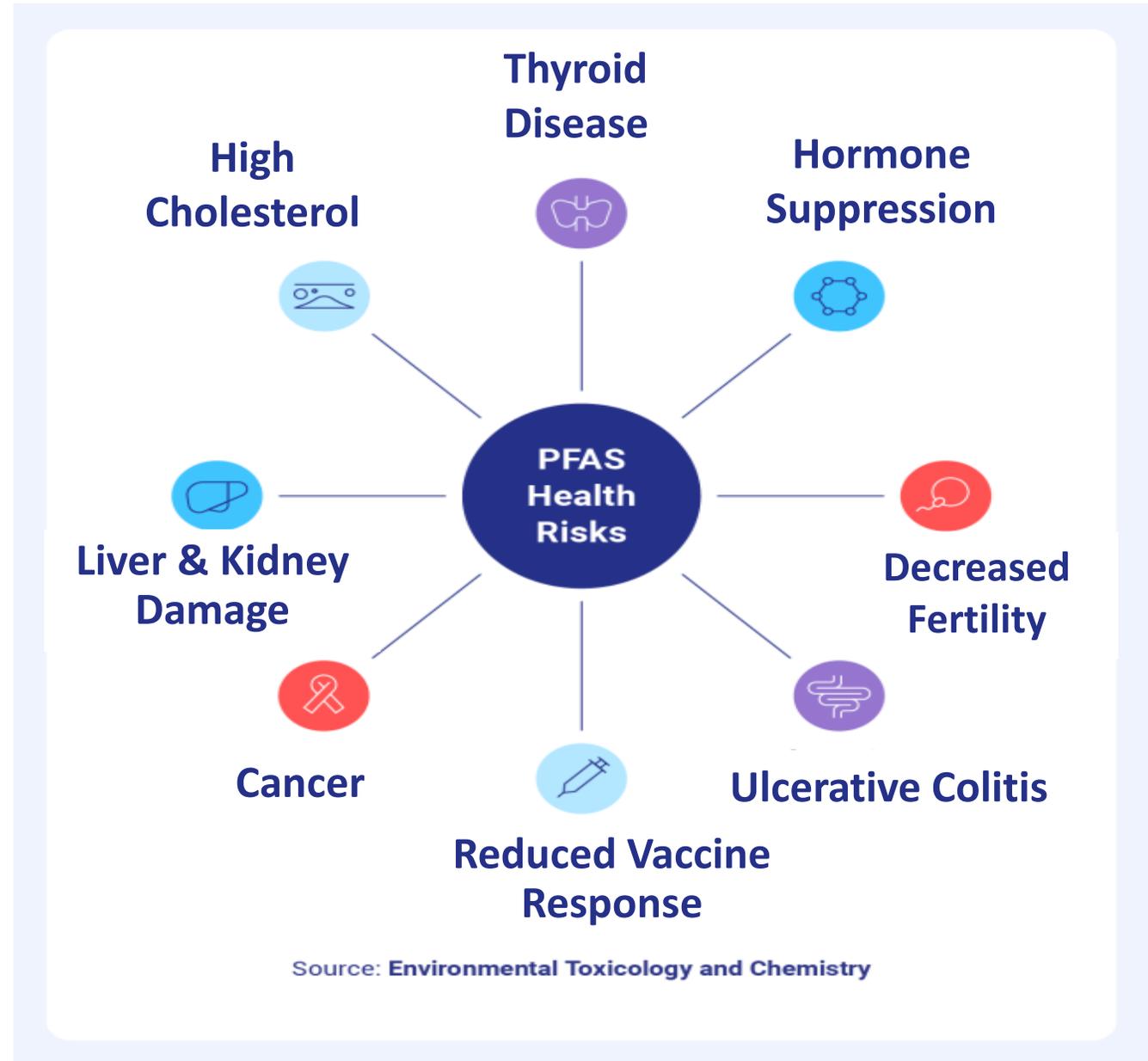
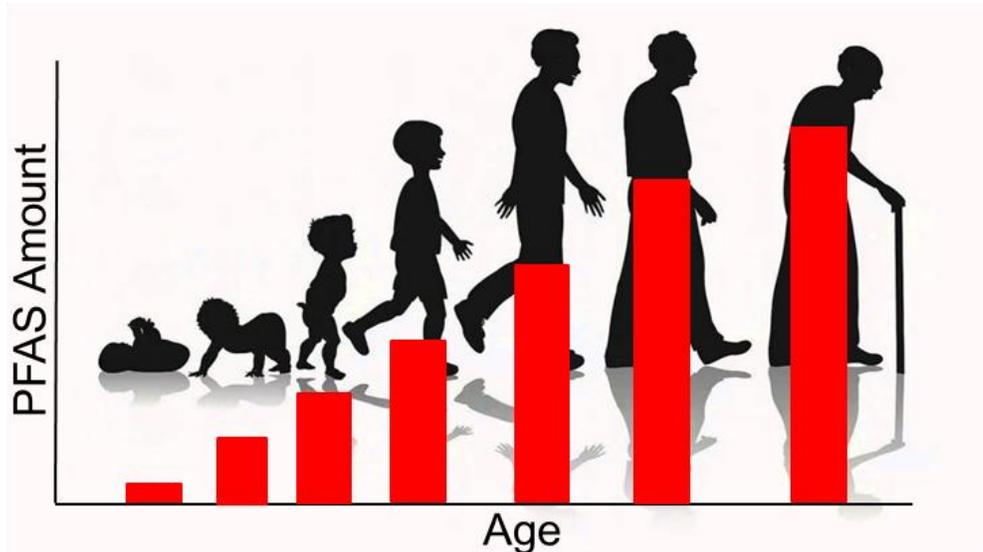
- Municipal water and waste treatment
- Industrial manufacturing of PFAS
- Oil and gas operations
- Metal plating and coating
- Aviation and transportation fire extinguishing

Products

- Water, oil, and stain-resistant textile
- Floor coatings and cleaners
- Food wrappers
- Pharmaceuticals & Personal care products
- Aqueous Film-Forming Foams (AFFFs)

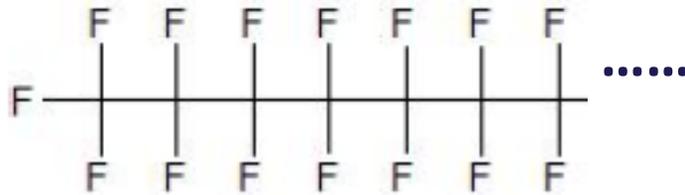
WHY THE GROWING CONCERN ABOUT PFAS?

- PFAS are **persistent**
- PFAS **bioaccumulate** in humans , plants, and animals
- Some PFAS **biomagnify** up the trophic chain
- Exhibit **toxicity**

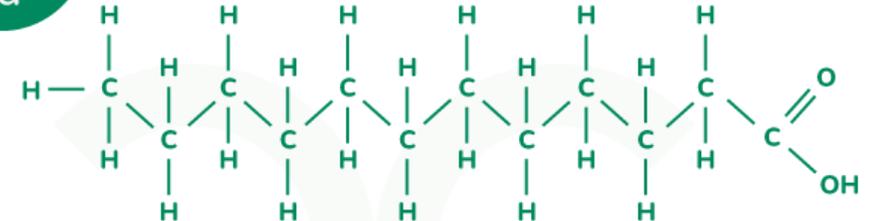


PFAS: PER- & POLYFLUOROALKYL SUBSTANCES – A LARGE SYNTHETIC DIVERSE CHEMICAL FAMILY

> 15,000 PFAS produced



Fatty Acid



- Fluorine-saturated chain of varying length
- Numerous subclasses
 - Each has a unique differentiating characteristic
 - Each with several different perfluoroalkyl chain lengths
- An individual PFAS like PFOS may be multiple molecules (isomers, same atoms but different arrangements)

TIME

NOV 26, 2025 9:52 AM ET

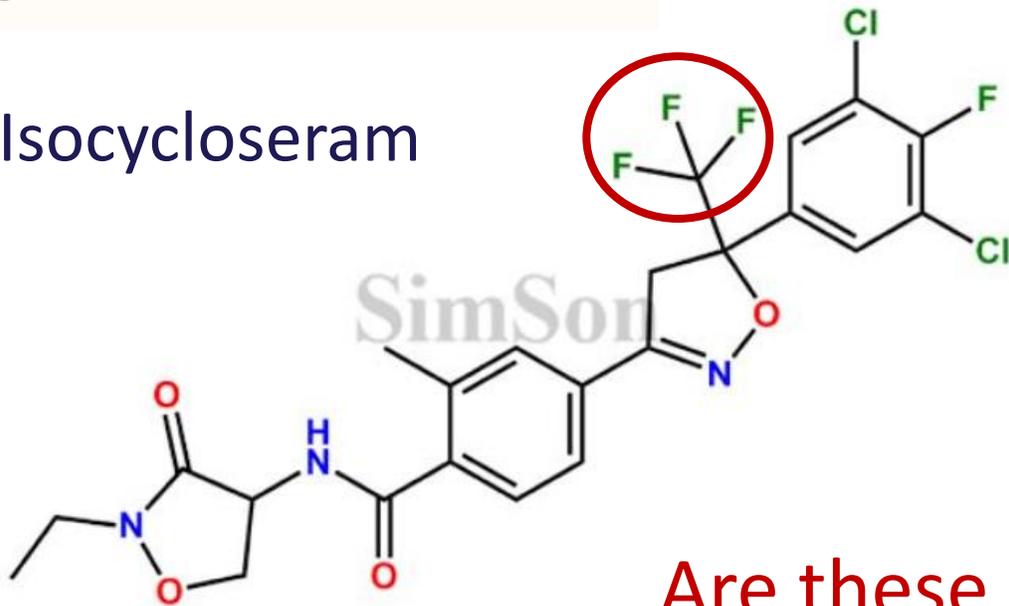
The EPA Is Embracing
PFAS Pesticides.
These Are The Health
Risks

Is it a PFAS or not?

It is all about definition. Two main ones:

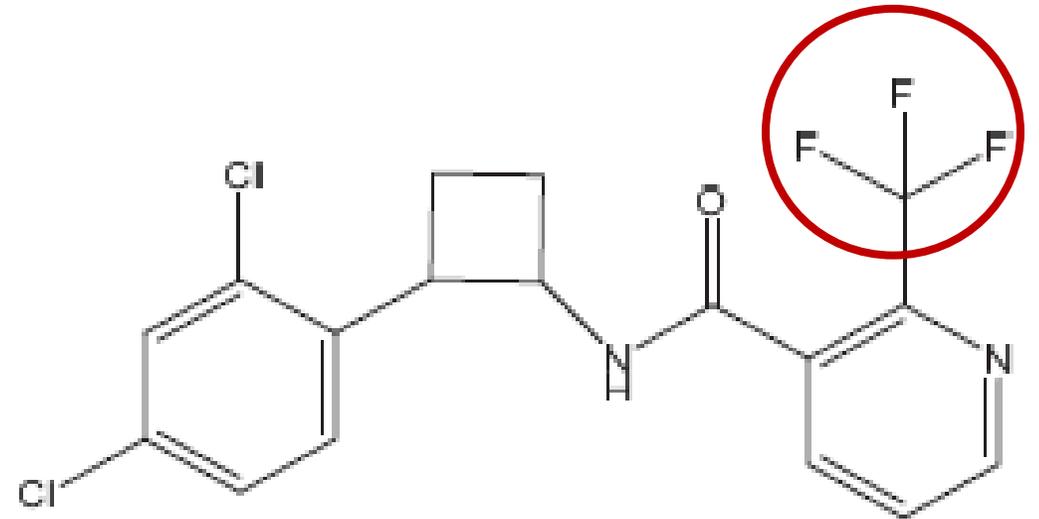
- *European Union - one perfluorocarbon*
- *EPA- two adjacent carbon atoms,*

Isocycloseram



Are these PFAS?

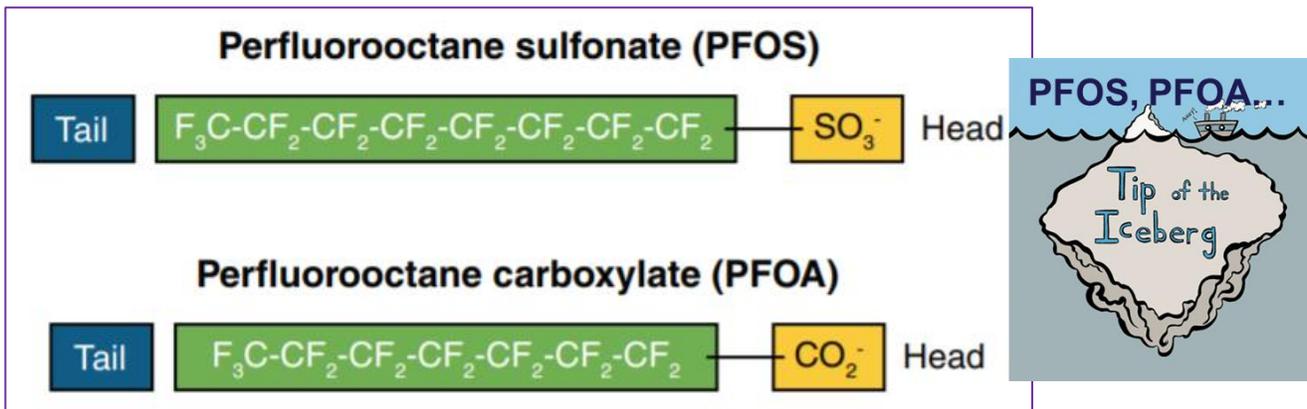
Only by EU definition



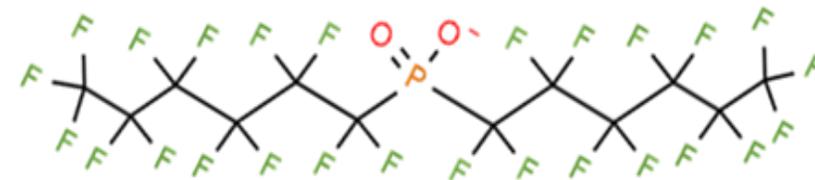
Cyclobutrifluram

PER VERSUS POLYFLUOROALKYL SUBSTANCE

Per-

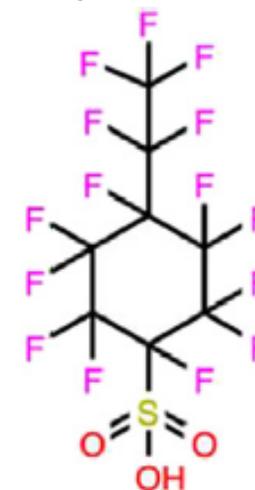


PFAS 'Replacements'

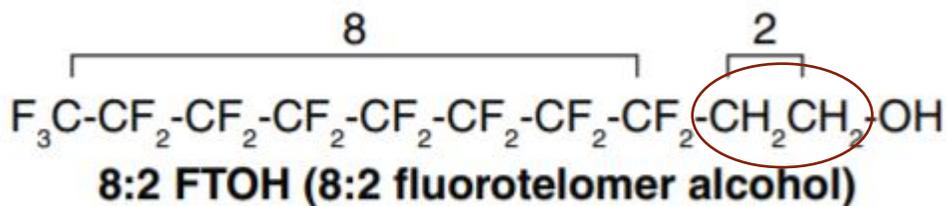


6:6 perfluorophosphinate (6:6 PFPI)

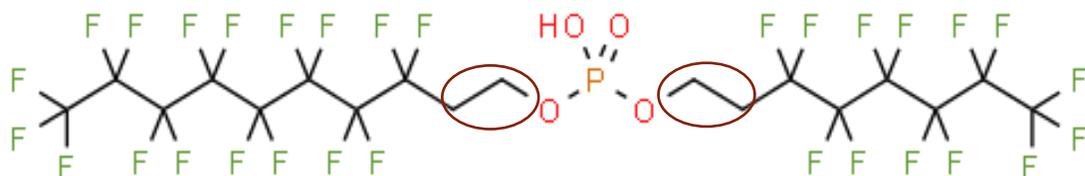
Perfluoroethylcyclohexane
sulphonate (PFECHS)
erosion inhibitor in
aircraft hydraulic fluids



Poly-

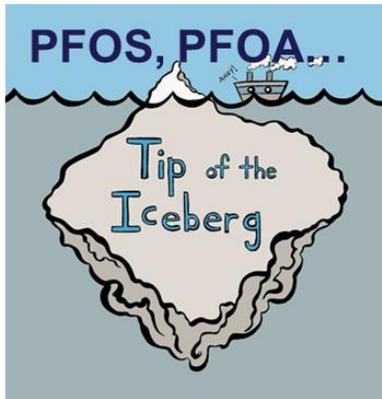


6:2 Fluorotelomer sulfonate (6:2 FTS)



8:2 Fluorotelomer perfluoroalkyl phosphate diester (8:2 diPAP)

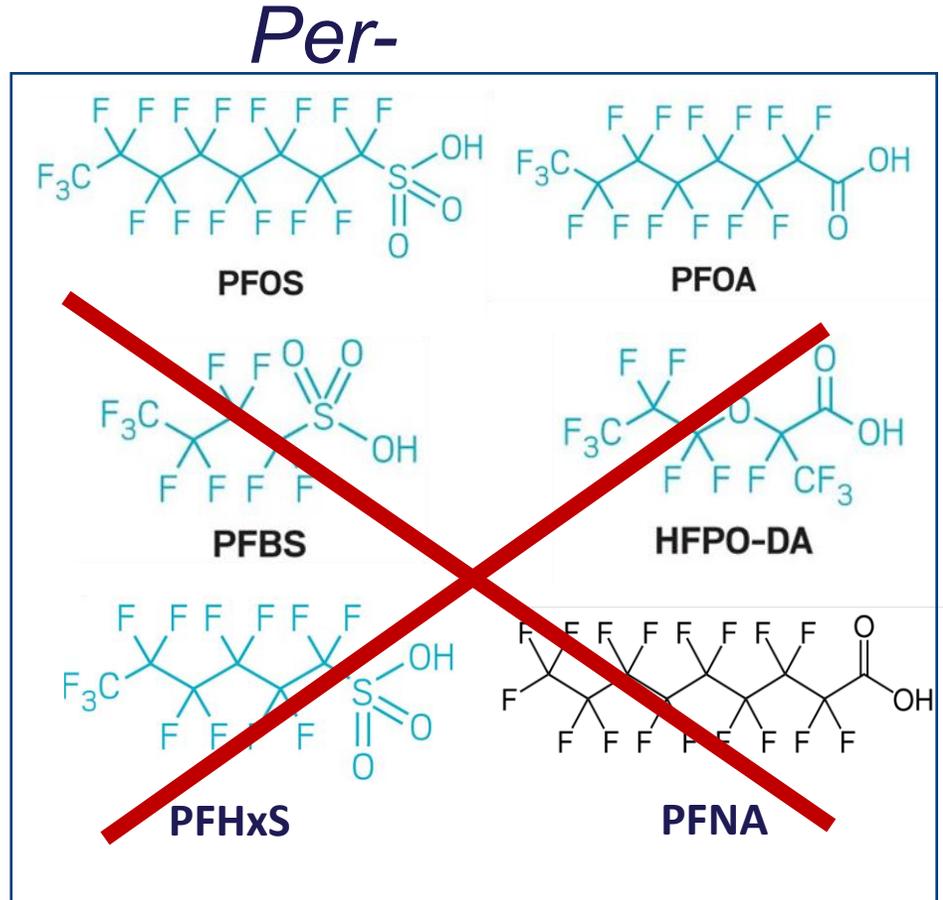
APRIL 10, 2024 U.S. EPA SETS PFAS MAXIMUM CONCENTRATION LEVELS (MCLS) IN PPT (NG/L)



PFAS	MCLG	MCL (enforceable levels)
PFOA (C8)	Zero	4.0 ppt
PFOS (C8)	Zero	4.0 ppt
PFNA (C9)	10 ppt	10 ppt
PFHxS (C6)	10 ppt	10 ppt
PFBS (C4)	1000 ppt	1000 ppt
HFPO-DA (GenX Chemicals)	10 ppt	10 ppt
Mixtures of 2 or more PFNA, PFHxS, PFBS, and HFPO-DA	1.0 (unitless) Hazard Index Σ MCL/measured concentration	

MCLG = maximum contaminant level goals

EPA 1633A Method:
'40 PFAS' Targeted



Rescinded for now

Units in the PFAS World

Water
(ng/L)

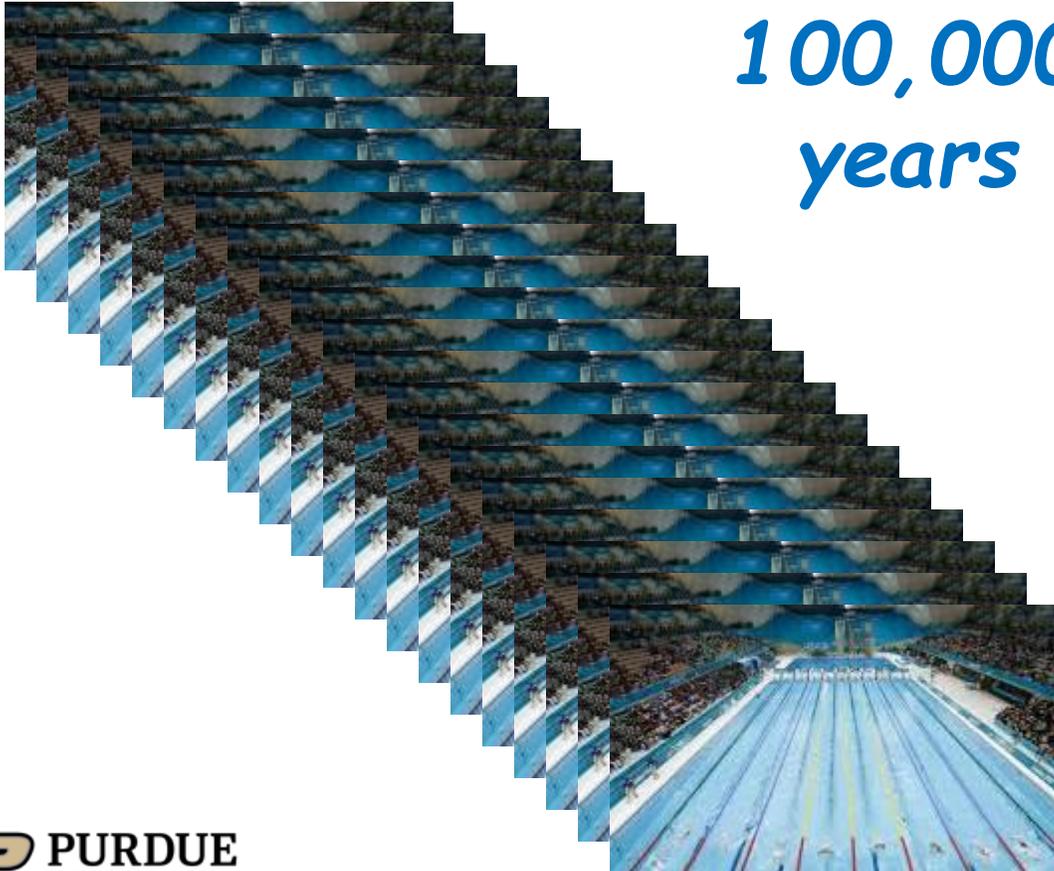


Bioaccumulation, Sorption

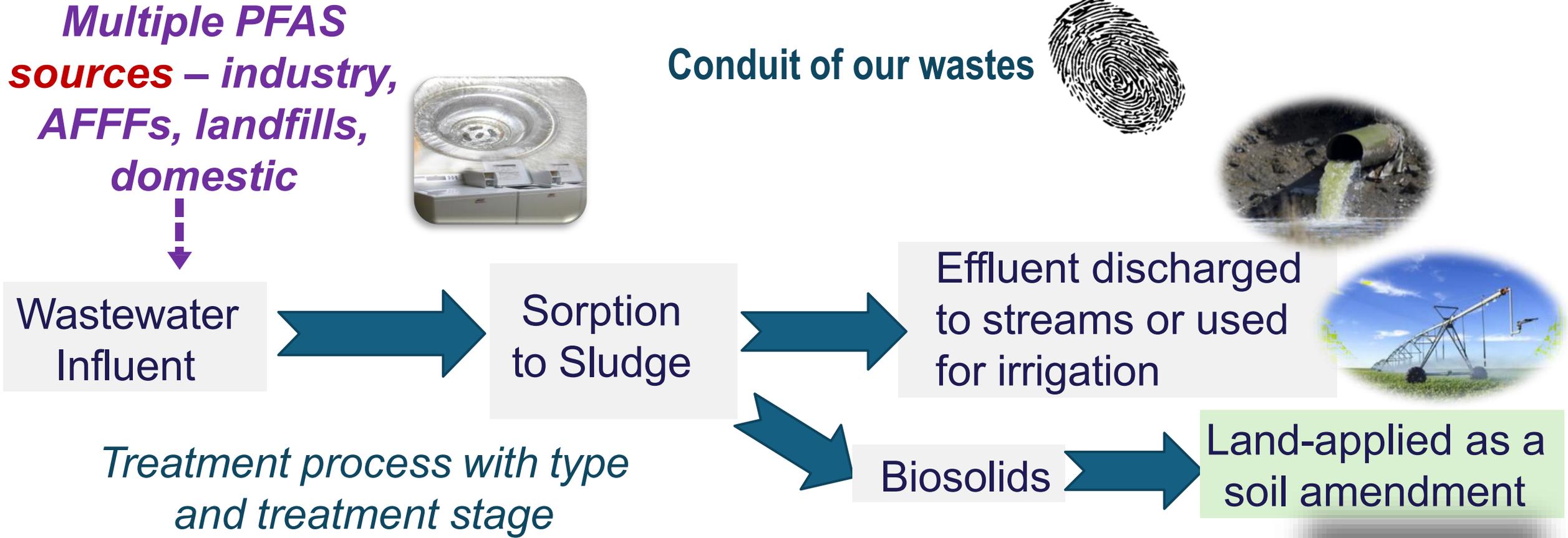
X 1000

*3 sec in
100,000
years*

**versus
Blood, Biota,
Soil, Biosolids
ppb (ng/g)**



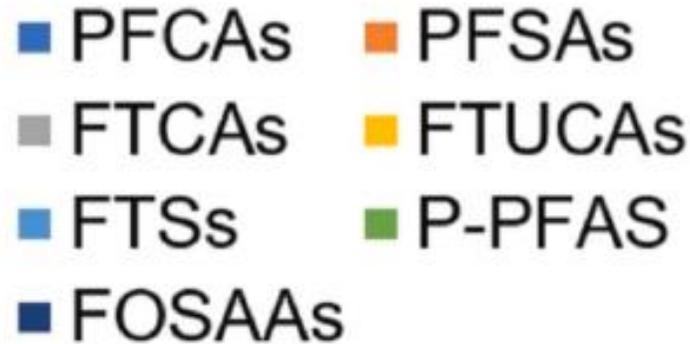
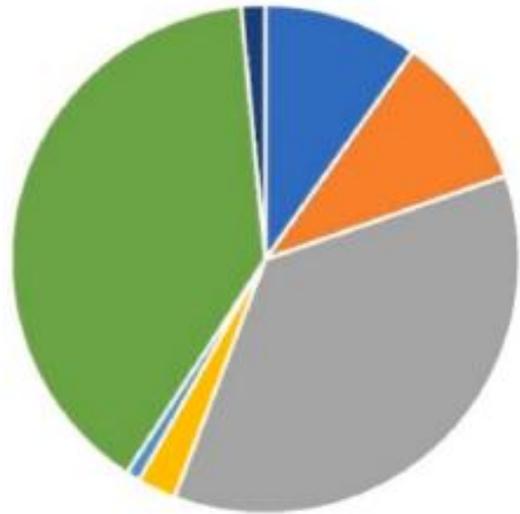
THE CHALLENGE: MANAGING PFAS IN WASTEWATER AND BIOSOLIDS MANAGEMENT



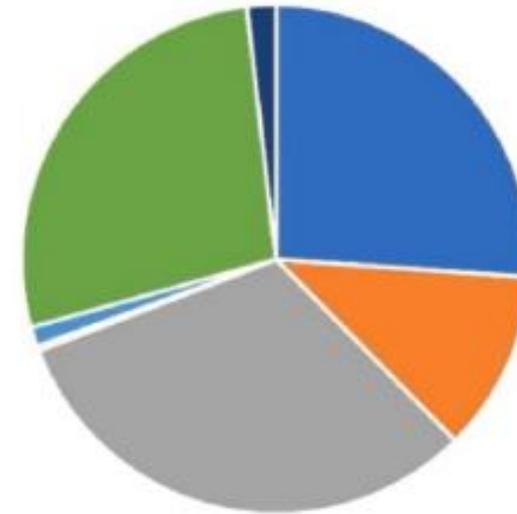
PFAS enter our wastewater treatment plants and then exit via effluent or sludge (or air) unaffected or transformed to other PFAS

PFAS Transformation in Solids Processing: Example for Anaerobic Digestion (AD)

Before Digestion



After Digestion



- Bulk of the PFAS are precursors (**green**) and intermediates (**gray**) and most not measured in the current USEPA 40 targets list in the USA
- Digestion to remove pathogens, etc. leads to PFAS conversion to PFAAs (**orange** and **blue**)
- Aerobic >> anaerobic transformation rates

Alukkal, Lee et al., 2024a,b

<https://doi.org/10.1016/j.chemosphere.2024.143406>

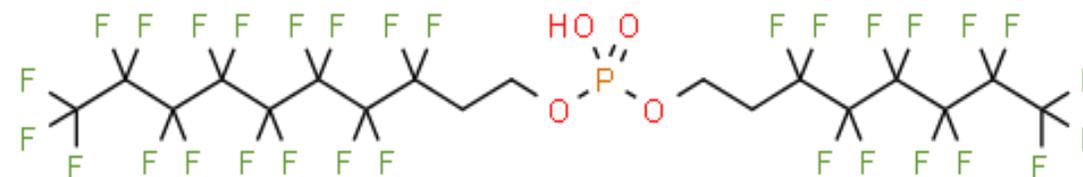
<https://doi.org/10.1016/j.chemosphere.2024.143357>

PFAS RANGES IN 2018-2025 USA BIOSOLIDS (PPB DRY WT)

	PFAS	~Min	~Max
Perfluoroalkyl acids (PFAAs) - terminal metabolites	PFOS	< LOD	130
	PFHxS	< LOD	50
	PFOA	< LOD	30
	PFHxA	< LOD	30
Precursors/intermediates	6:2 FTS	< LOD	15
	8:2 FTS	< LOD	30
	MeFOSAA	< LOD	100
	EtFOSAA	< LOD	50
PFAA intermediates	7:3 FTCA	< LOD	100
	5:3 FTCA	< LOD	220
	3:3 FTCA	< LOD	220

Some Additional Common Precursors

PFAS	~Min	~Max
6:2 diPAP	10	400
8:2 diPAP	0	200
6:2 PAP	20	350
6:6 PFPI	0	10
6:8 PFPI	0	10



- For most utilities, identified precursors are typically at least 75% of the quantifiable PFAS fluorine mole balance

Comment on PFAS Loads in Effluent Discharge

- Sanitation district-specific
- 40-90% of the total PFAS load leaving WWTPs
- Variation in the PFAS analyte list affects trends

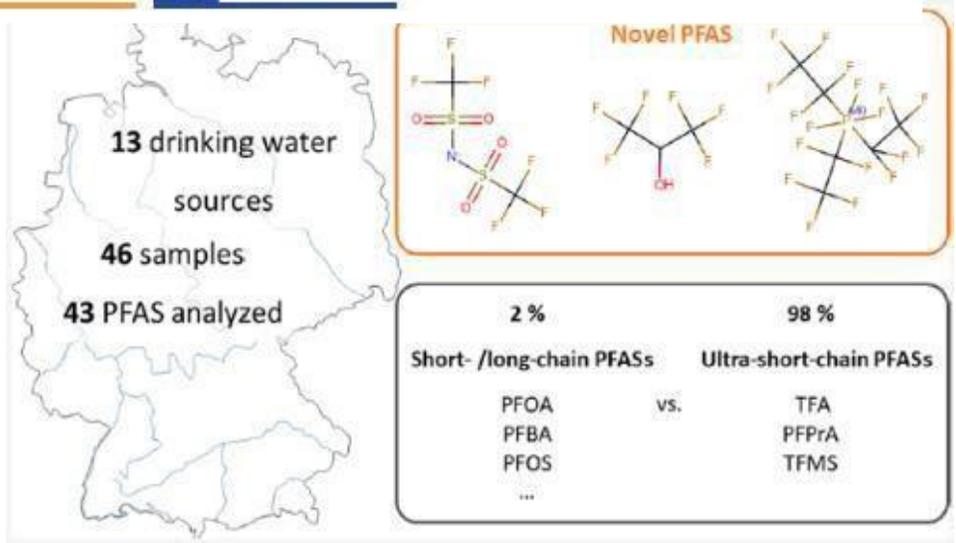
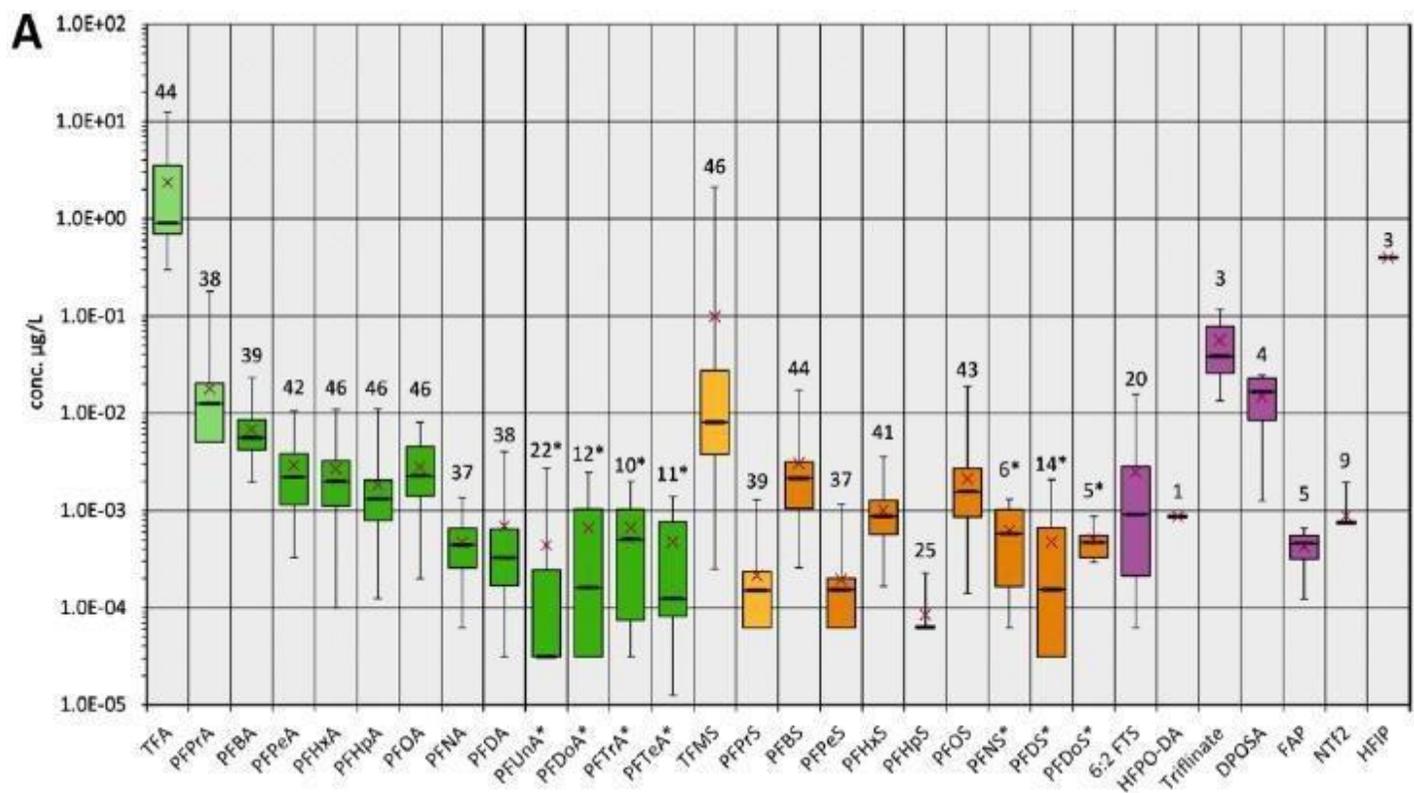
COMMENT ON ULTRA-SHORT CHAIN PFAS

Ultra-Short-Chain PFASs in the Sources of German Drinking Water: Prevalent, Overlooked, Difficult to Remove, and Unregulated

Isabelle J. Neuwald, Daniel Hübner, Hanna L. Wiegand, Vassil Valkov, Ulrich Borchers, Karsten Nödler, Marco Scheurer, Sarah E. Hale, Hans Peter H. Arp, and Daniel Zahn*

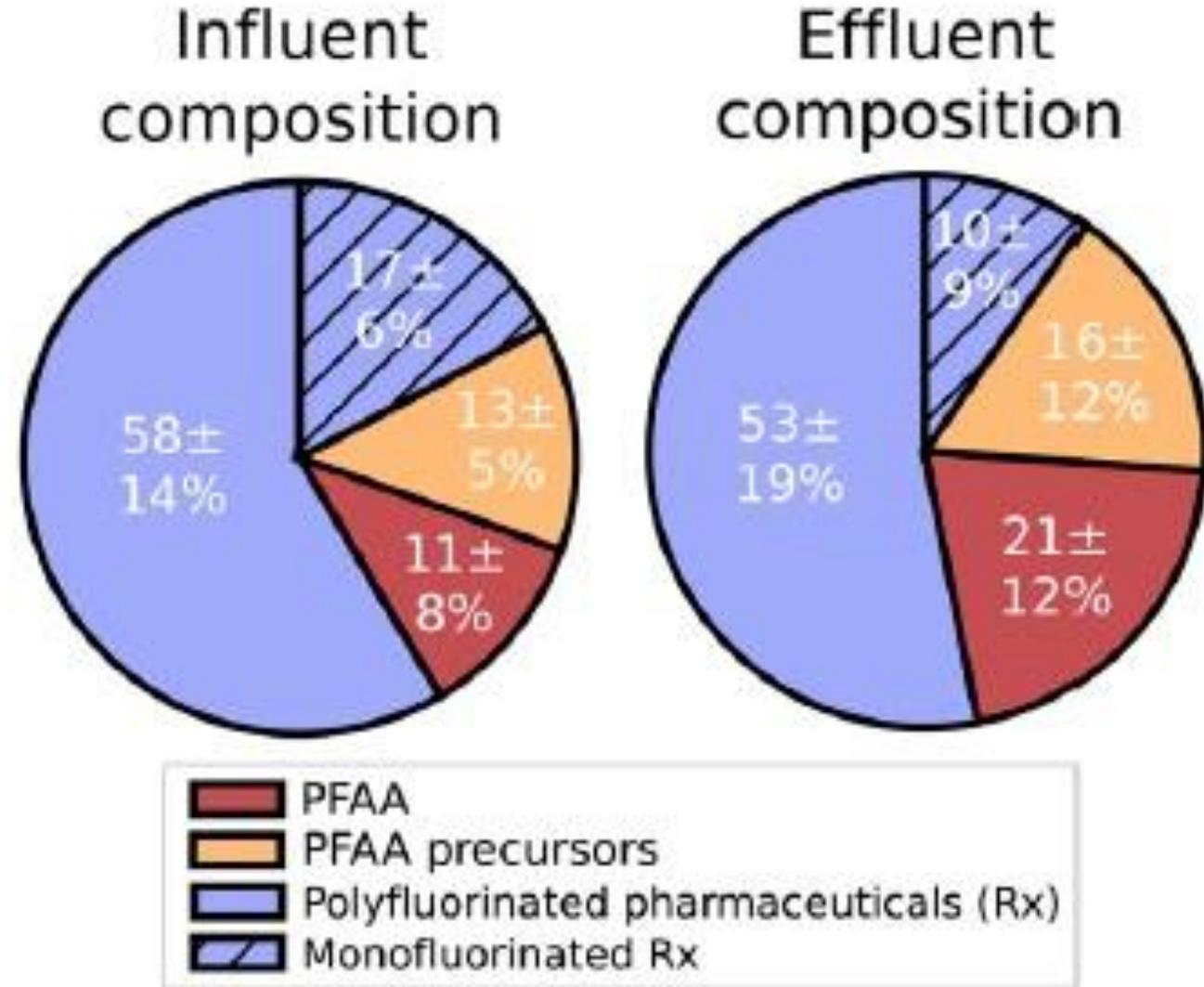
 Cite This: *Environ. Sci. Technol.* 2022, 56, 6380–6390

 Read Online

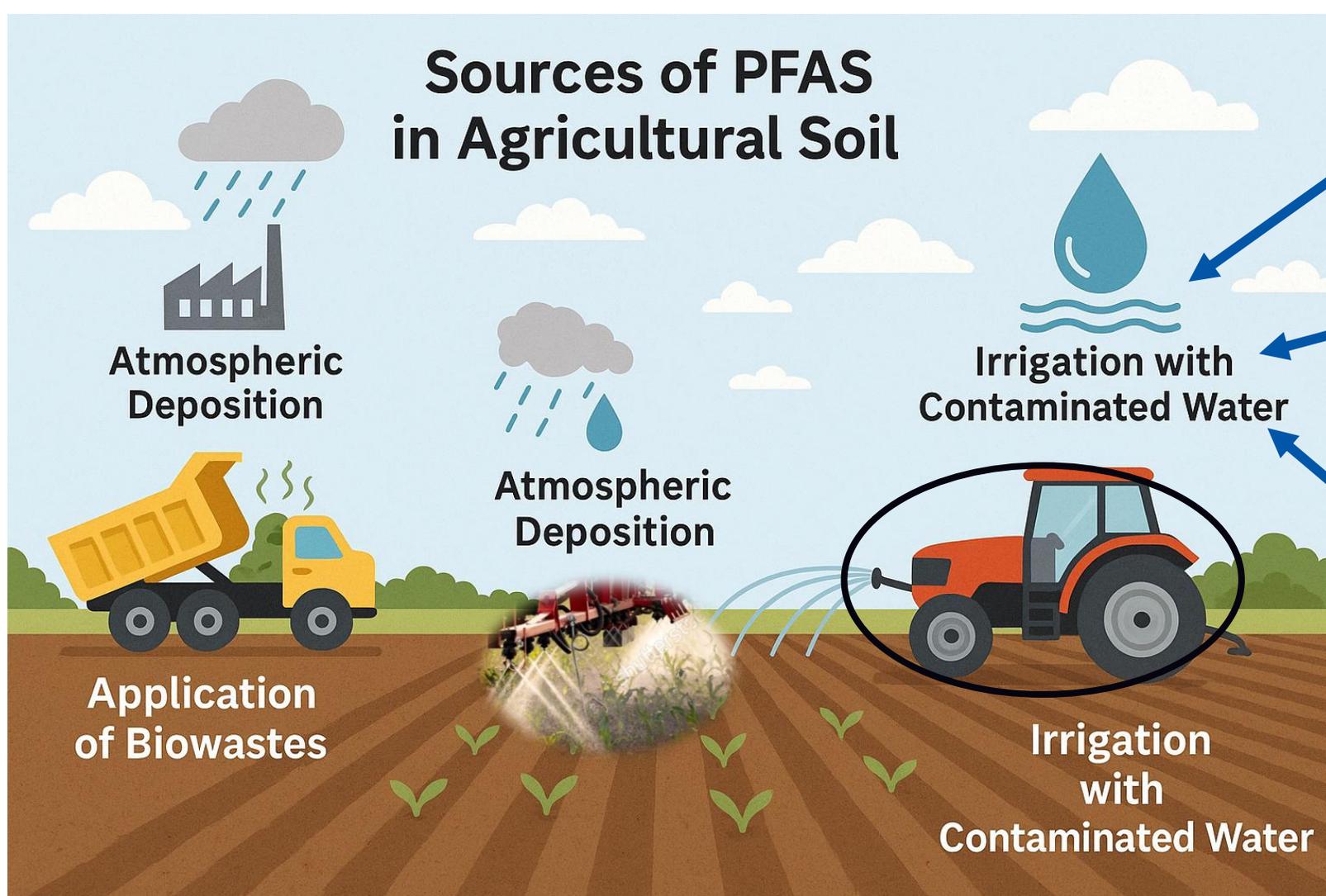


COMMENT ON UNDERSTAND TOTAL ORGANO-FLUORINE SOURCES

- Only about 25% may be PFAS
- Fluorinated pharmaceuticals make up the bulk of organofluorine in wastewater (8 facilities)
- Total organo-fluorine does not change much between influent and effluent



Sources of PFAS in Agricultural Soil



Most common PFAS source in agriculture is inadvertent through biosolids application as fertilizers, a great source of carbon and slow-release nutrients

PFAS Fate after Discharge/Application to Land

Sources to Agriculture



PFAS Fate

Chemical Properties

Soil Properties

Air-water interface accumulation (PFAS)

Solid Phase adsorption

Biotransformation

Plant Uptake

Leaching

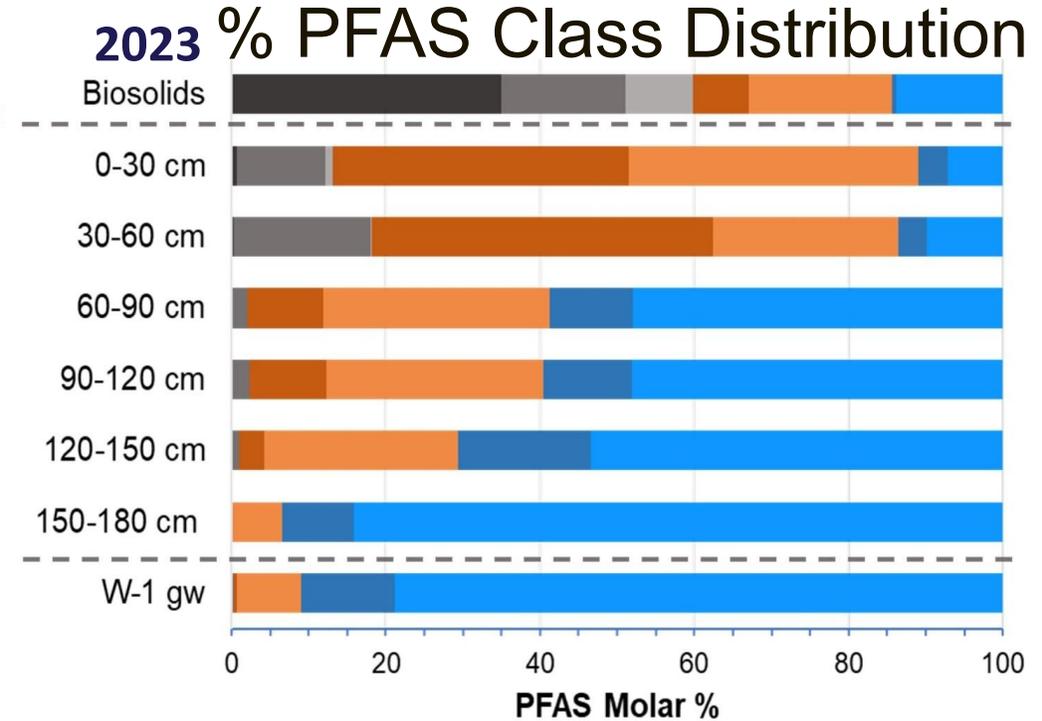
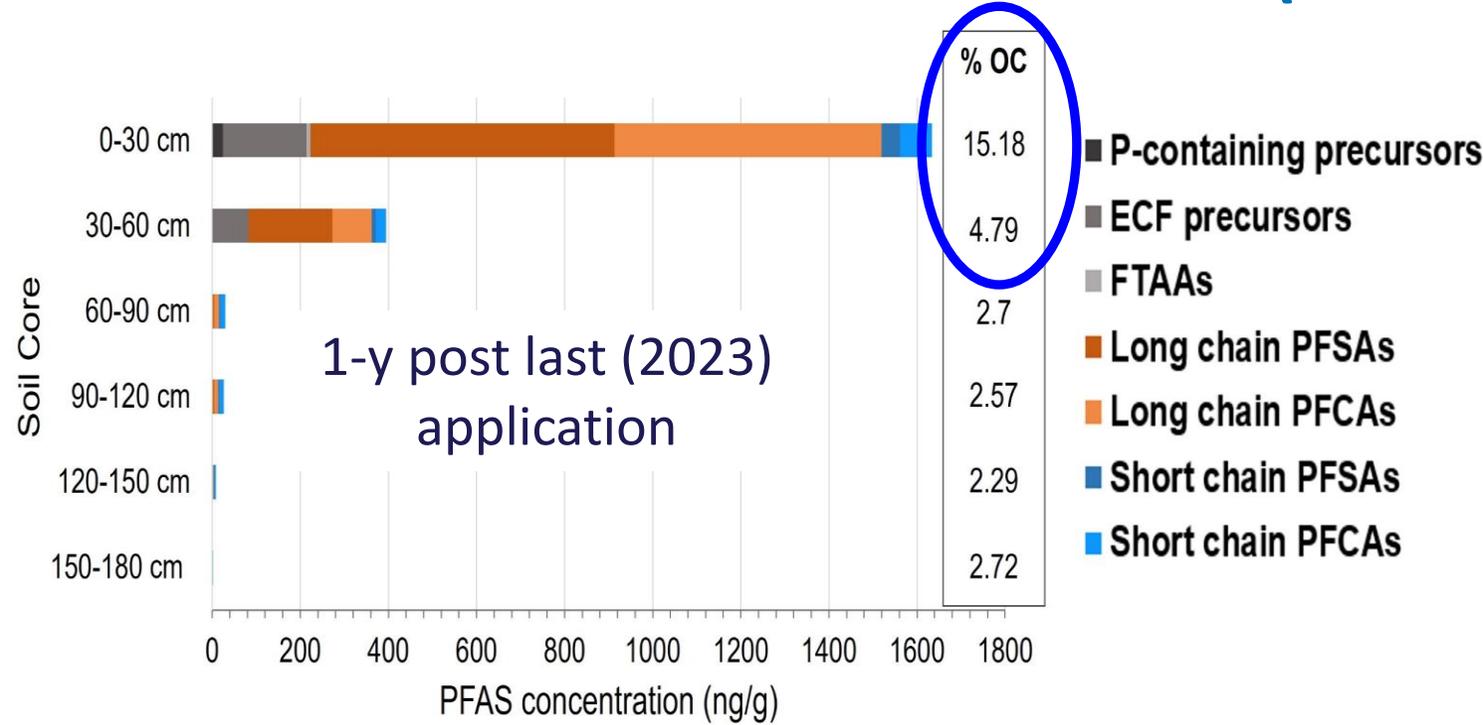
Runoff

Tile-drain discharge

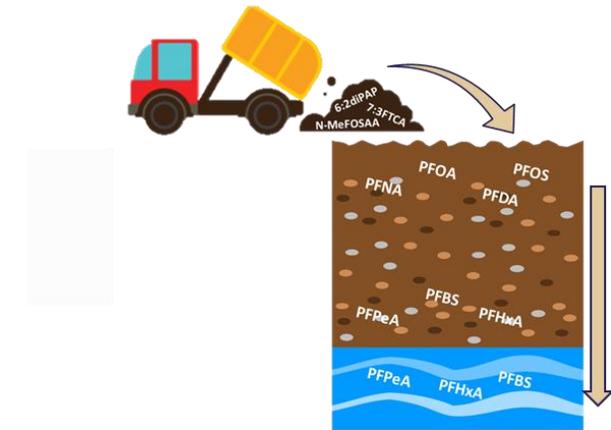


Peter, L. & Lee, L.S. 2025. PFAS as contaminants in agricultural soils, Chapter 3 IN: Contaminants in agricultural soils: Challenges and solutions (ed. Laureate Prof. Ravi Naidu), burleigh dodds Science Publishing, <http://dx.doi.org/10.19103/AS.2025.0151.03>

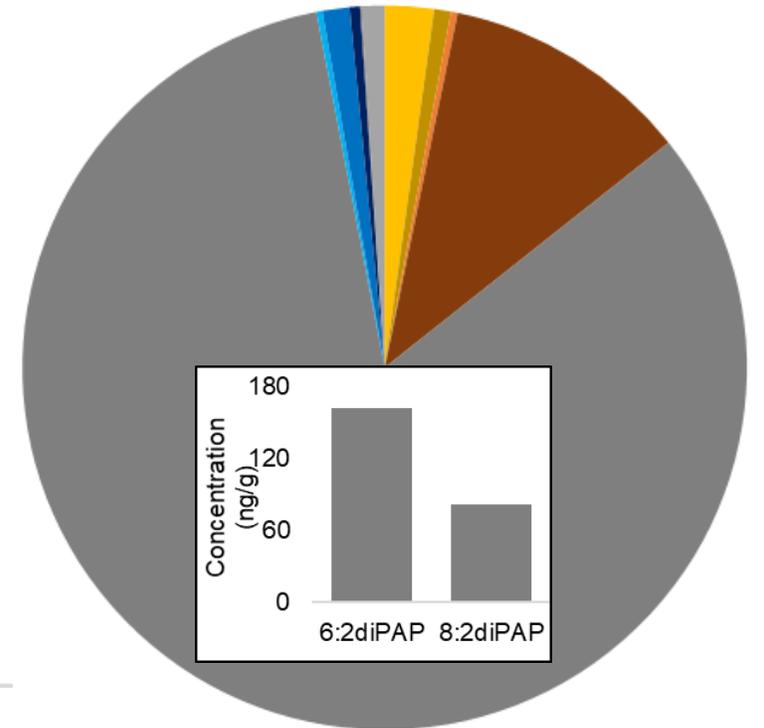
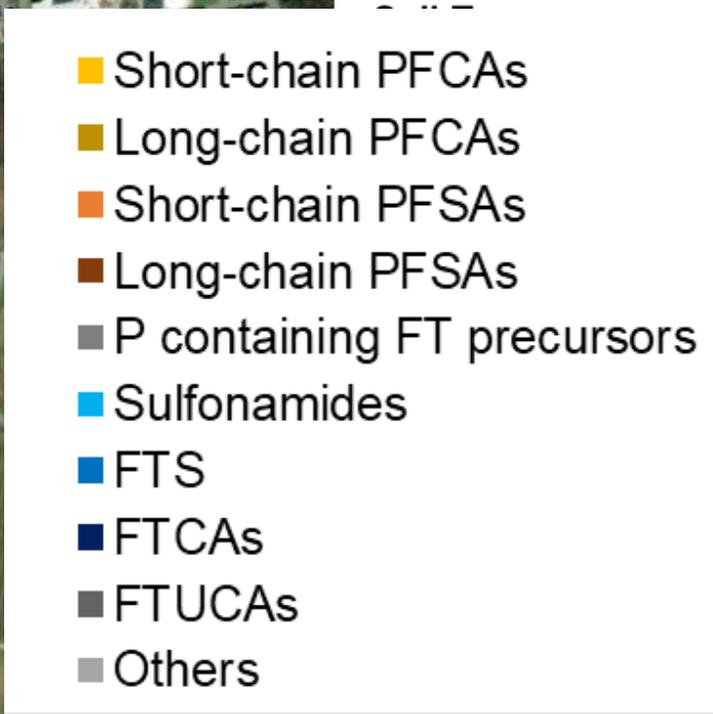
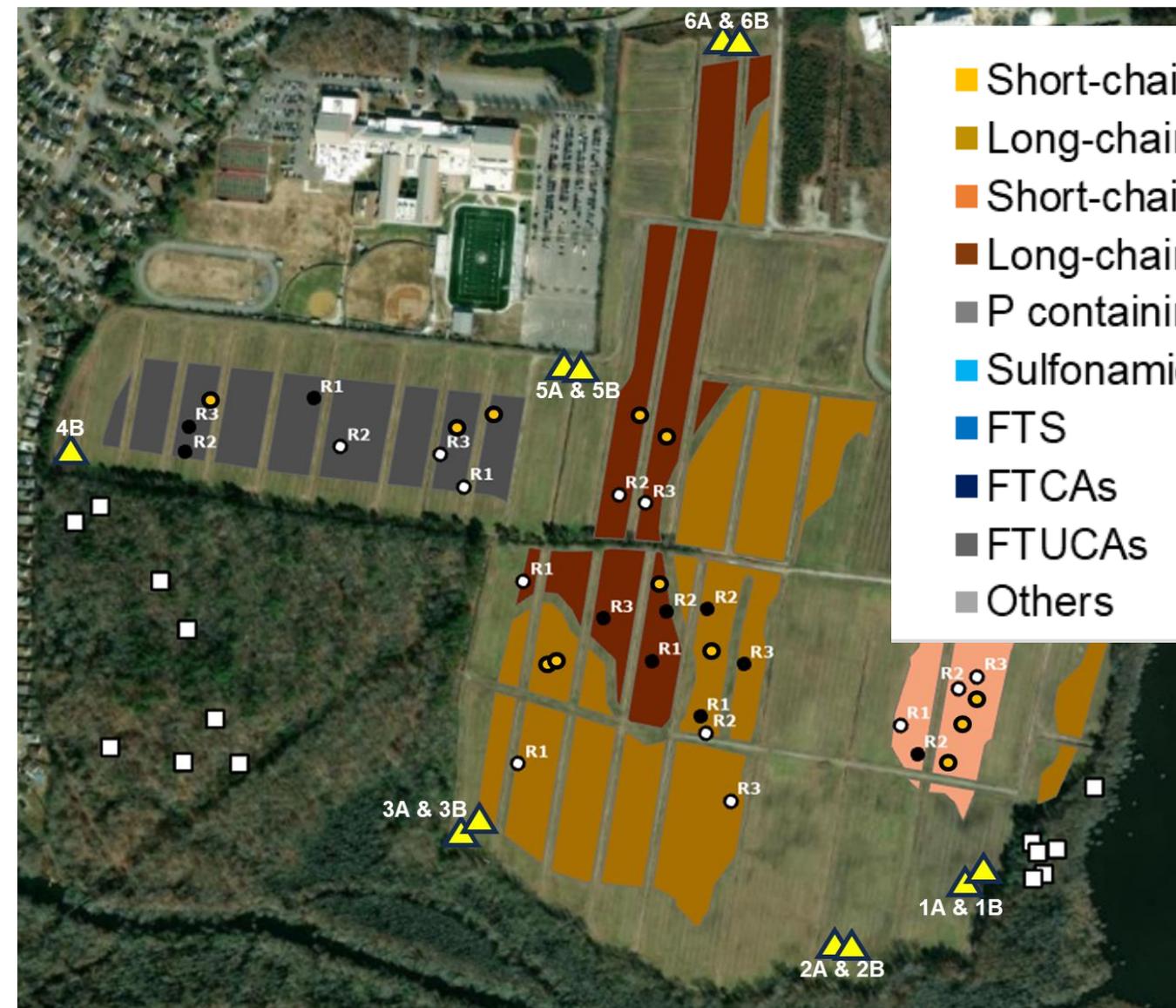
40-Y SURFACE DISPOSAL SCENARIO (CA SITE 1 USA)



- Annual and high biosolids application rates led to PFAS and organic carbon (% OC) accumulation in soil over time
- Long-chain PFAS retained in the upper soil profile
- Most precursors degrade to PFAAs within 1 year
- Short-chain PFAAs dominate what is getting to groundwater



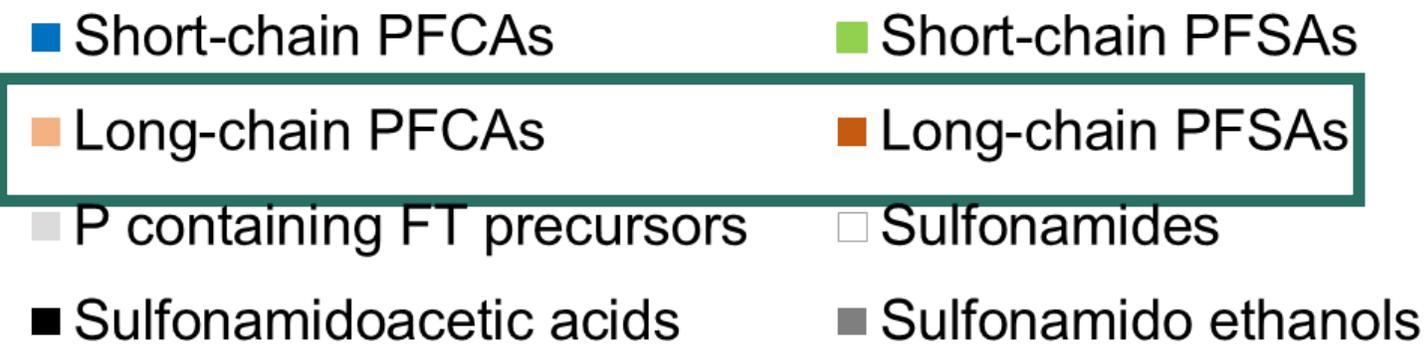
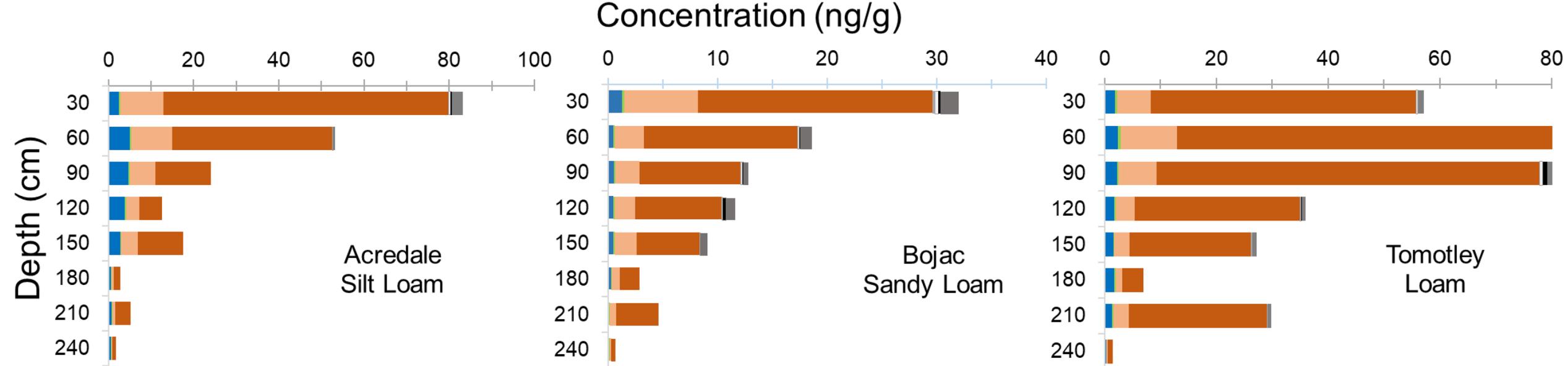
38-Y AGRONOMIC BIOSOLIDS APPLICATION VA, USA STUDY SITE



- 3 soil types – low to high permeability
- Class B biosolids application 1986 – 2014
- Mostly Corn/soybean rotations – animal feed
- Switch to Class A in 2023 (after a 9-y pause)
- PFAS in 2023 biosolids mostly diPAPs

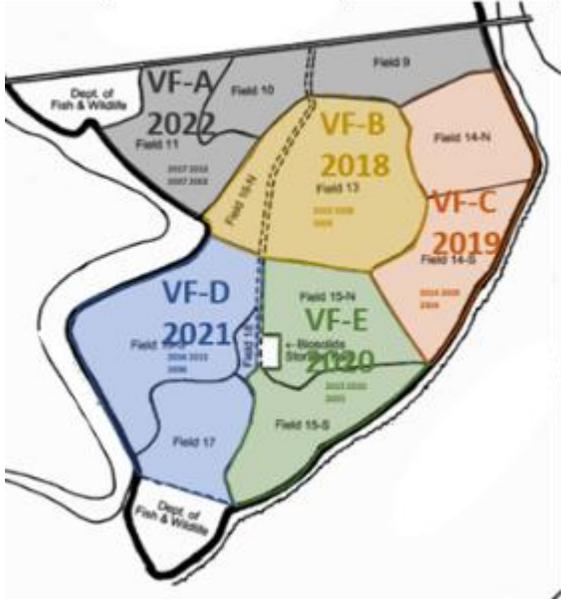
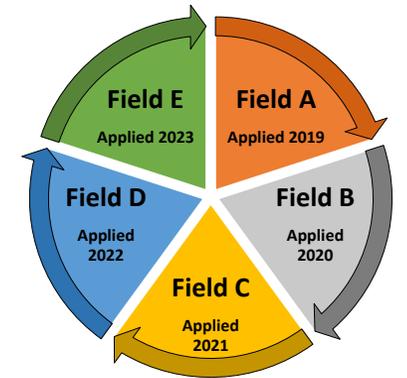
38-Y AGRONOMIC BIOSOLIDS APPLICATION, HRSD VA STUDY SITE

DISTRIBUTION WITH DEPTH



- Long-chain PFASs (**oranges**) persist, mobility limited
- Textural driven processes evident
- Post-2023 application no different than Acredale reference site (*not shown*)
- *MWs mostly < 20 ppt Total PFAS*

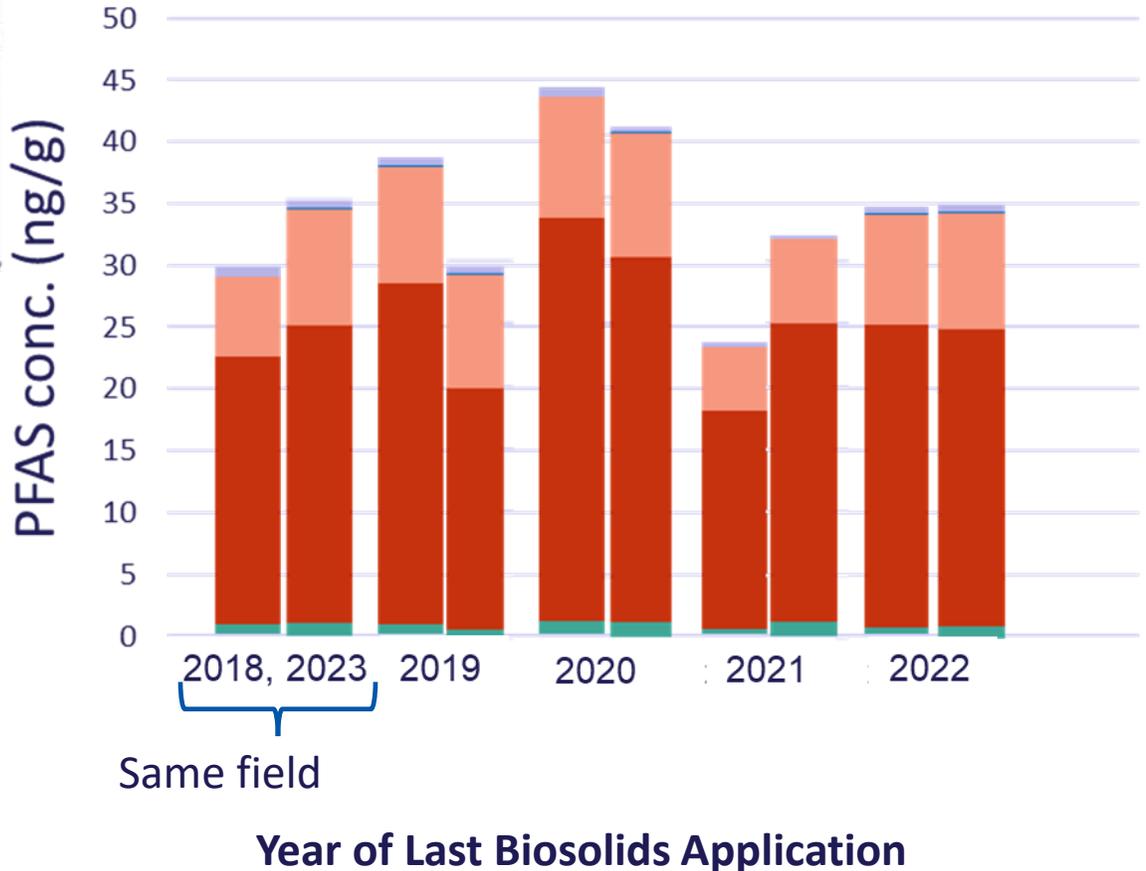
West Coast Site: 5-year Biosolids Application Cycle PFAS snapshot



- 274 acres application rate 73 yds/acre
- 275 acres application rate 73 yds/acre
- 260 acres application rate 77 yds/acre
- 268 acres application rate 75 yds/acre
- 340 acres application rate 59 yds/acre

Surface Soil Sampling Times twice:

- Pre-2023 biosolids application
- In 2024, post 2023 application



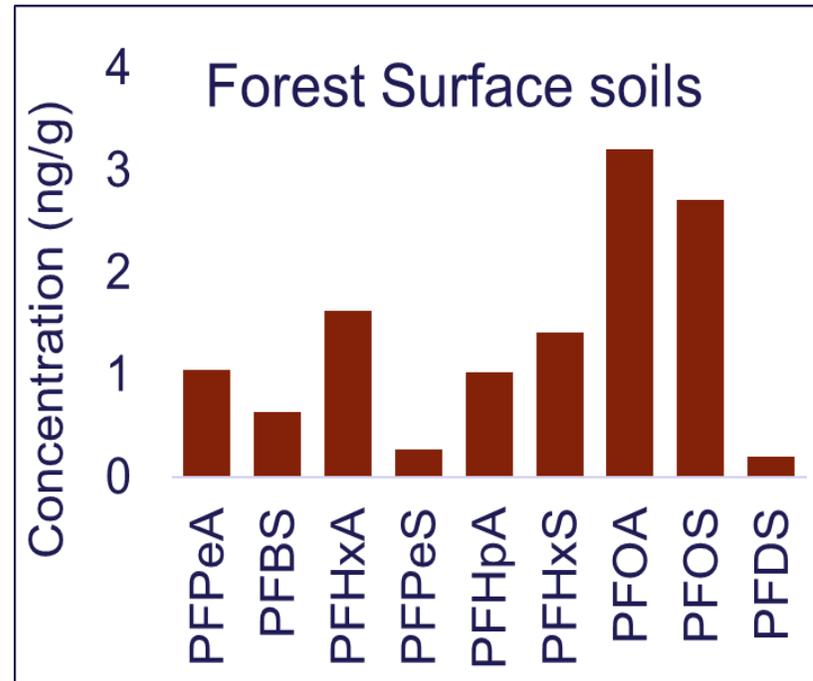
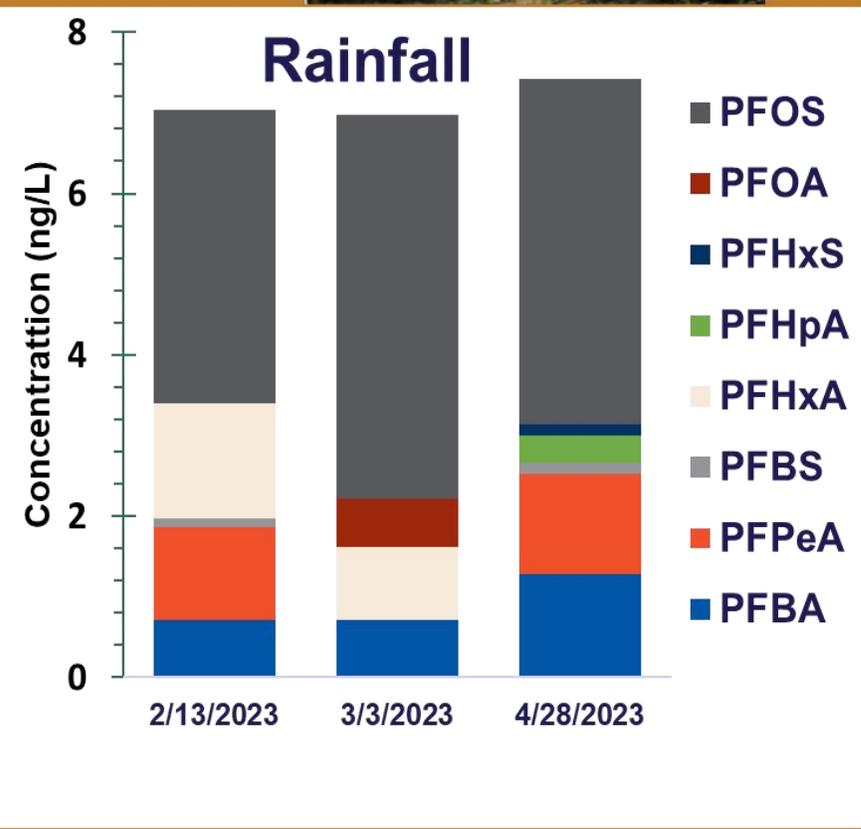
- P-containing precursors
- Fluorotelomers
- ECF precursors
- long chain PFSA
- long chain PFCA
- short chain PFSA
- short chain PFCA

OTHER PFAS SOURCES EXEMPLIFIED FOR THE VA, USA STUDY SITE

Wet/dry deposition



- Rainwater had PFAS signature
- Military base, airport within 5-mi radius
- Multiple PFAS source receiving Lake borders

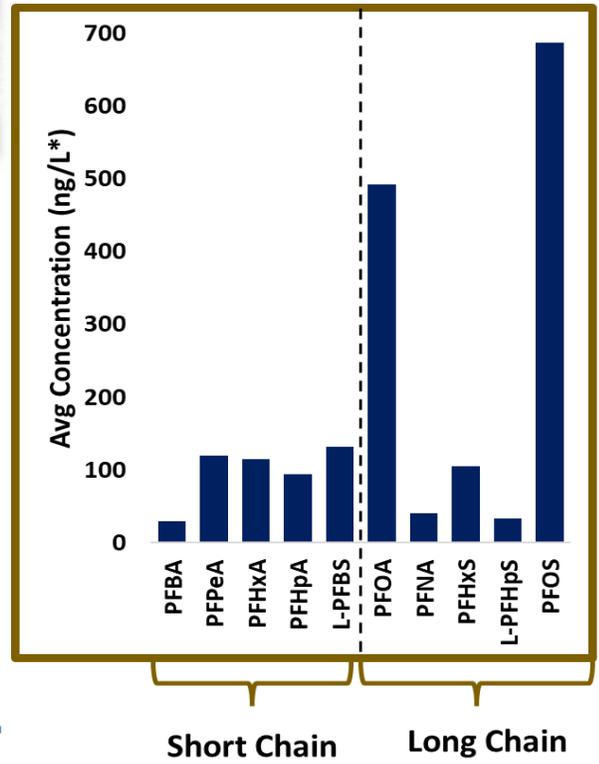
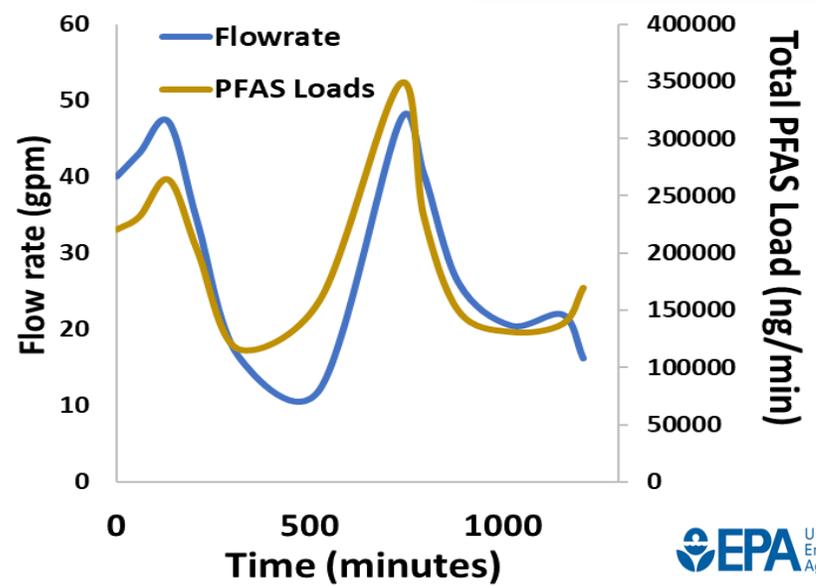


- Forest soil with no history of biosolids application similar to PFAS signature in rainwater
- Note: These soil concentrations are much higher than observed at sites with recent and a few biosolids application events (< 0.5- 1 ppb)

Peter, Lee et al. 2025a

<https://doi.org/10.1016/j.jenvman.2025.128137>

POTENTIAL IMPACT OF RUNOFF FROM PFAS-CONTAMINATED LAND



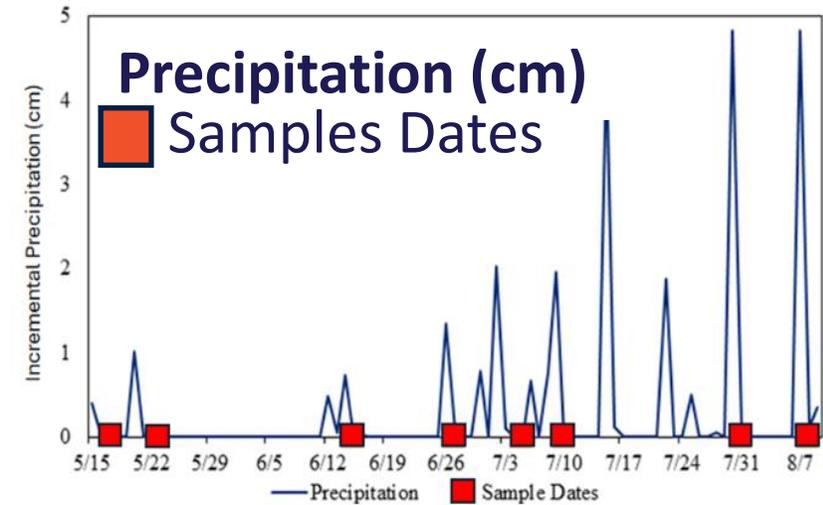
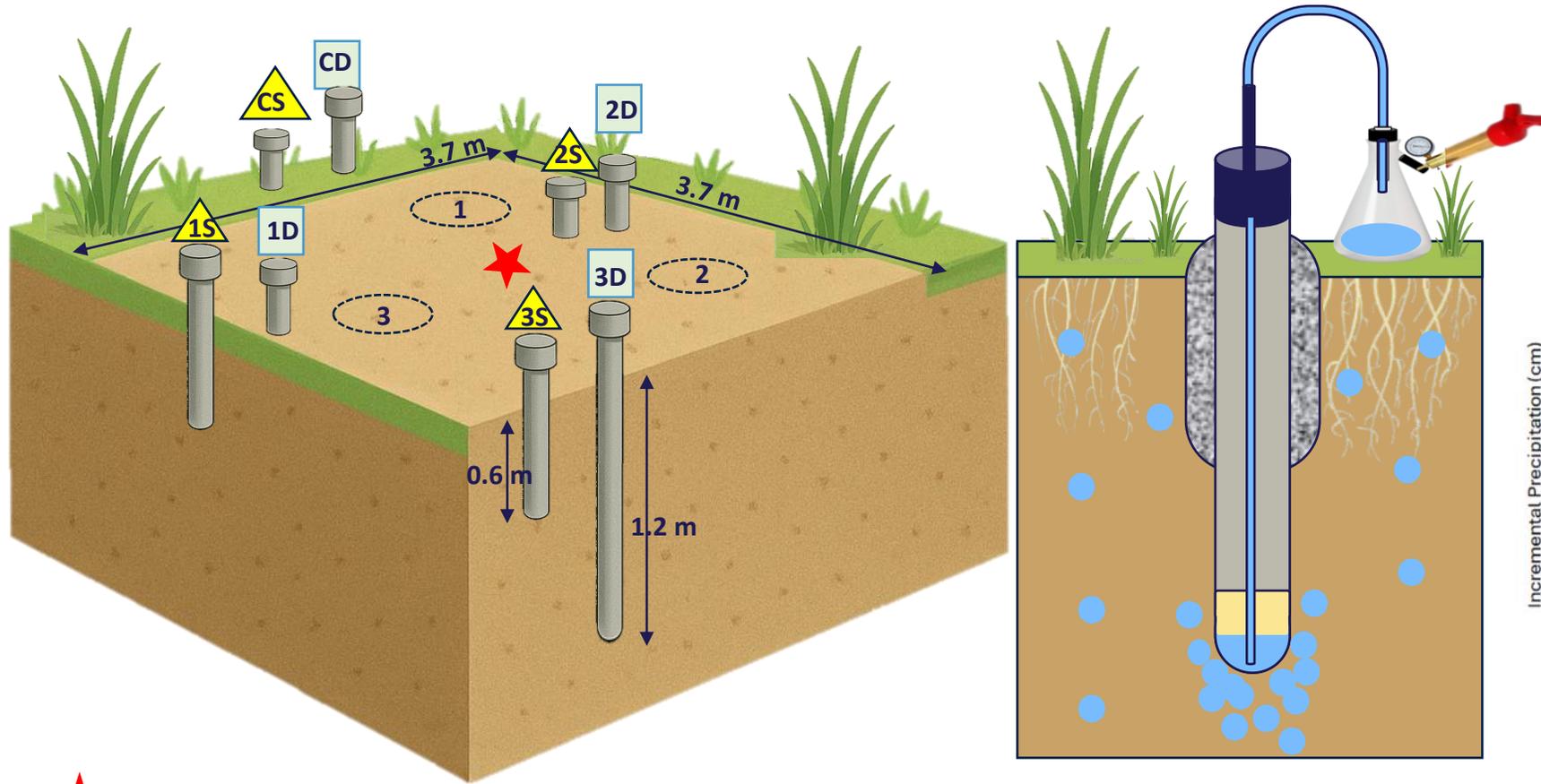
With high PFAS retention in surface soils, runoff into streams, wetlands, and farm ponds may be a significant PFAS exposure pathway to fish, wildlife, and grazing cattle, and subsequently, humans.

- Examples – are different sites:
- 200-1400 ppb PFOS in fish in farm ponds surrounded by farms with legacy biosolids application (pre-2002)
 - 150-200 ppt in milk from free grazing dairy cattle; an AFFF-contaminated stream is their drinking water source

Confidential, unpublished data

USDA FSA, USGS 104B

Leachate Monitoring: First time app versus Historic site



- ★ Soil moisture probe
- Deep lysimeters
- ▲ Shallow lysimeters
- Soil cores

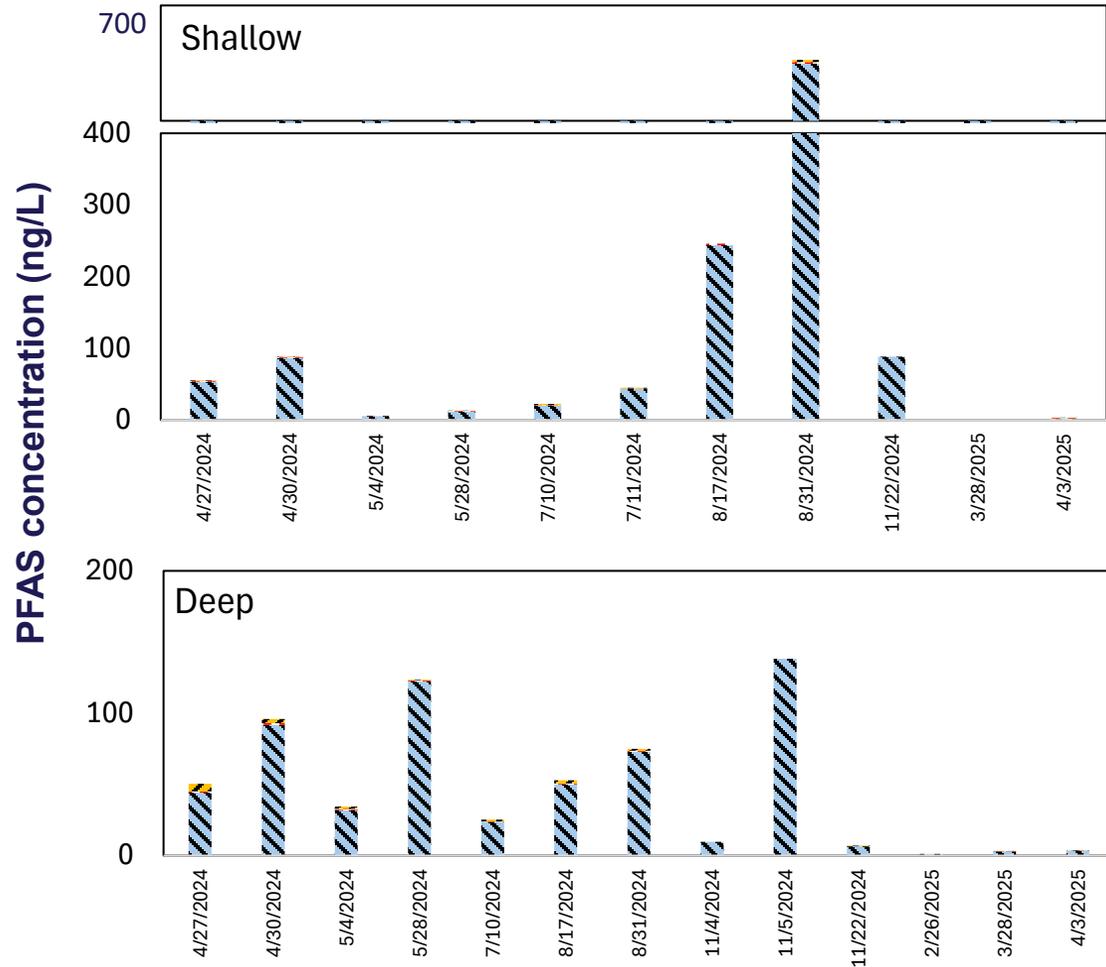
- Both studies at agricultural sites in Indiana.
- First time biosolids plot on pastureland and historic site corn/soybean rotations
- Plants removed in both case
- Subsurface injection

Temporal Porewater monitoring

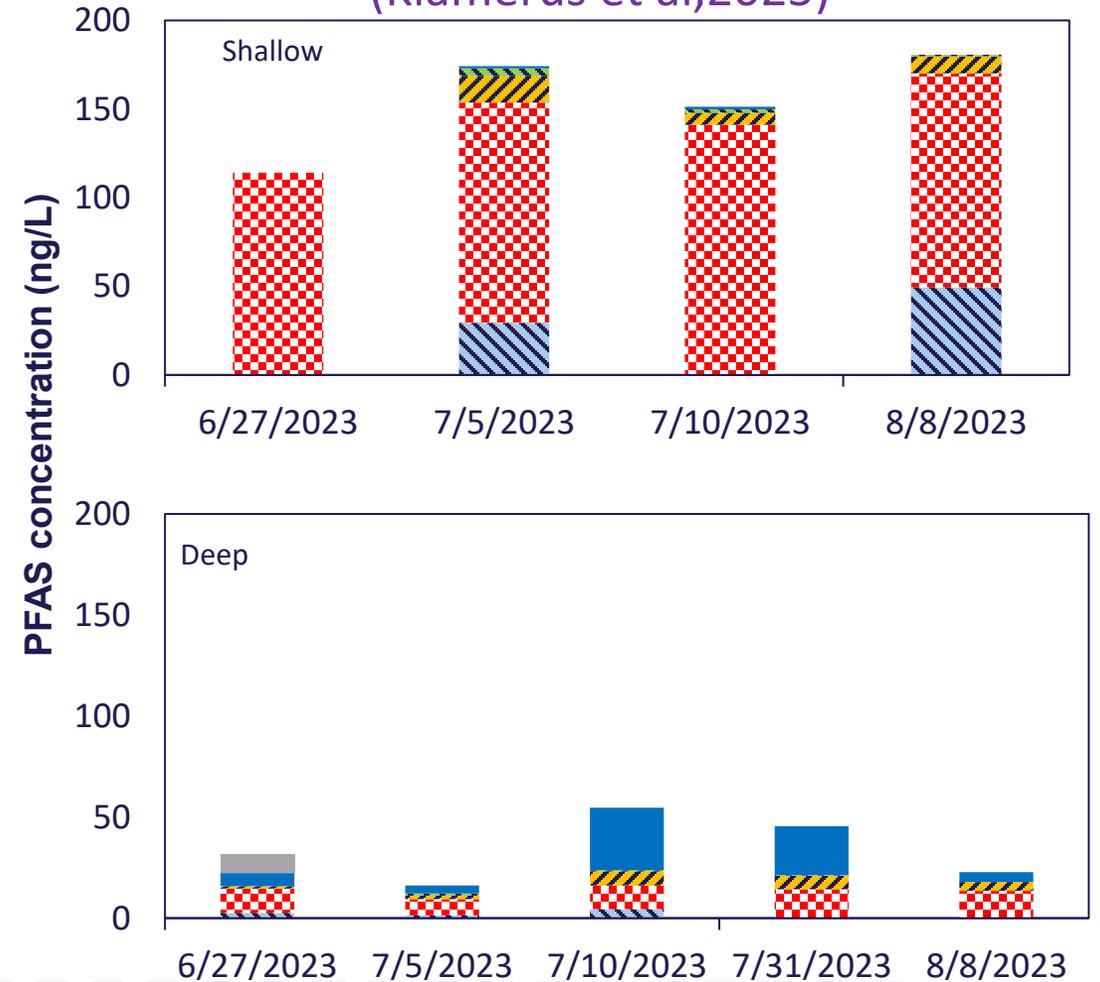
Confidential, unpublished data

FIRST-TIME APPLICATION, Monitoring commenced with first rain event post application

*Confidential- publication in preparation



~ Annual applications for ~ 40 y
Monitoring started on year after last application
 (Klamerus et al, 2025)



PFAS Concentrations and Profile with Depth in Soil Cores

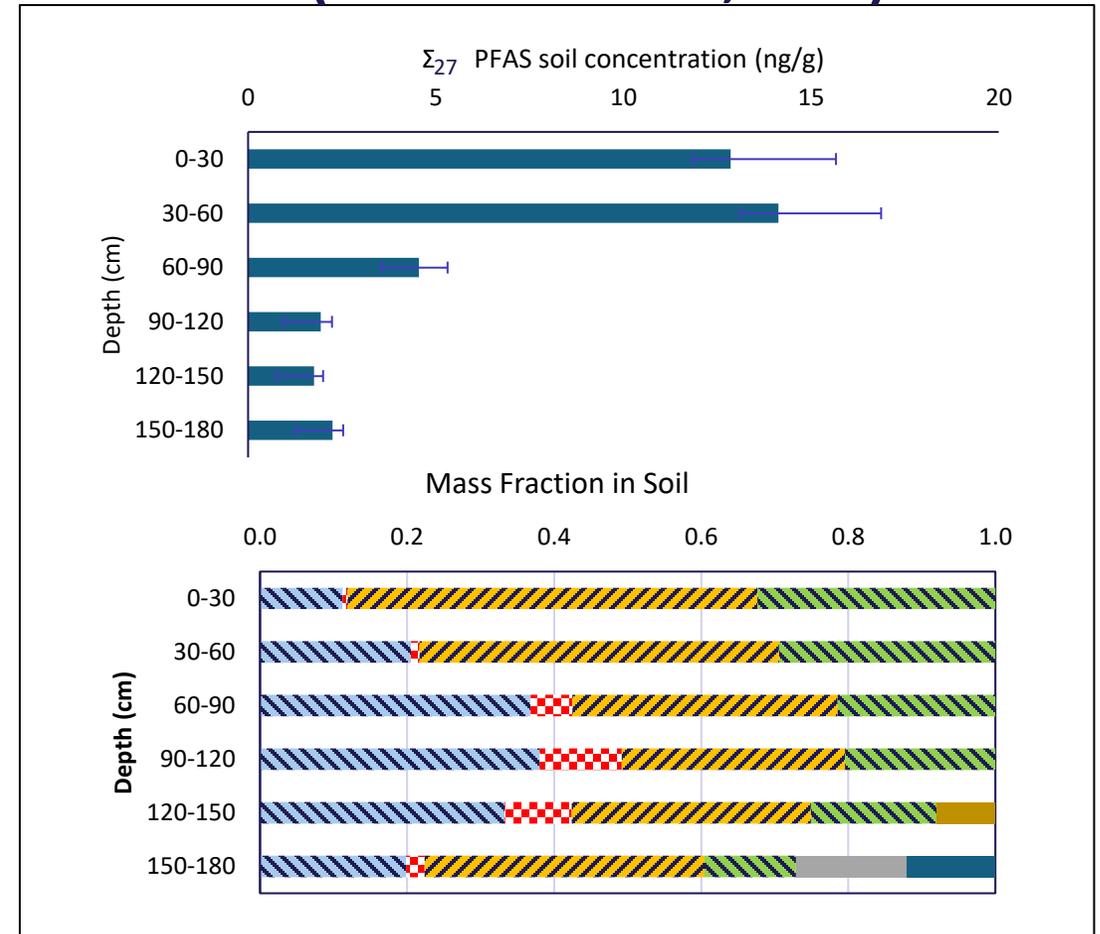
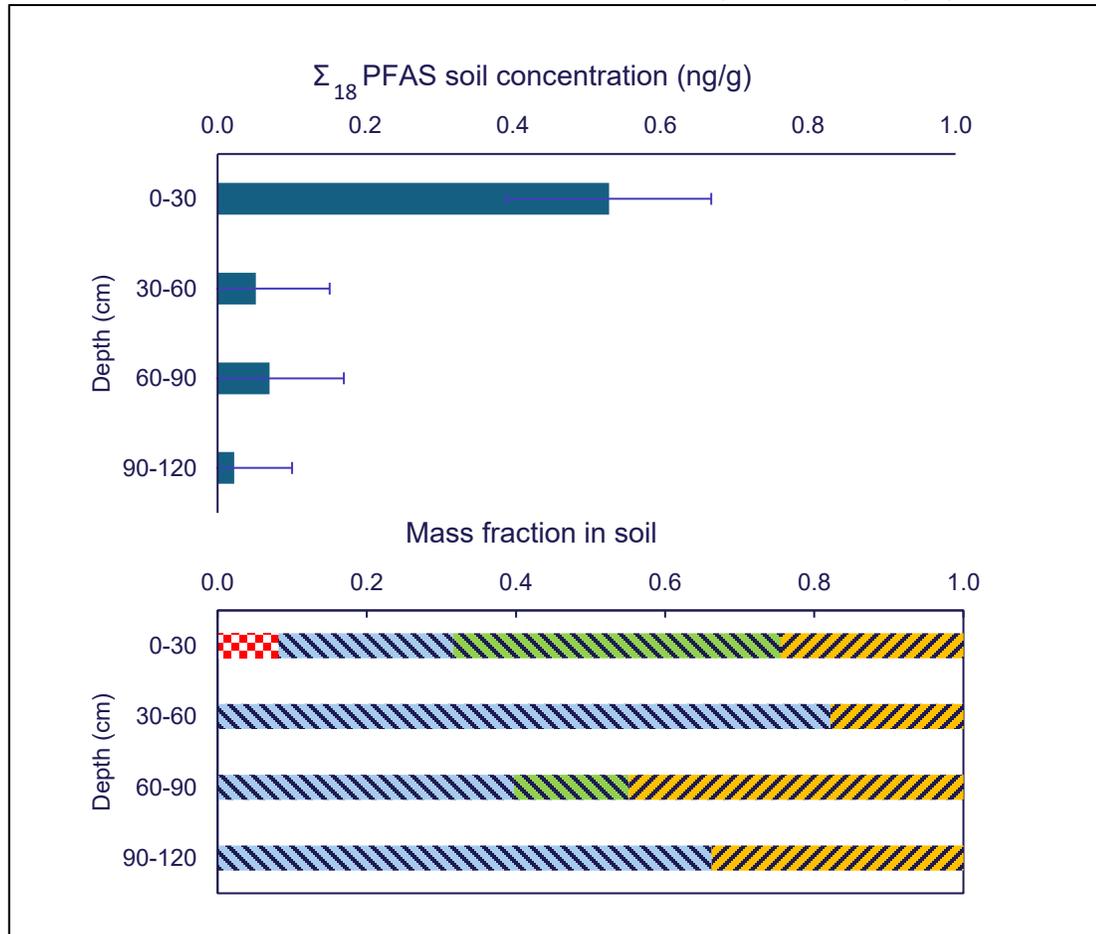
Confidential, unpublished data

First-Time application

*Confidential- publication in preparation



**Long-term (40 y annual) application
(Klamerus et al., 2025)**

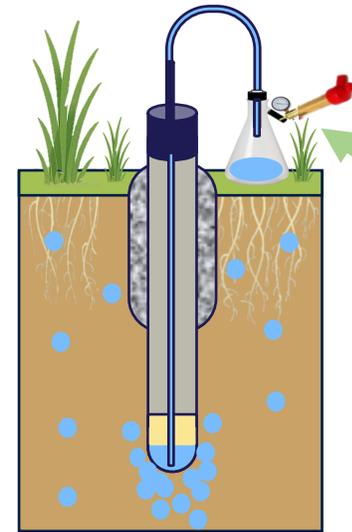
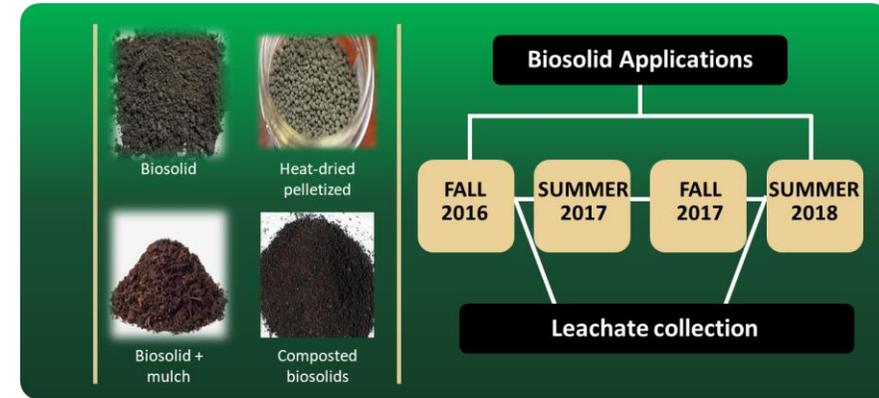
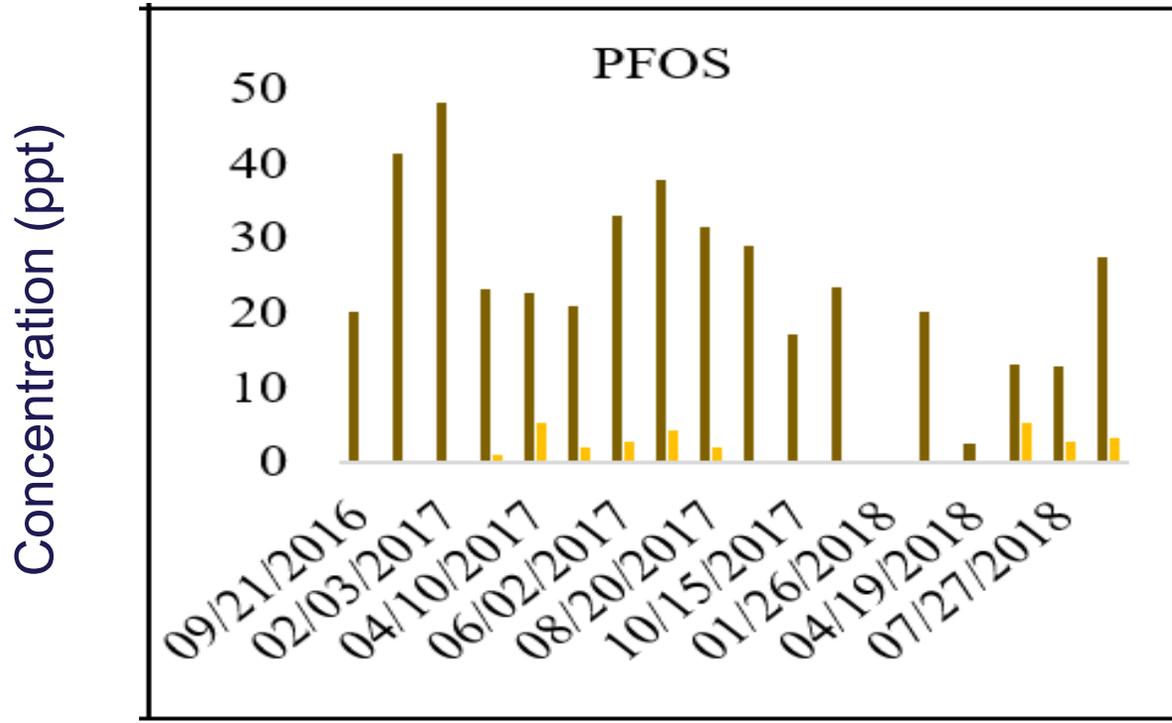


Short PFCAs
Short PFSA
Long PFSA
Long PFCAs
Other
FTCAs
ECF Intermediate

LAND RECLAMATION SITE (5X AG RATE): BIOSOLIDS: MULCH BLENDING

EXAMPLE FOR REDUCING PFAS LEACHATE CONCENTRATIONS

Leaching captured 15-cm below the surface

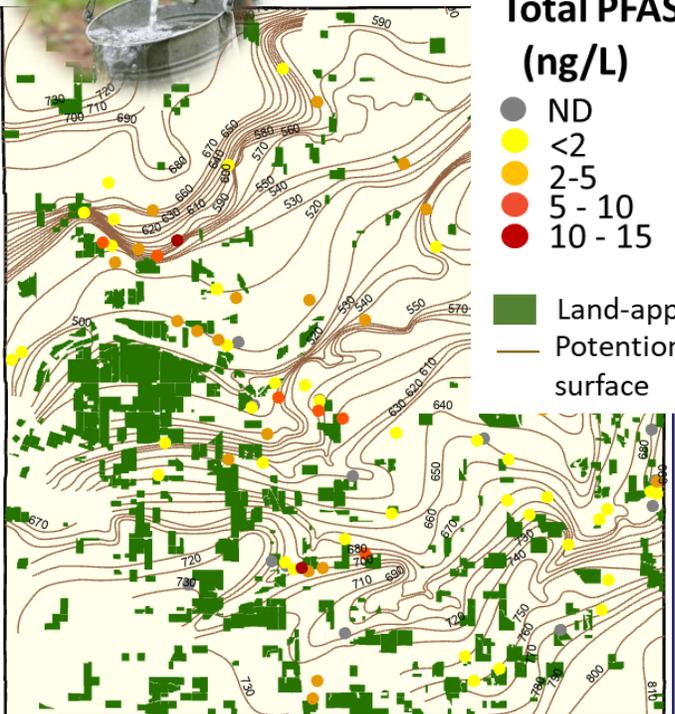


Biosolids only
Biosolids-mulch blend

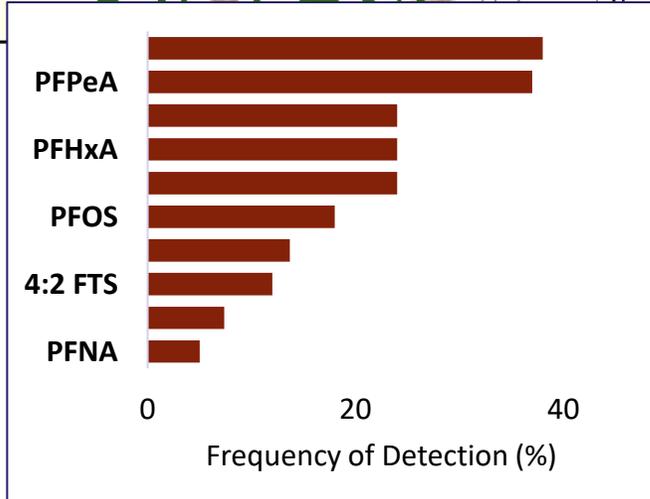
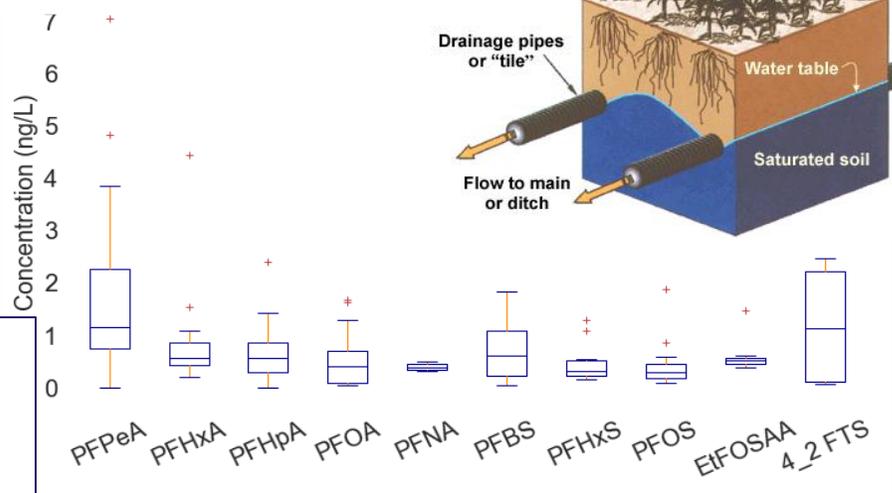
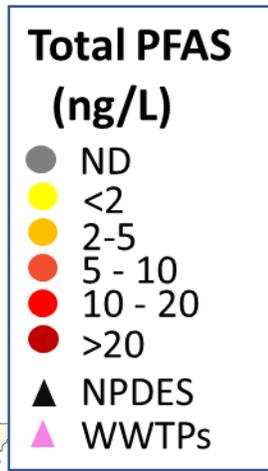
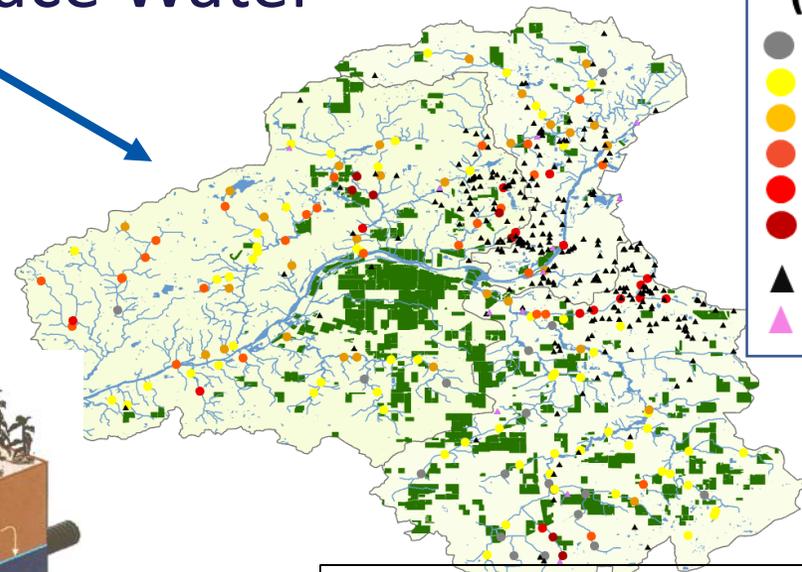
Biggest impact observed for PFOS



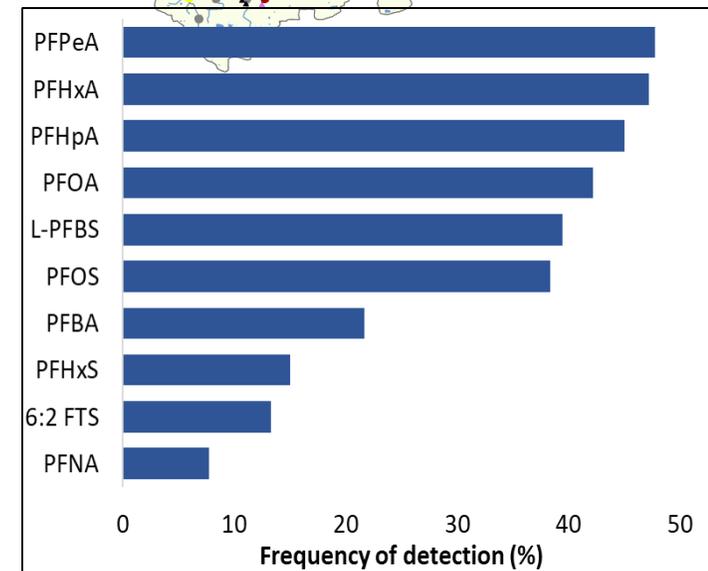
Indiana: Greater Tippecanoe County: PFAS in Rural Water Supplies & Surface Water



- Major sources: agricultural, industrial and WWTP discharges
- Most agriculture fields are tile-drained



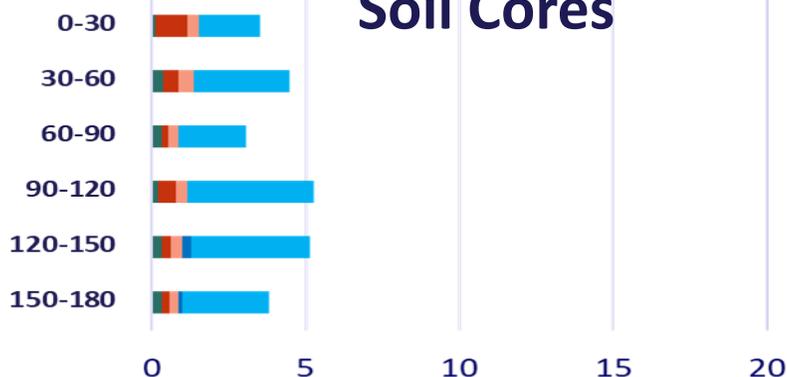
- PFAS detected in 88% of surface water samples.
- 20 PFAS detected in surface water with highest for PFBS @ 85 ng/L



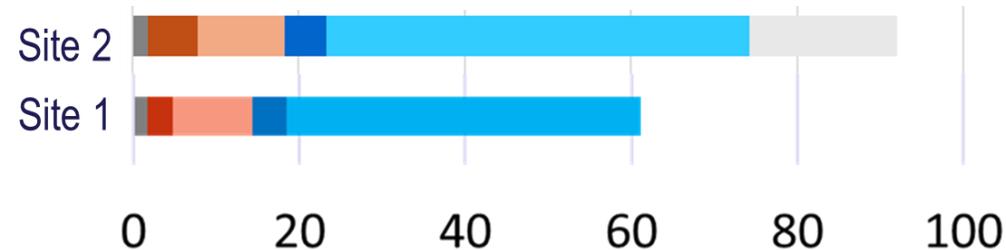
Treated WW Irrigation Only vs Both Biosolids and WW Irrigation



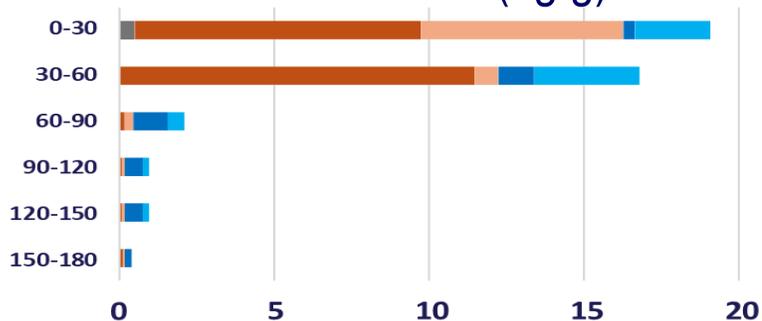
Soil Cores



Irrigation Water



PFAS Conc. (ng/g)

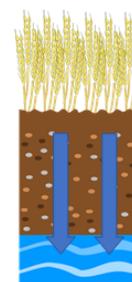


PFAS Conc. (ng/g)

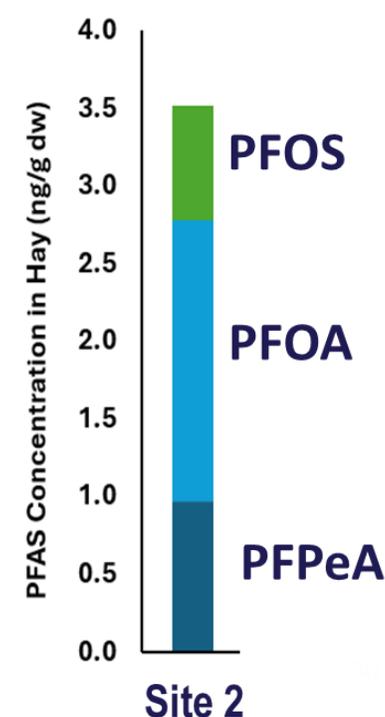
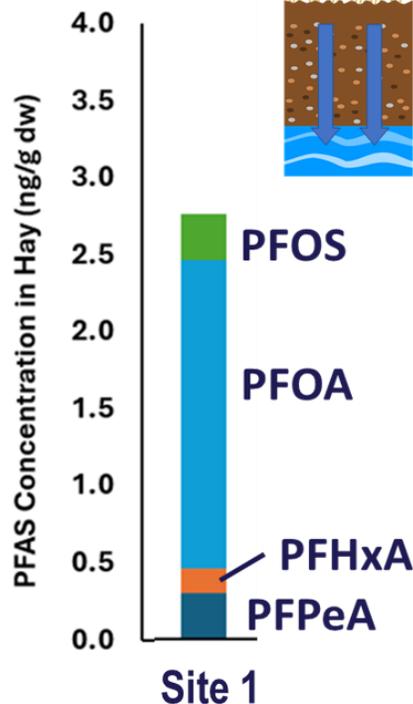
Confidential, unpublished data

- Long-chain PFASAs
- Long-chain PFCAs
- Short-chain PFASAs
- Short-chain PFCAs

- PFOA
- P-containing PFAS
- ECF precursors
- FTAAAs

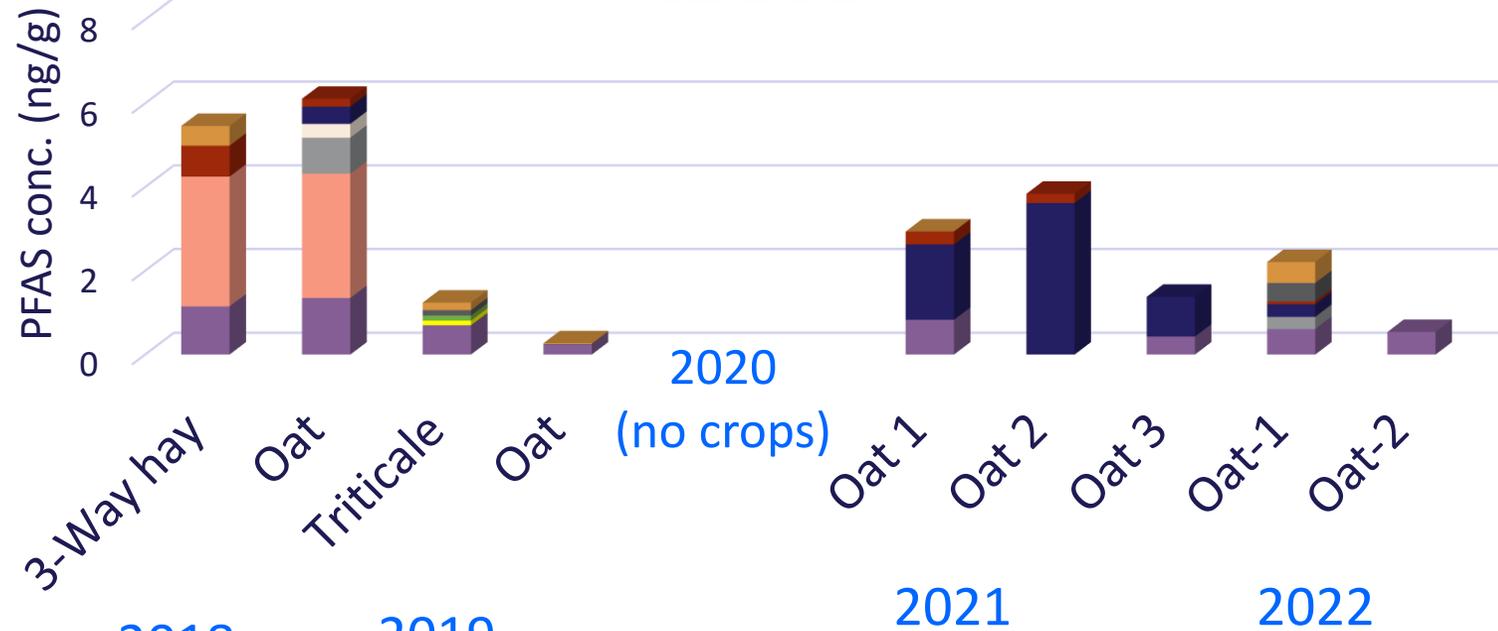
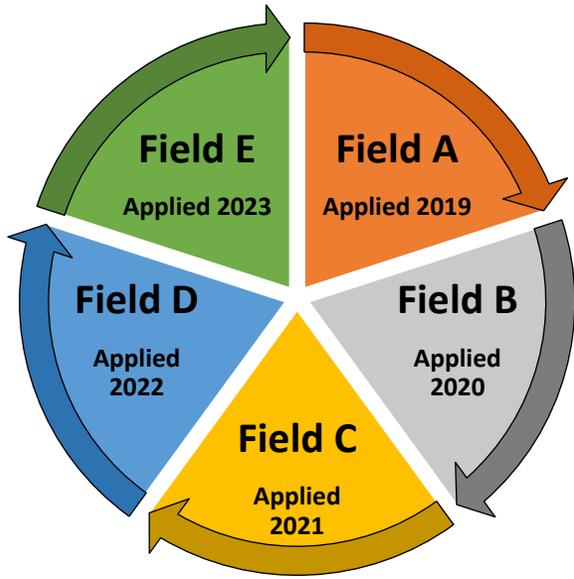


Hay



Color code different

FEED CROP UPTAKE EXAMPLE: 5-Y CYCLE BIOSOLIDS-APPLIED SITE IN CA



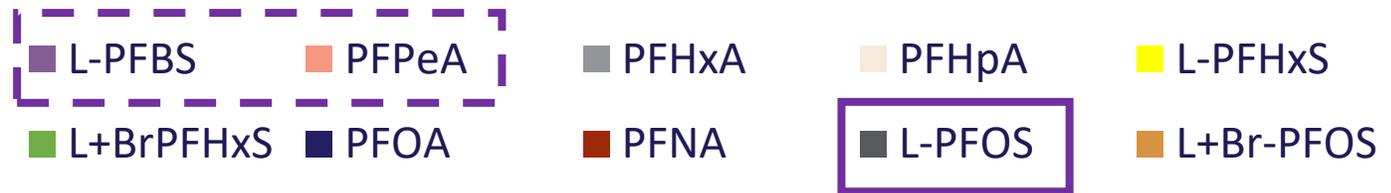
Last Biosolids Application → 2018

2019

2021

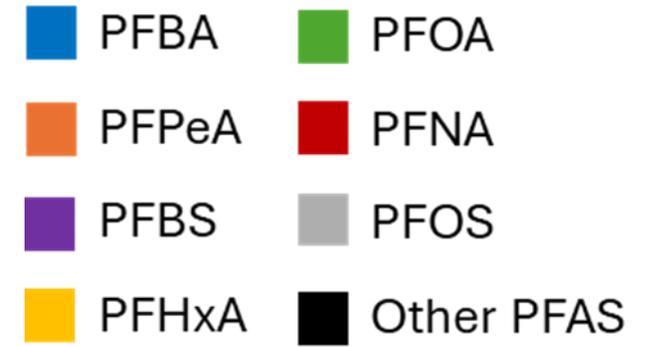
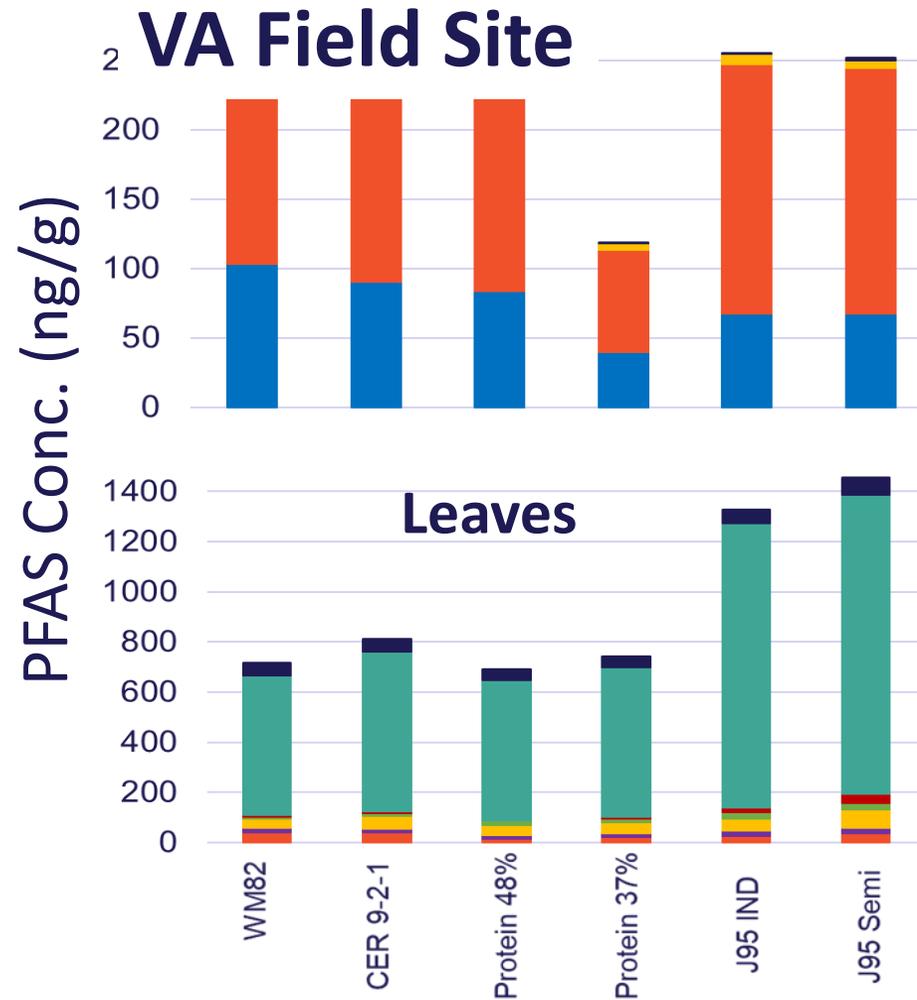
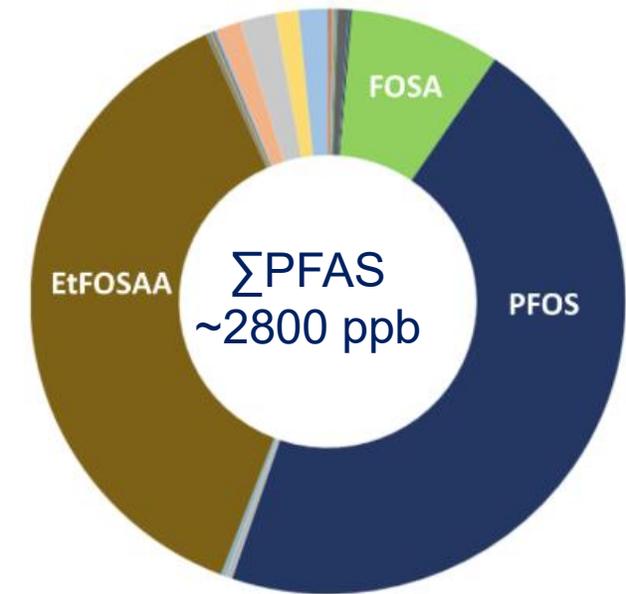
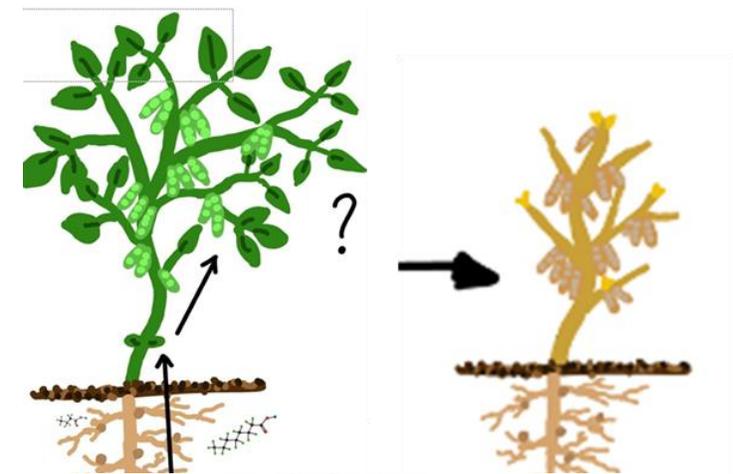
2022

Confidential, unpublished data



SOYBEAN GREENHOUSE STUDY:

PFAS TREND **LEAVES > STEMS > BEANS > PODS**



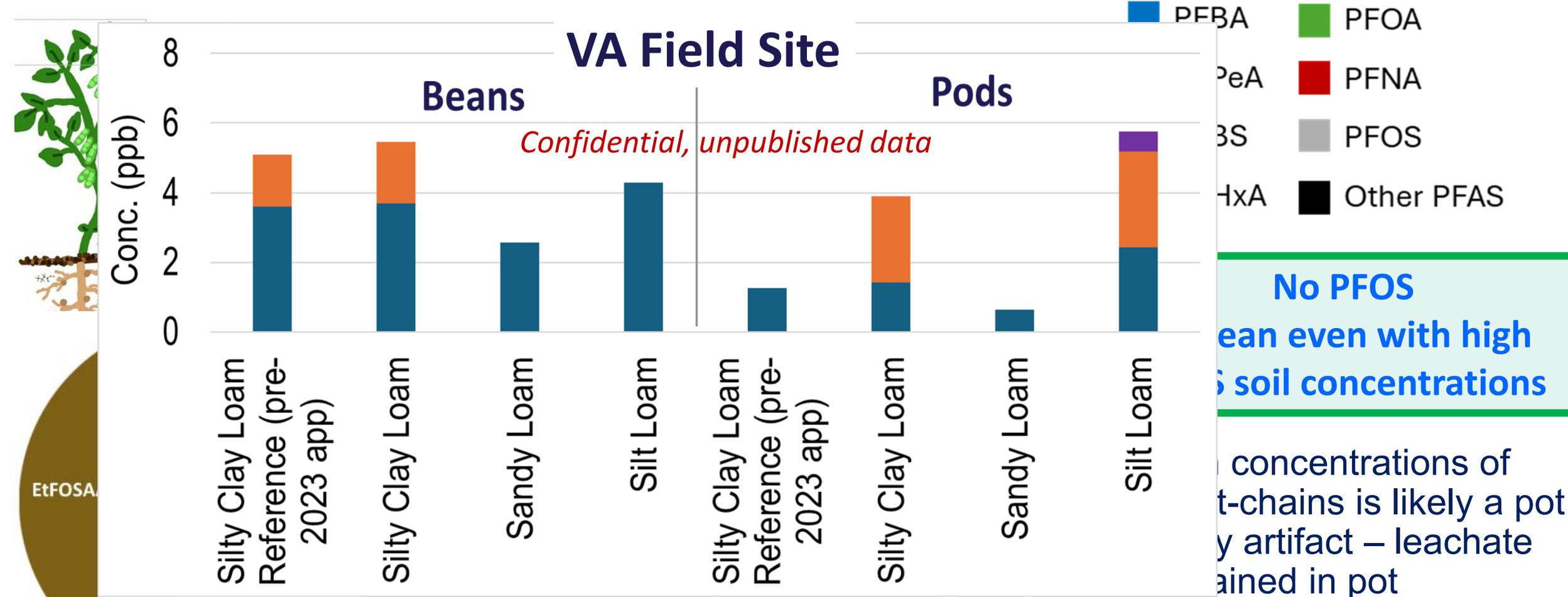
**No PFOS
in Bean even with high
PFOS soil concentrations**

- High concentrations of short-chains is likely a pot study artifact – leachate remained in pot
- Soybean field study on 3 soil types supports this hypothesis

Confidential, unpublished data

SOYBEAN GREENHOUSE STUDY:

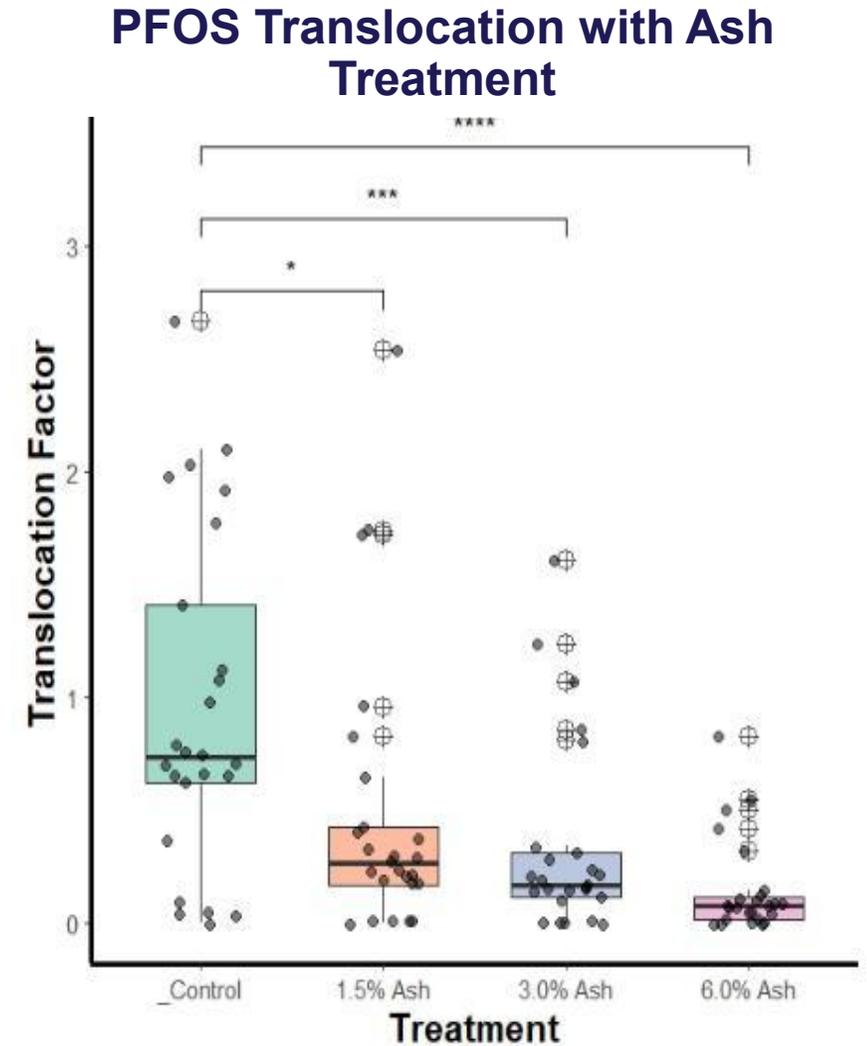
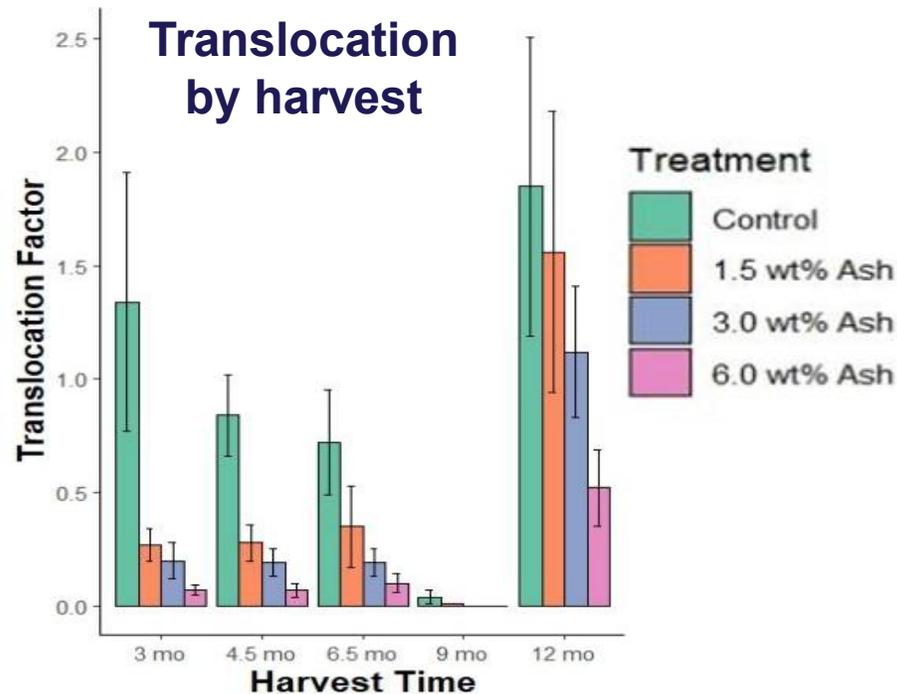
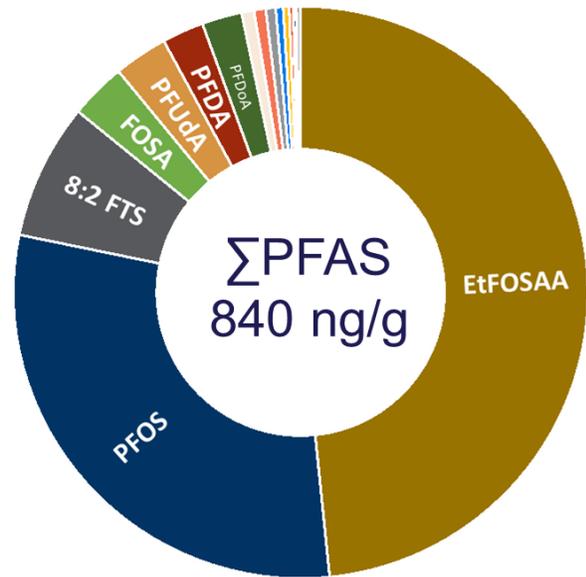
PFAS TREND LEAVES > STEMS > BEANS > PODS



- Soybean field study on 3 soil types supports this hypothesis

Feed Grass Greenhouse Studies: Uptake and Mitigation

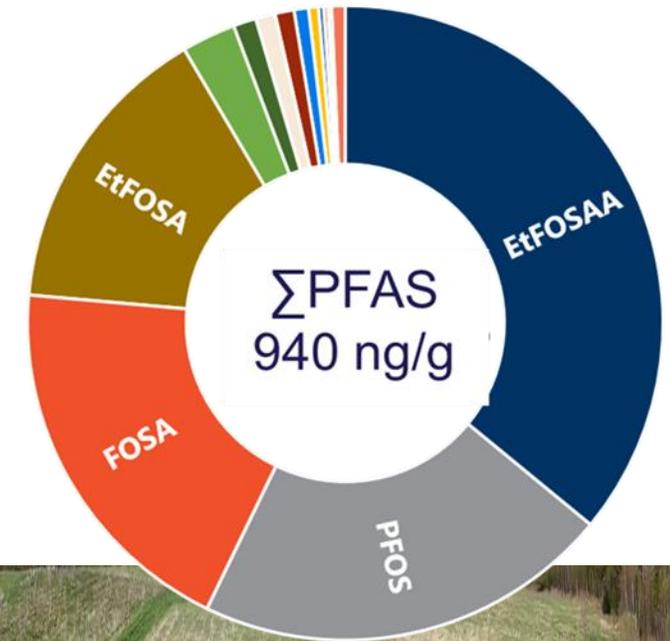
- Soil from a closed Maine Farm
- Soil received biosolids for 2-3 decades
- Wood-based biochar or wood ash
- Three sorbent rates
- Wood ash worked best



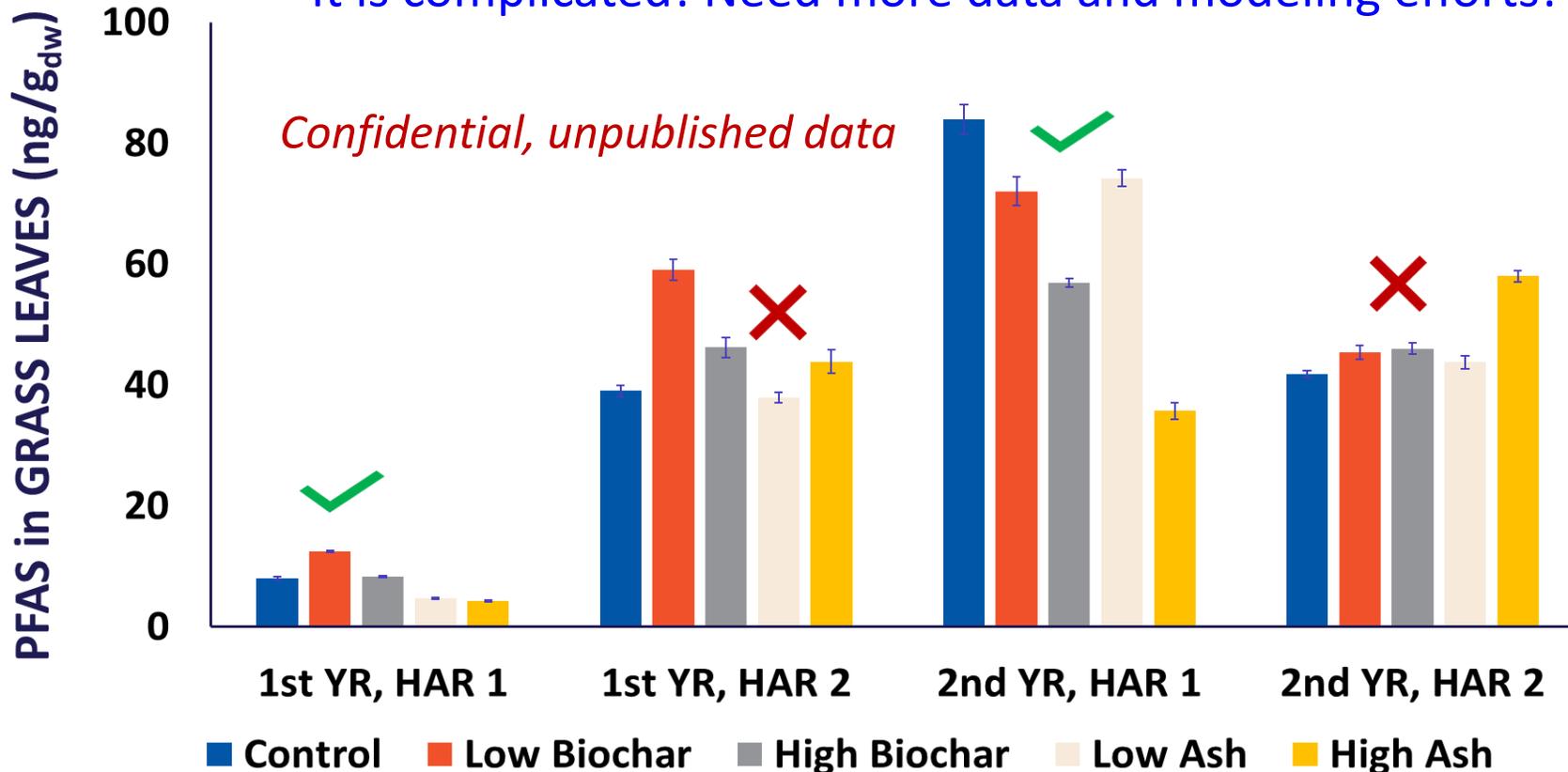
Openiyi, Lee, Carpenter et al., *J. of Agricul. & Food Chem.*,
<https://doi.org/10.1021/acs.jafc.5c08985>

Maine Feed Grass Field Studies: Evaluating High Carbon Sorbent Mitigation Potential

- 1st harvests (June-July) some sorbent mitigation exhibited
- 2nd harvests (September-October) no mitigation observed
- Prior to 2nd harvests, hotter and drier conditions existed. High carbon amendments aid in water retention, thus potentially enhancing PFAS uptake into grass, negating mitigation effects.
- It is complicated! Need more data and modeling efforts!



After tilling:
 Low rate ~1.5 wt%
 High rate ~6 wt%



MY BIGGEST CONCERN WITH PLANT UPTAKE: BIOACCUMULATION IN LIVESTOCK



- **Low PFAS concentrations bioaccumulate in plants, then biomagnify in livestock (milk and meat) - particularly long chain like PFOS**
- **PFAS in the feed**
 - PFAS uptake is greatest into leaves and stalk (e.g., grasses and silage)
 - PFAS uptake is small into fruit (e.g., tomatoes), seeds (e.g., soybeans, corn kernels and cob)
- *Additional PFAS bioaccumulates from drinking water*



Key Take-Aways

- Limited migration of long-chain PFAS from soil to groundwater, dominated by short-chain PFAS but of the long chain, PFOA most often highest conc in the groundwater
- Long-chain PFAS persistence in surface soils and the upper soil profile leads to longer term availability for plant uptake, runoff into water bodies
- Application of new biosolids have small PFAS signatures, that are not statistically different than PFAS loads on legacy sites and similar or less than ‘background’ levels.
- Sorbent mitigation strategies may be tricky to predict and achieve positive outcomes
- Reduce PFAS uptake into crops through crop choices and selected harvests while awaiting future other mitigation strategies currently being evaluated
- Tile-drained fields divert contaminants to streams protecting groundwater
- Our biggest PFAS ‘land’ issues are **legacy and industrial-impacted biosolids** applications prior to phase outs of the highly bioaccumulative long-chain
- Treated WW irrigation impact on PFAS loads in crop needs more attention



Q&A



Acknowledgments *Lee Lab*



EPA Disclaimer: Data and views shared have not been formally reviewed by EPA and are solely the views of the researchers and not the agency.

