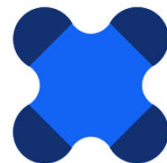
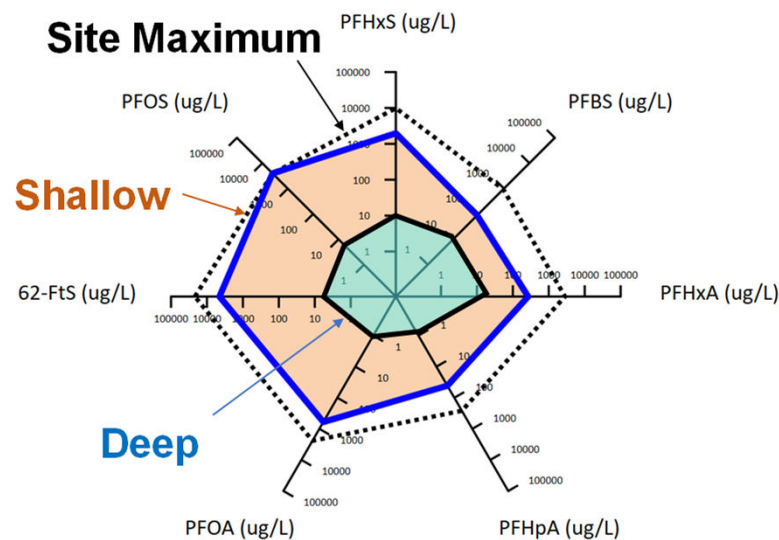


SPLP vs. Porewater for Remedial Decision-Making: Ellsworth AFB, South Dakota

By Grant Carey, Ph.D.

Porewater Solutions

Email: gcarey@porewater.com



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4 Tablespoons of soil
(0.1 kg ~ 0.06 L)



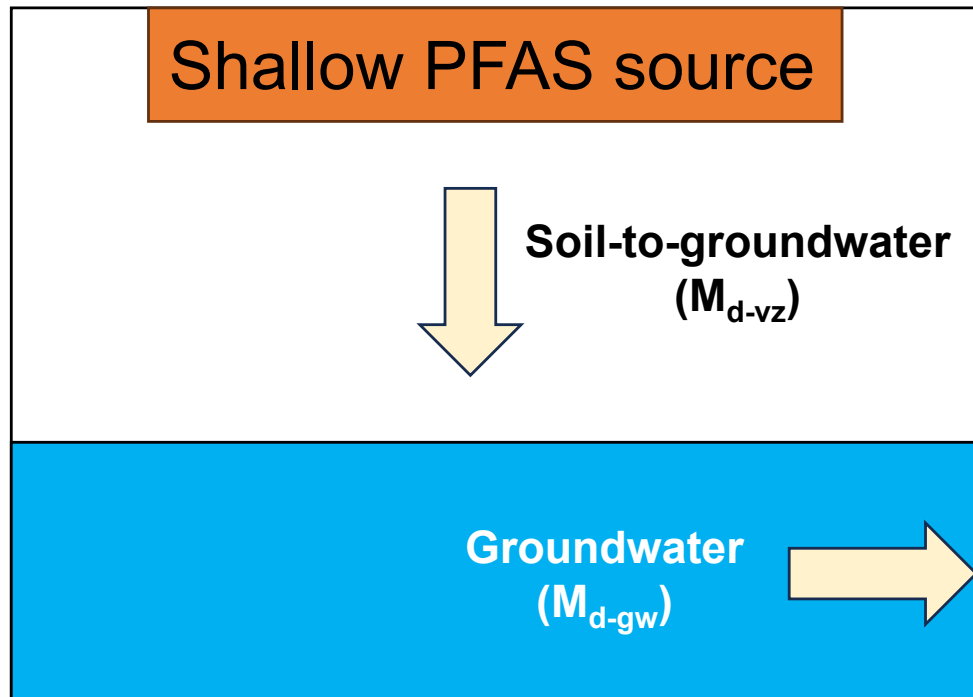
Mixed with 2 liters of water



SPLP vs Porewater

April 15, 2026

Mass Discharge (M_d) Affects Remediation Strategy



Determining groundwater recharge for quantifying PFAS mass discharge from unsaturated source zones

Charles J. Newell¹ | Emily B. Stockwell¹ | Jessica Alanis¹ | David T. Adamson¹ | Kenneth L. Walker¹ | R. Hunter Anderson²

¹GSI Environmental Inc., Houston, Texas, USA

²Air Force Civil Engineer Center, San Antonio, Texas, USA

Newell et al. (2023)

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Assigned to Associate Editor Clare
Robinson.

[Correction added on 2 July 2024, after first
online publication: Equation 6 is changed.]

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Environmental Security Technology
Certification Program, Grant/Award
Number: ESTCP Project ER22-7381

Abstract

Soil-to-groundwater contaminant mass discharge (M_d) is the authoritative metric defining source strength at sites impacted by per- and polyfluoroalkyl substances (PFAS) and is increasingly being reported. Accurate estimates of groundwater recharge at representative spatial scales, however, is critical to quantitatively estimating M_d , which to date has received comparatively little attention relative to PFAS-specific partitioning and retention processes within unsaturated zone source areas despite a plethora of available literature. The objective of this review is to summarize the concept of M_d as it applies to PFAS-impacted sites, present standardized terminology, and collate published literature on groundwater recharge for

M_{d-vz} **low** relative to M_{d-gw}

- “high-intensity, high-cost remediation of the unsaturated zone is likely counter-productive.”

M_{d-vz} **large** proportion of M_{d-gw}

- Remediation to manage risk from the unsaturated zone

Estimating Soil-to-Groundwater Mass Discharge

Newell et al. (2023): $M_{d-vz} = C_{pw} \times \text{Net Recharge} \times \text{Area}$

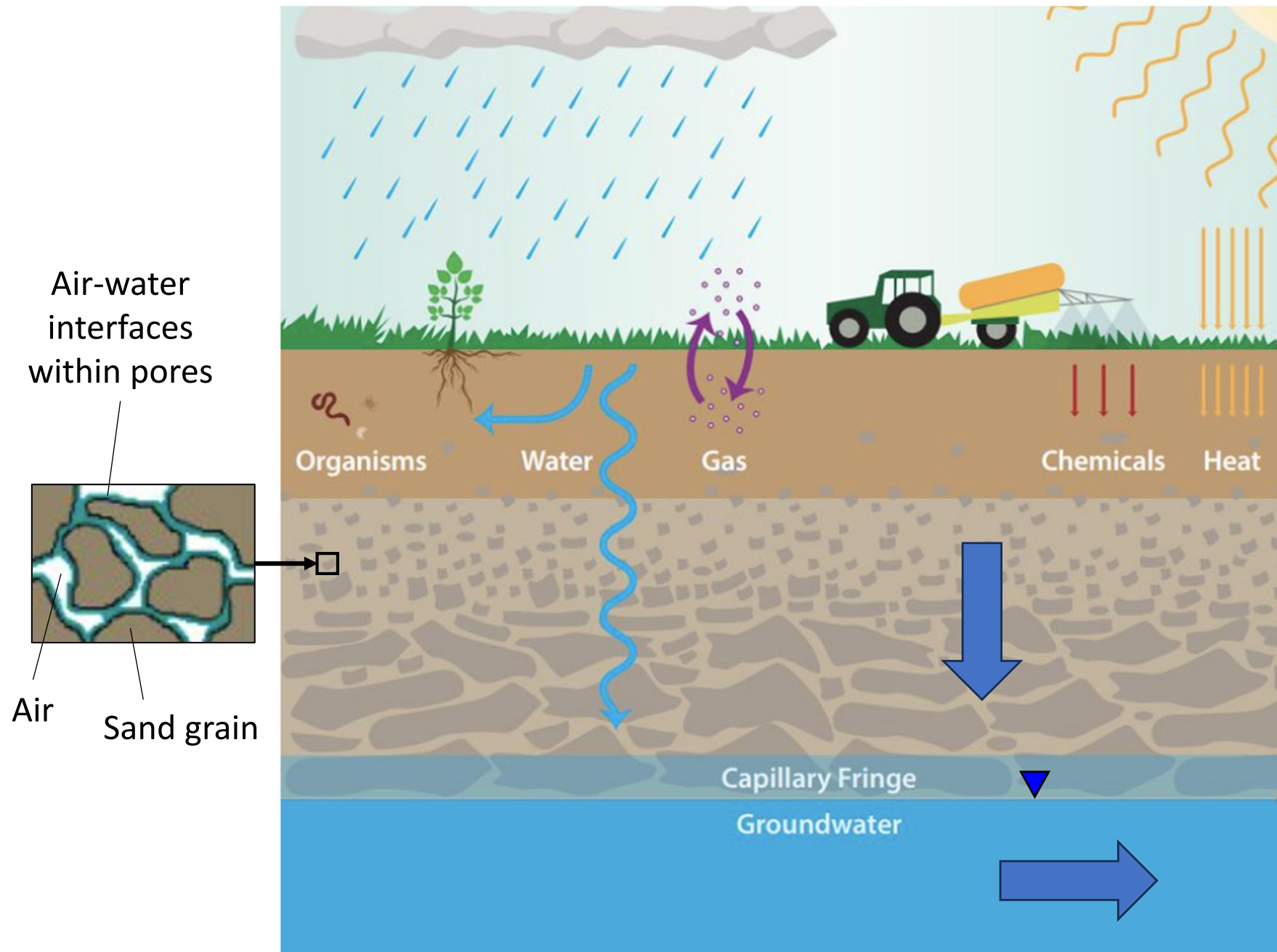
Costanza et al. (2025): Porewater samples should be shown to be representative prior to sole reliance for remedial decision-making

- Recommend a multiple lines-of-evidence approach for site cleanup levels
 - Lysimeters (PW), soil samples, groundwater transects, and leaching tests
- **Carey et al. (2026b):** SPLP leaching test results were not representative of PFAS porewater concentrations at Ellsworth AFB without modification

Agenda

- 1** Vadose Zone Primer
- 2** Ellsworth AFB FFTA: 3-D Soil and PW Samples
- 3** Are Porewater Samples Representative?
- 4** Are SPLP results representative of porewater?
- 5** Conclusions

Vadose Zone Cross-Section



Retardation Coefficient (R)

R = Retardation coefficient (dimensionless)
 K_{oc} = organic carbon partitioning coefficient (L/kg)
 f_{oc} = fraction of organic carbon content (g/g)
 ρ_b = dry bulk density (kg/L)
 θ_w = water-filled porosity (m³/m³)
 K_{aw} = air-water interfacial adsorption coefficient (cm³/cm²)
 A_{aw} = air-water interfacial area (cm²/cm³)

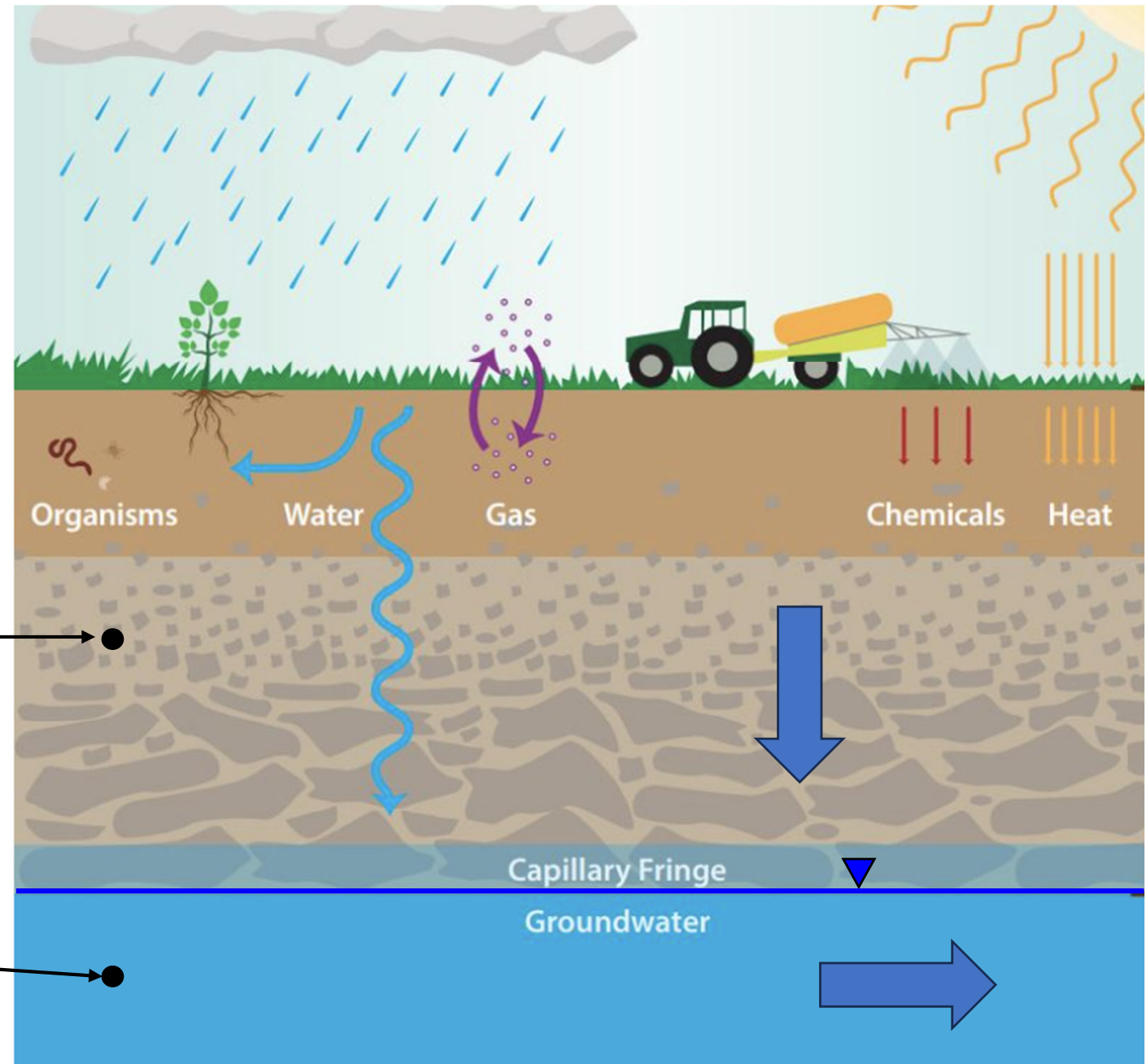
Brusseu and Guo (2022)

Unsaturated Zone

$$R = 1 + \frac{\rho_b}{\theta_w} K_{oc} f_{oc} + \boxed{\frac{K_{aw} A_{aw}}{\theta_w}}$$

Saturated Zone

$$R = 1 + \frac{\rho_b}{\theta_w} \underbrace{K_{oc} f_{oc}}_{K_d}$$



Long-Chain PFAS Adsorb to Air-Water Interfaces

Brusseau et al. (2018)



Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv



Assessing the potential contributions of additional retention processes to PFAS retardation in the subsurface

Mark L. Brusseau

429 Shantz Bldg, Soil, Water and Environmental Science Department, Hydrology and Atmospheric Sciences Department, School of Earth and Environmental Sciences, University of Arizona, United States



HIGHLIGHTS

- A comprehensive model for PFAS retention in porous media is proposed.
- Adsorption at the air-water interface contributes greatly to PFOA/PFOS retention.
- Adsorption at the NAPL-water interface and NAPL partitioning are also significant.

GRAPHICAL ABSTRACT

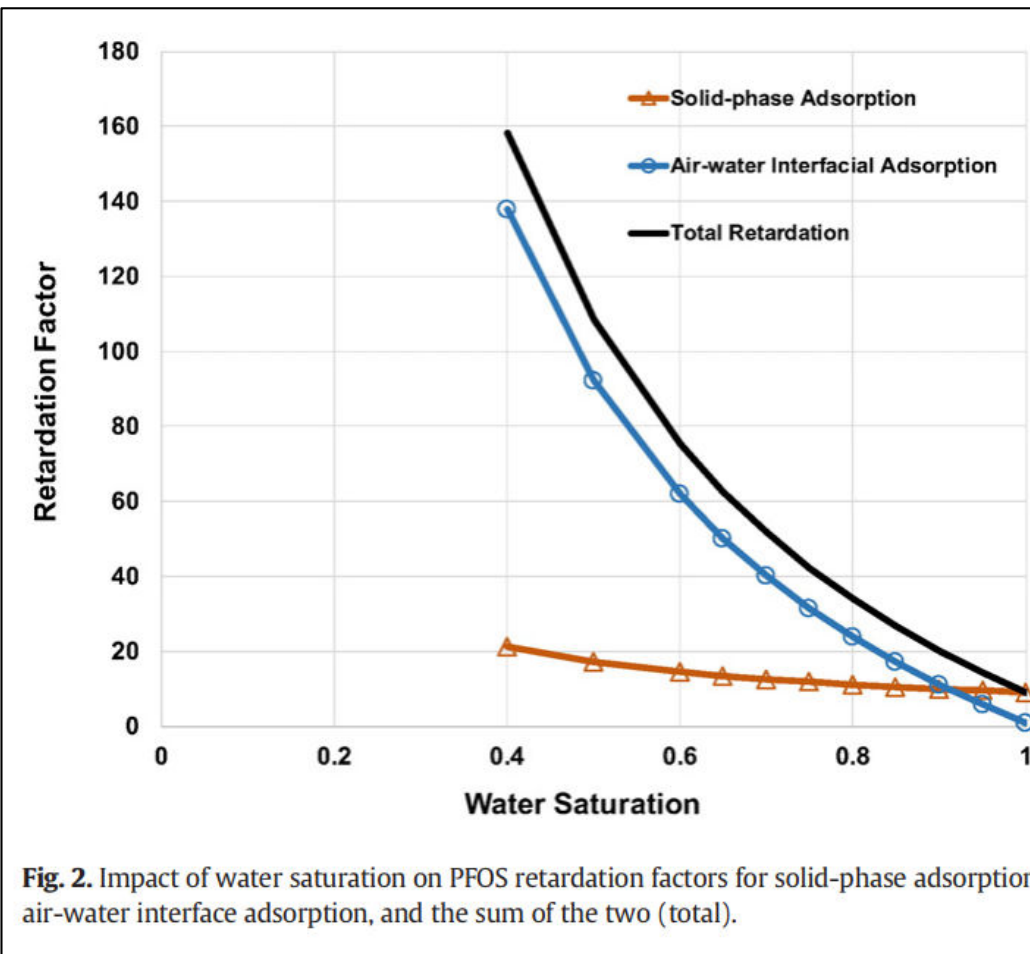
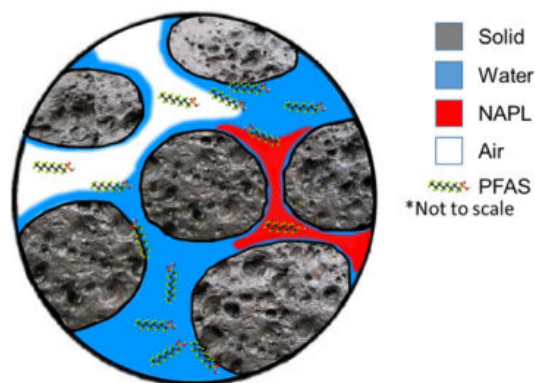
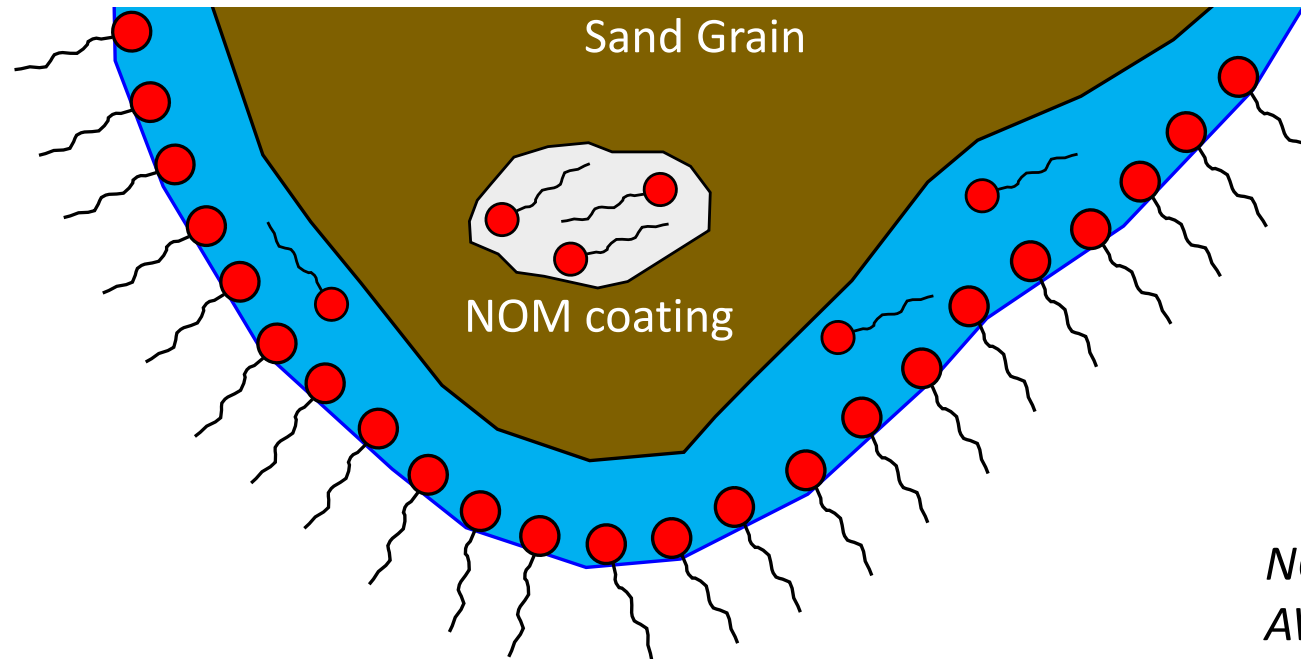


Fig. 2. Impact of water saturation on PFOS retardation factors for solid-phase adsorption, air-water interface adsorption, and the sum of the two (total).

PFOS Mass Components in Soil (Low Saturation)



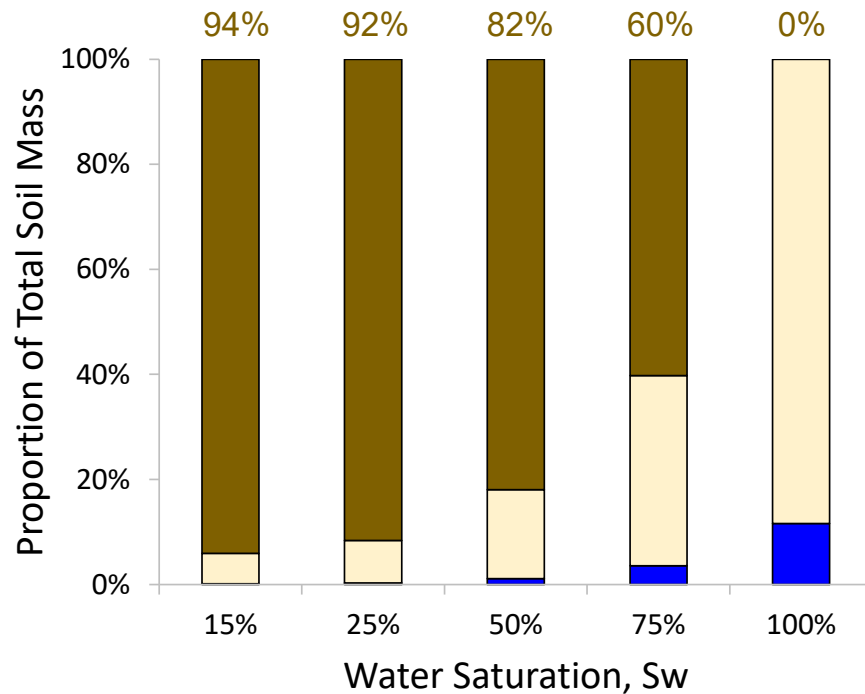
*NOM: Natural organic matter
AWI: Air-water interface*

Three Mass Components in total soil concentration:

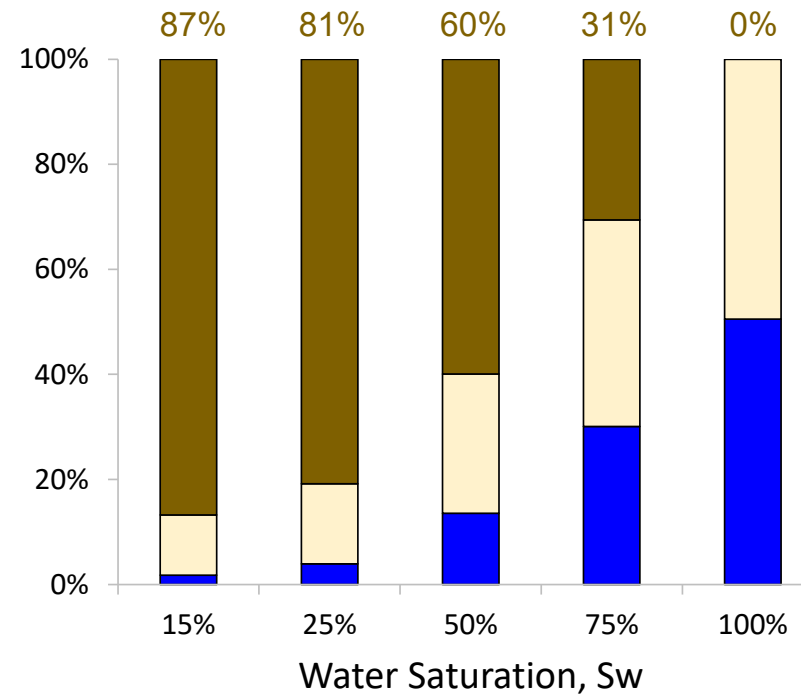
1. Aqueous phase
2. Adsorbed to NOM
3. Adsorbed to AWI

PFAS Mass Distribution in the Vadose Zone

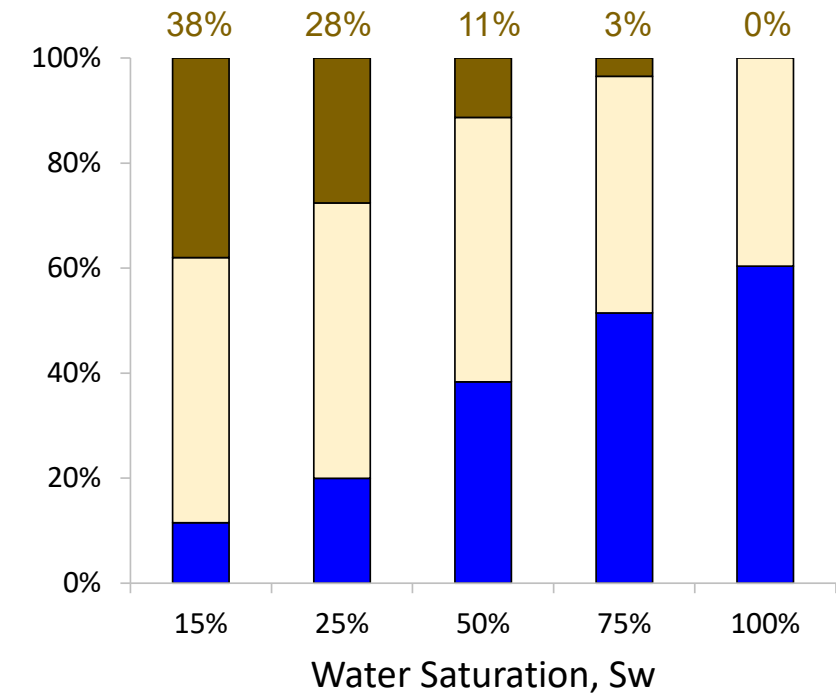
a) PFOS ($K_{aw} = 0.05 \text{ cm}^3/\text{cm}^2$)



b) PFOA ($K_{aw} = 0.003 \text{ cm}^3/\text{cm}^2$)



c) PFHxA ($K_{aw} = 0.0002 \text{ cm}^3/\text{cm}^2$)



■ Aqueous phase ■ Adsorbed to NOM ■ Adsorbed to AWI

Gravimetric Moisture Content

Carey et al. (2026a)

Water saturation (S_w) may be estimated from the gravimetric moisture content using

$$S_w = \frac{\rho_b MC}{\rho_w \theta_t} \quad (2)$$

where ρ_b = soil dry bulk density (g/L); MC = gravimetric moisture content (g/g); ρ_w = water density (g/L); and θ_t = total porosity (L/L).

S_w = % of total pore space filled with water

Commercial labs provide free gravimetric moisture content results with every soil sample PFAS analysis!

Ellsworth AFB Vadose Zone Case Study

Carey et al. (2026a,b)

Remediation Journal

WILEY

RESEARCH ARTICLE

OPEN ACCESS

PFAS Vadose Zone Mass Discharge at an AFFF-Impacted Site: 1. Validation Based on a Multiple Lines-of-Evidence Approach

Grant R. Carey^{1,2} | David T. Adamson³ | Rita K. Krebs⁴ | Mia Rebeiro-Tunstall¹ | Kevin G. Mumford⁵ | Bo Guo⁶ | Gabriel T. Carey⁷ | Kiera Rooney¹ | Sabrina Moga¹

¹Porewater Solutions, Ottawa, Ontario, Canada | ²Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada | ³CSI Environmental Inc., Houston, Texas, USA | ⁴Air Force Civil Engineer Center (AFCEC), Ellsworth AFB, South Dakota, USA | ⁵Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada | ⁶Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona, USA

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Received: 3 November 2025 | **Revised:** 2 January 2026 | **Accepted:** 7 January 2026

Keywords: AFFF | air-water interface | mass discharge | PFAS | vadose zone

ABSTRACT

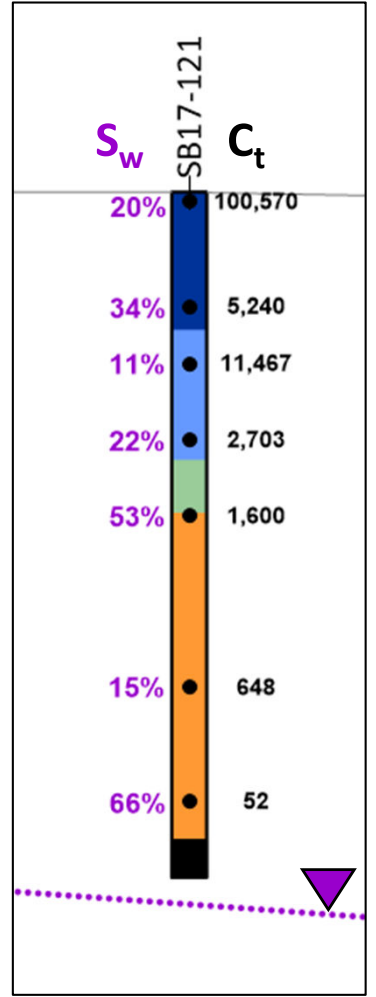
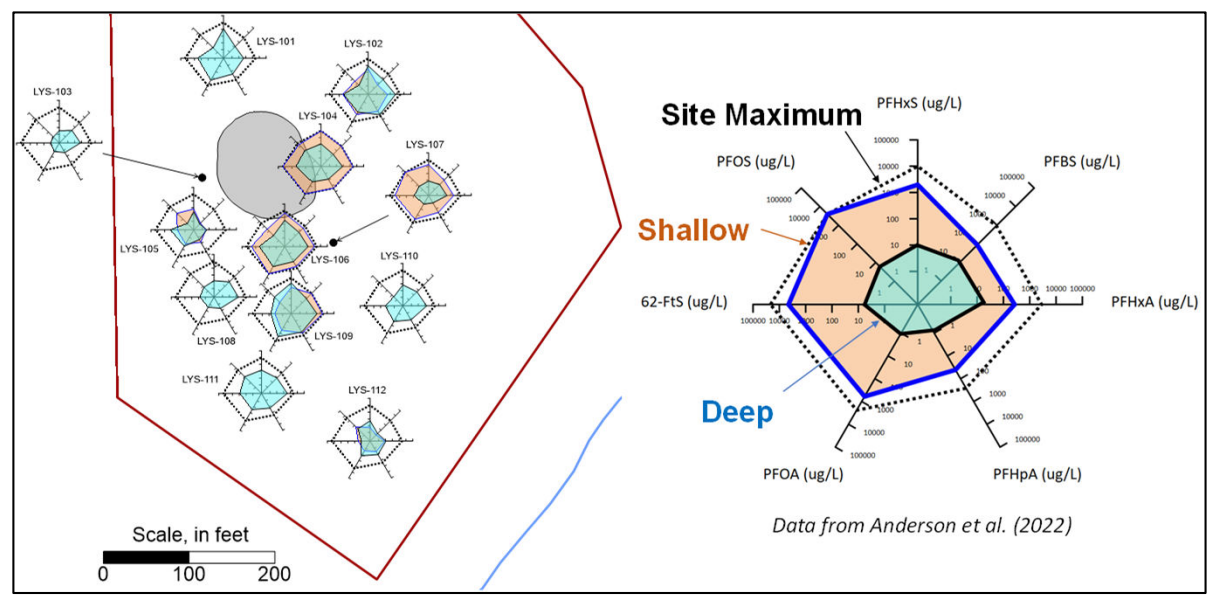
Questions have recently been raised about the suitability of using porewater samples collected with suction lysimeters to estimate per- and polyfluoroalkyl substances (PFAS) mass discharge in the vadose zone. Multiple lines of evidence were evaluated to determine if porewater samples collected during a data gaps investigation in the former fire training area (FFTA) at Ellsworth Air Force Base were reproducible and representative. Lines of evidence used include supplemental geologic and hydrogeologic data, which show the presence of a semi-continuous silt/clay layer directly above the water table throughout much of the FFTA, and gravimetric moisture content results that demonstrate vertical water flow at a depth of 15 ft is substantially limited due to semi-arid climatic conditions. Radial diagrams were used to visually demonstrate that there was negligible variability in porewater concentrations caused by varying sample yields in the deep zone. Additional lysimeters installed in the FFTA during the remedial investigation did not result in a significant difference in the estimated vertical mass discharge, which demonstrates that the number of lysimeter sampling points in this area is sufficient. Strong attenuation in PFAS soil concentrations with depth validates the order(s) of magnitude reduction between shallow and deep porewater concentrations observed near the former burn pit. Vadose zone PFAS mass discharge is shown to be 4%–19% of groundwater mass discharge below the water table for regulated constituents. Recommendations for field data collection and estimation of PFAS mass discharge in the vadose zone are presented.

1 | Introduction

The application of aqueous film-forming foam (AFFF) containing per- and polyfluoroalkyl substances (PFAS) at civilian and military airfields has impacted soil and groundwater at some of these sites (Adamson et al. 2020; Leeson et al. 2020; Carey et al. 2022). The use of AFFF in former fire training areas (FFTAs) typically involved the spraying of diluted AFFF products into burn pits to put out fires on a regular basis. Prior to the 1990s, these burn pits were typically unlined. Carey et al. (2025) discuss the challenges associated with analyzing comprehensive PFAS data sets collected at AFFF-impacted sites. The utility of radial diagrams for differentiating between AFFF product uses and for evaluating ratios indicative of precursor biotransformation was demonstrated with a case study at Ellsworth Air Force Base (Ellsworth AFB) in South Dakota by Carey et al. (2025). The surfactant qualities associated with PFAS cause many of these chemicals to adsorb to air-water interfaces, which will

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Rita Krebs



Dave Adamson



Kevin Mumford



Bo Guo



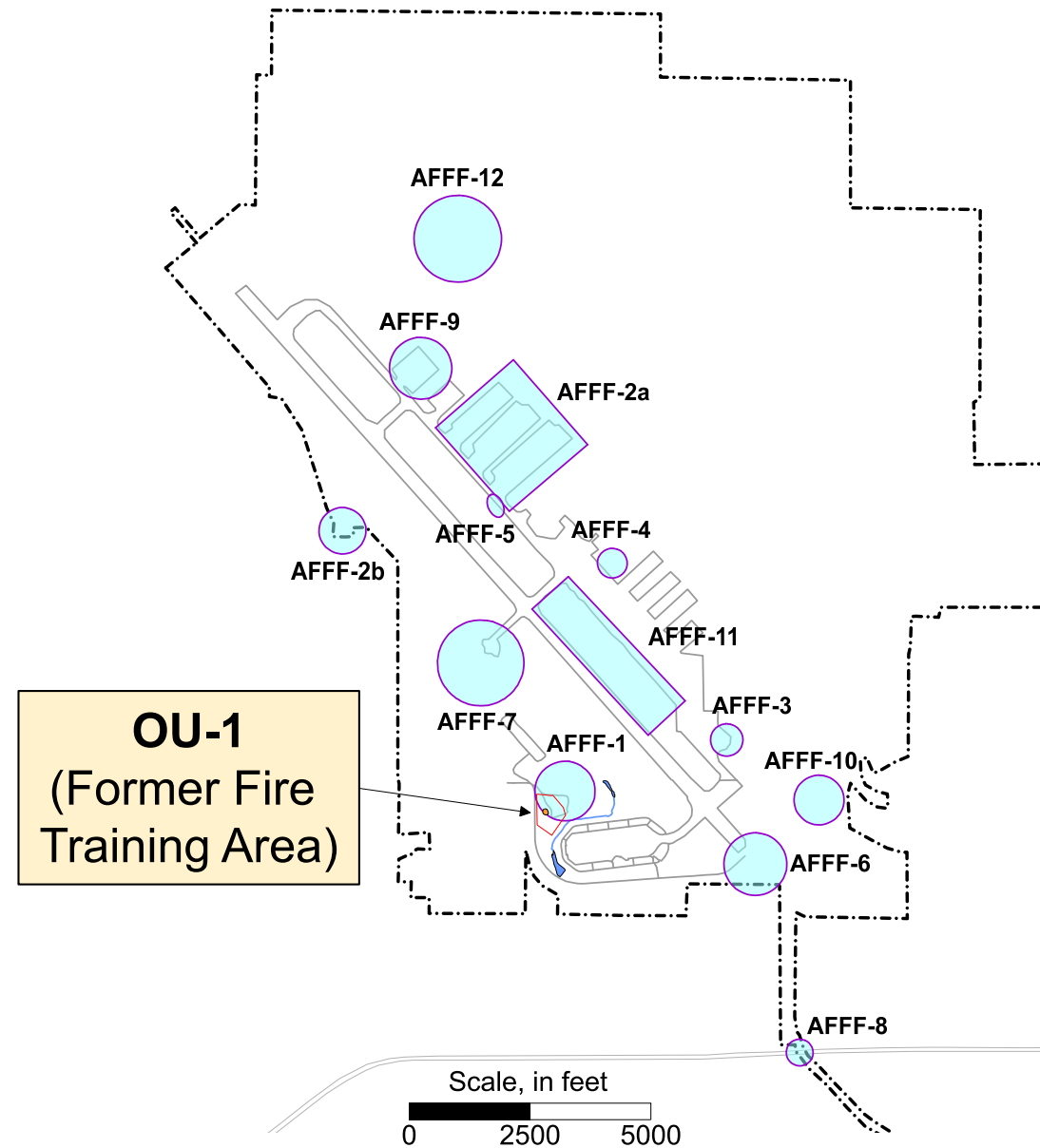
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**Mia Rebeiro-Tunstall
Gabriel Carey**

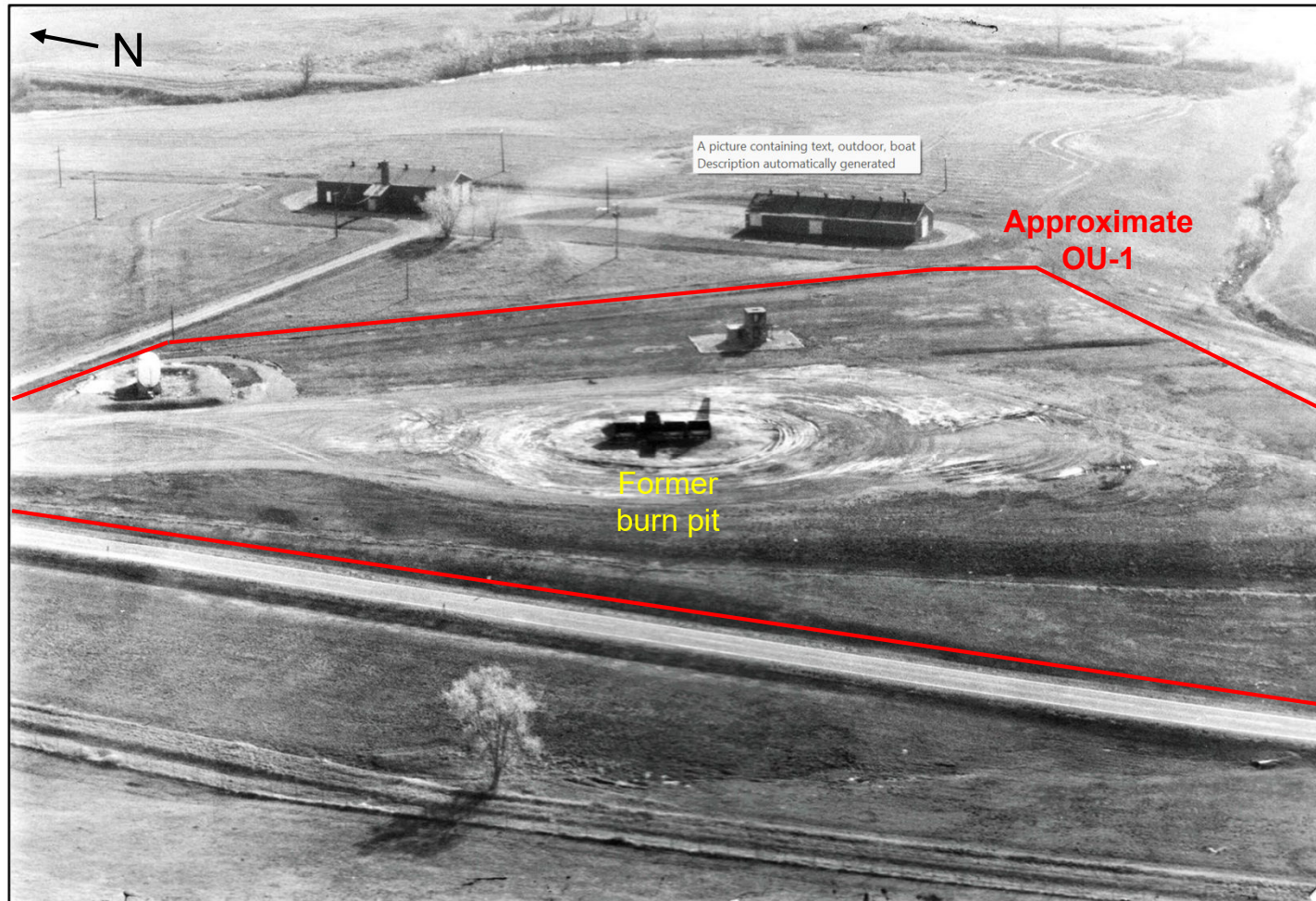
**Kiera Rooney
Sabrina Moga
Maya Worthing**

Ellsworth AFB: Former Fire Training Area



Ellsworth AFB Former Fire Training Area (FFTA)

Former fire training area in 1985 (Rita Krebs, 2025)



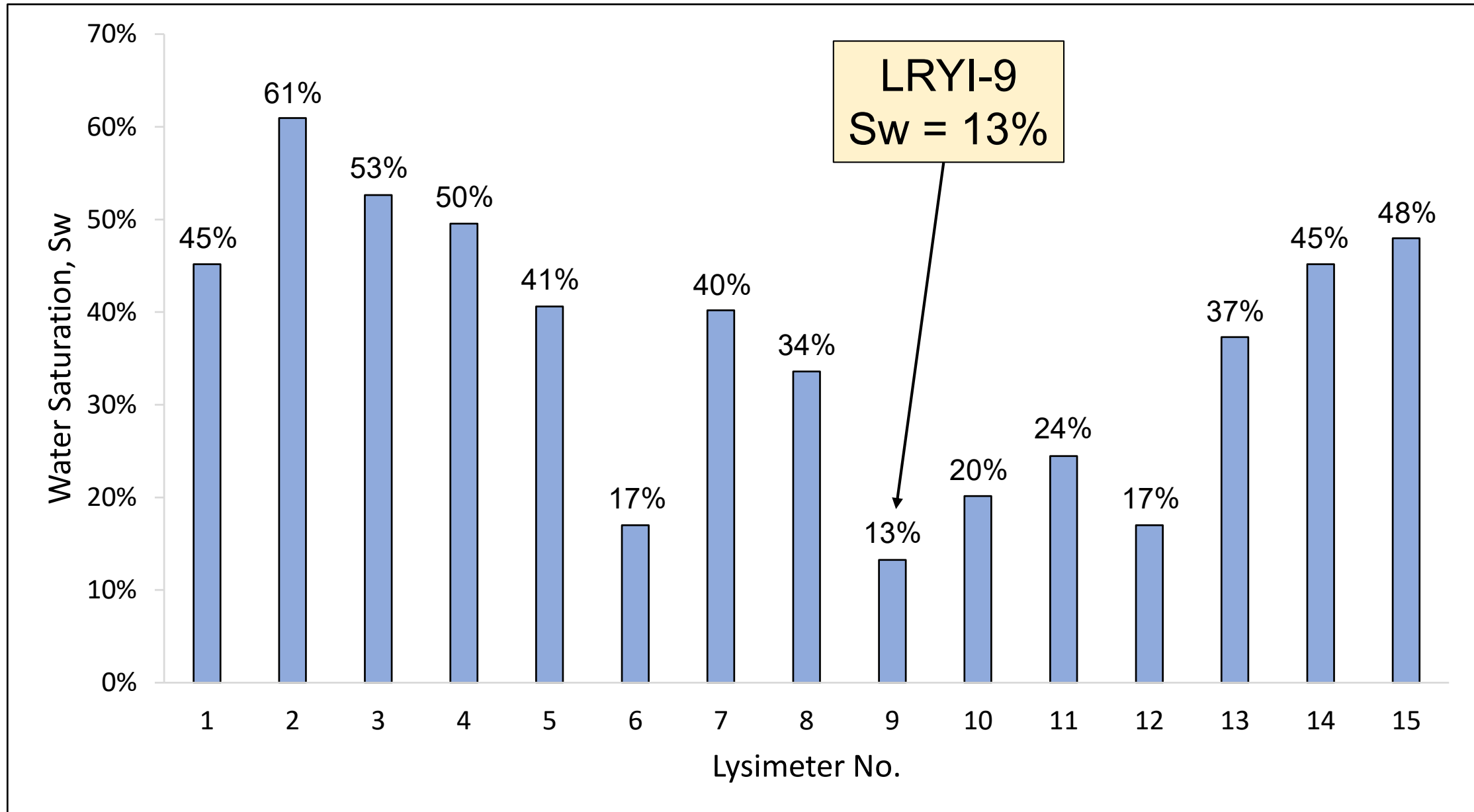
OU-1 (FFTA) AFFF Use

- PFAS-containing AFFF used early 1970s to 1990
- Mixed with water
 - Periodic flushing
- AFFF use ceased in 1990

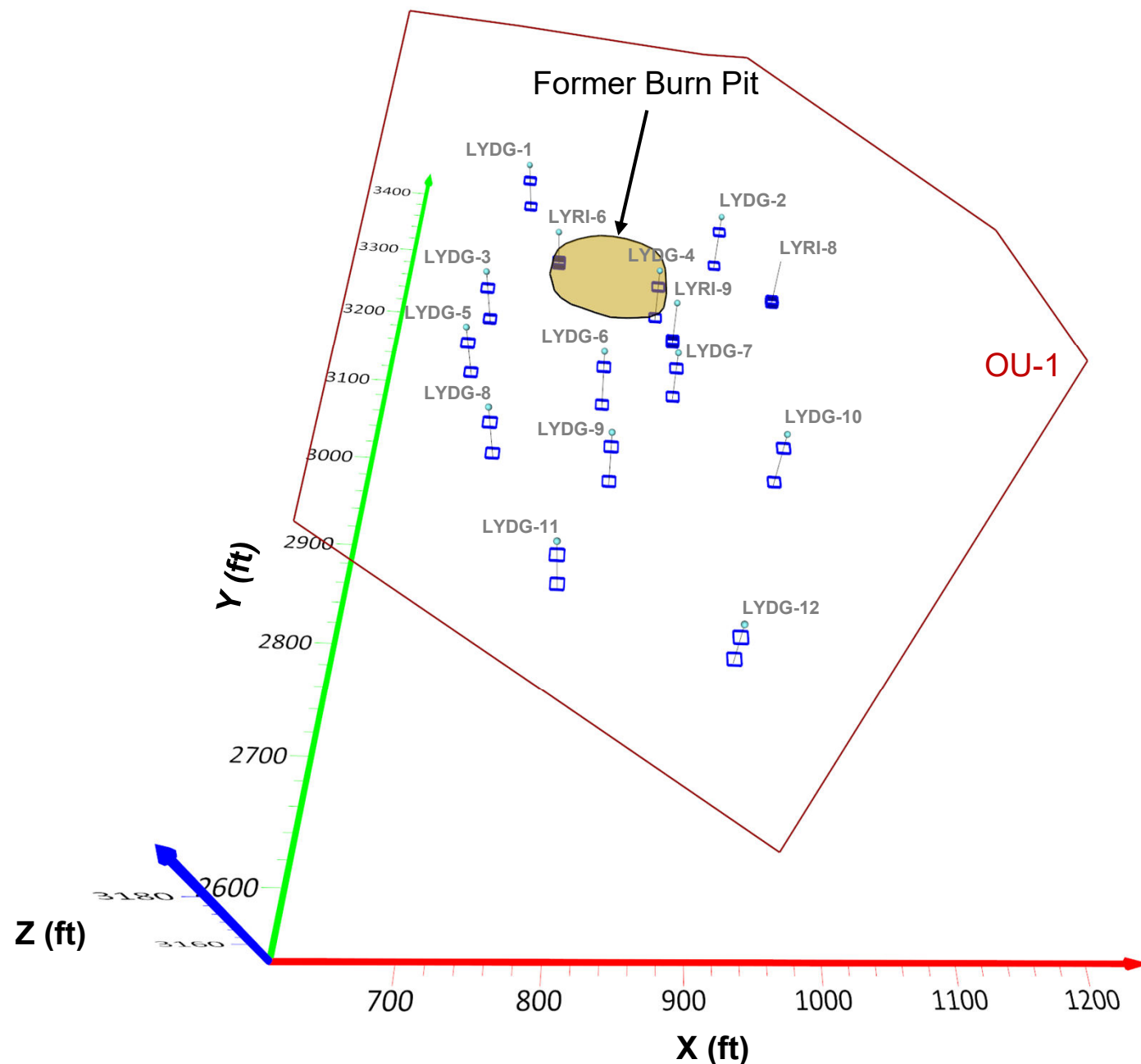
Current Conditions

- PFAS plume in groundwater

Heterogeneity in Water Saturation at RI Lysimeters

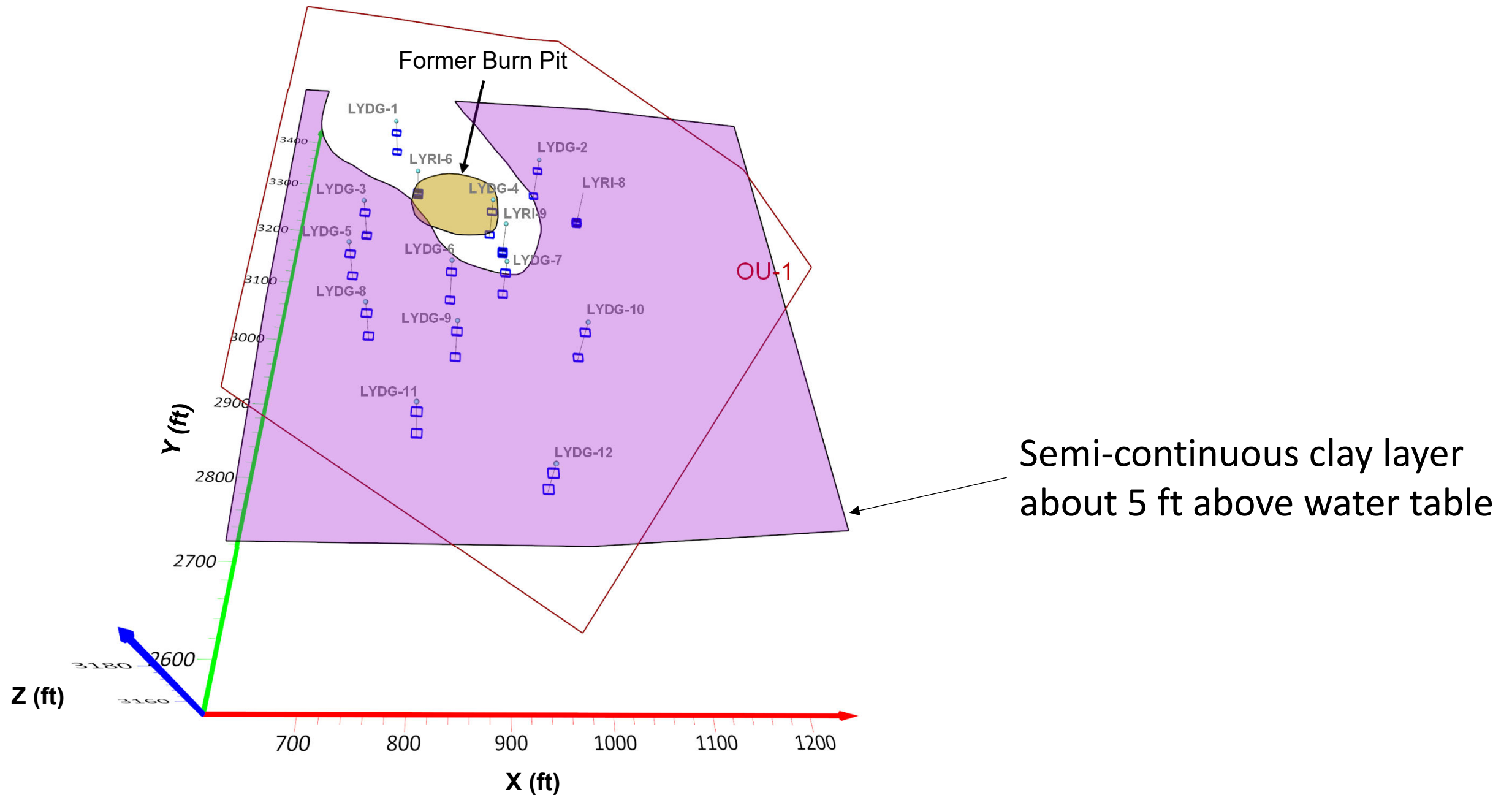


Ellsworth AFB OU-1 Lysimeters in 3-D

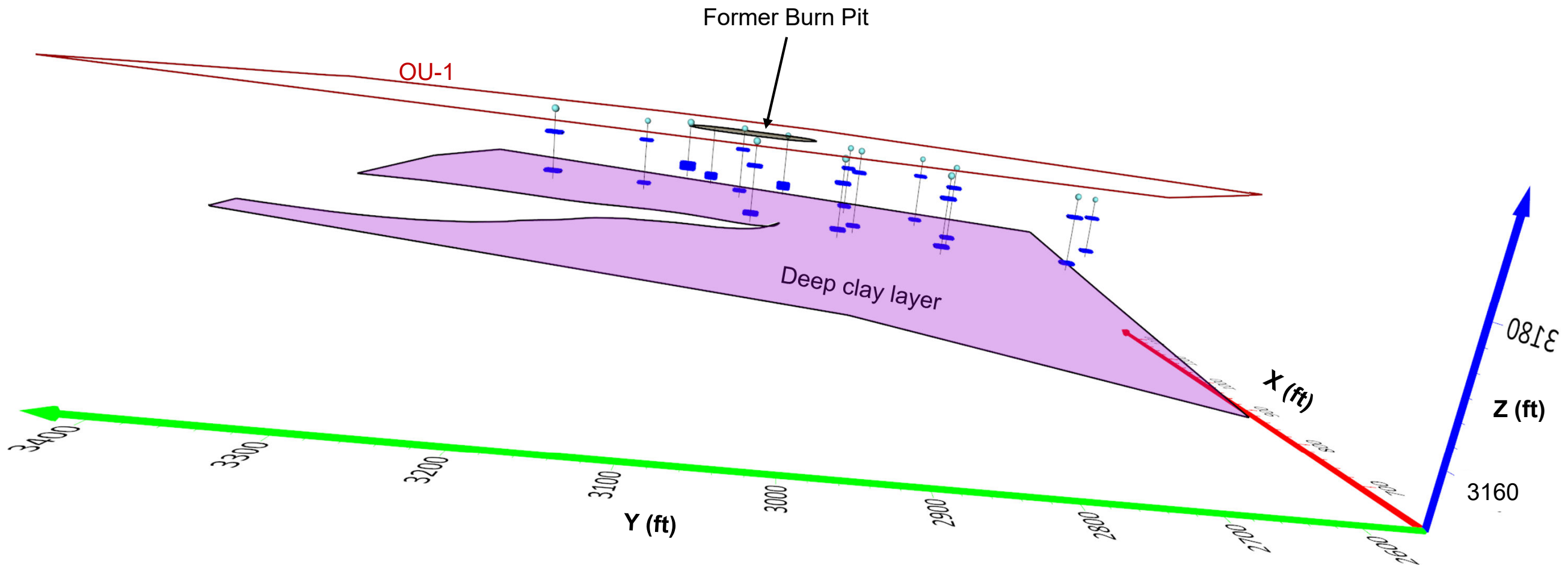


- 15 lysimeters sampled 2021-22
 - DGI – 12 Nested
 - RI – 3 Deep
 - Shallow: 3 ft bgs
 - Deep: 8 to 10 ft bgs
- Water table ~ 20 to 25 ft bgs

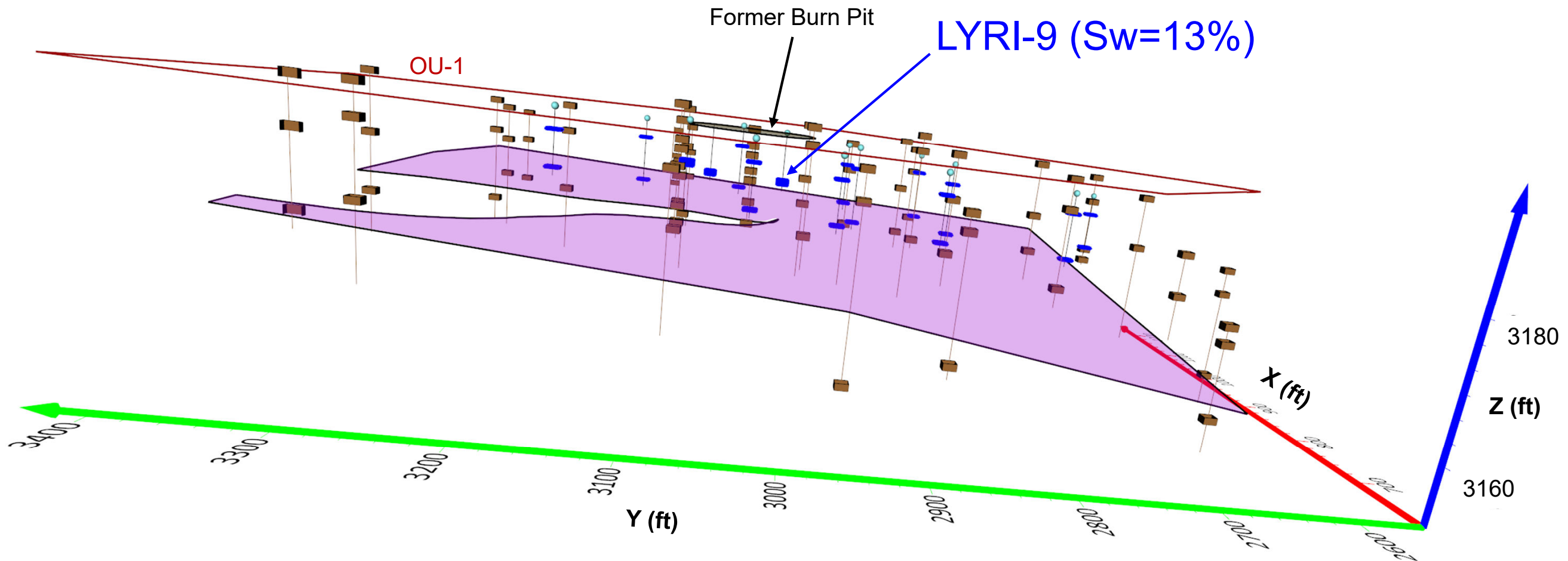
Deep Clay Layer Above Water Table



Side View of Lysimeters in Vadose Zone

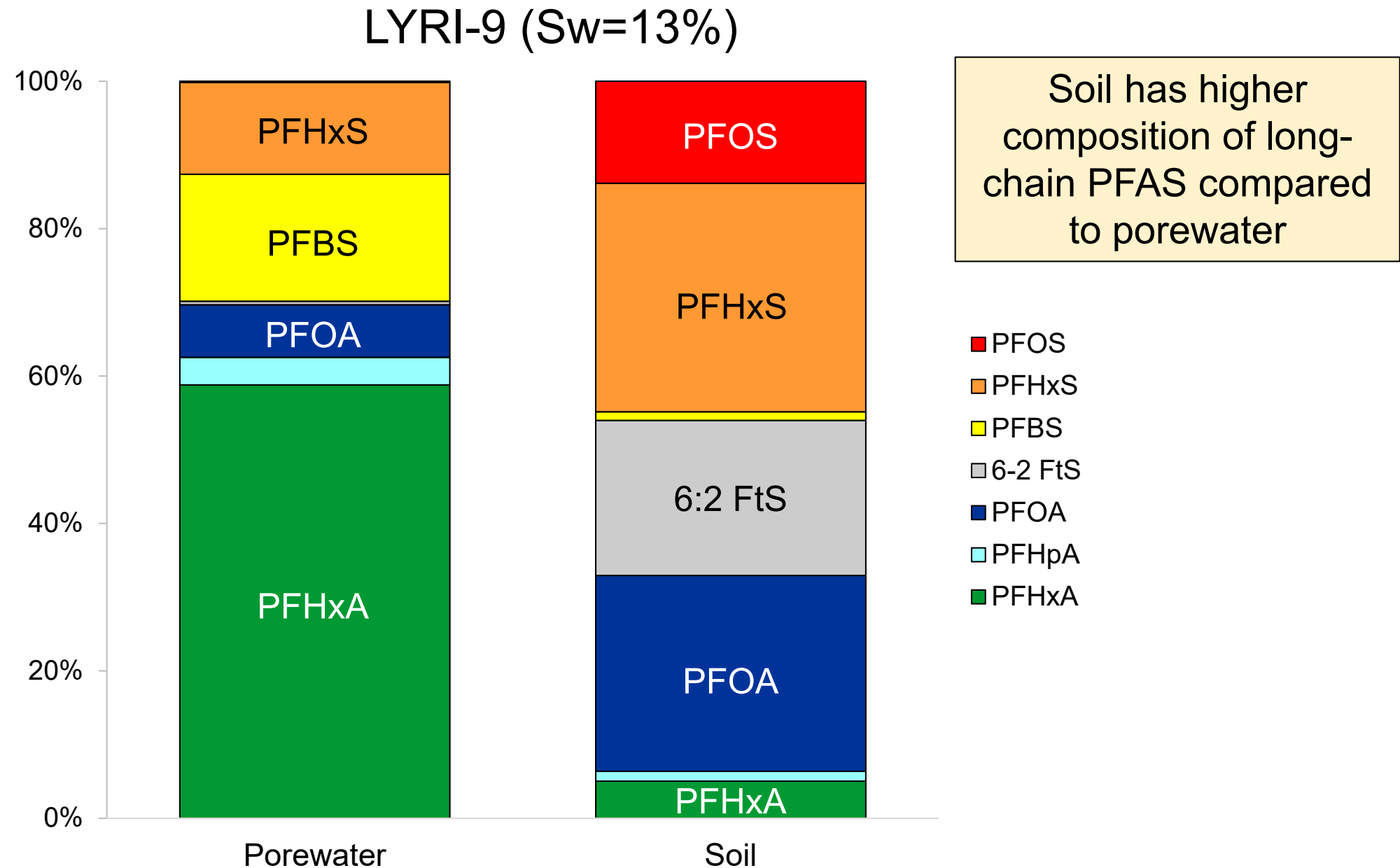


Soil Sample Locations and Lysimeters

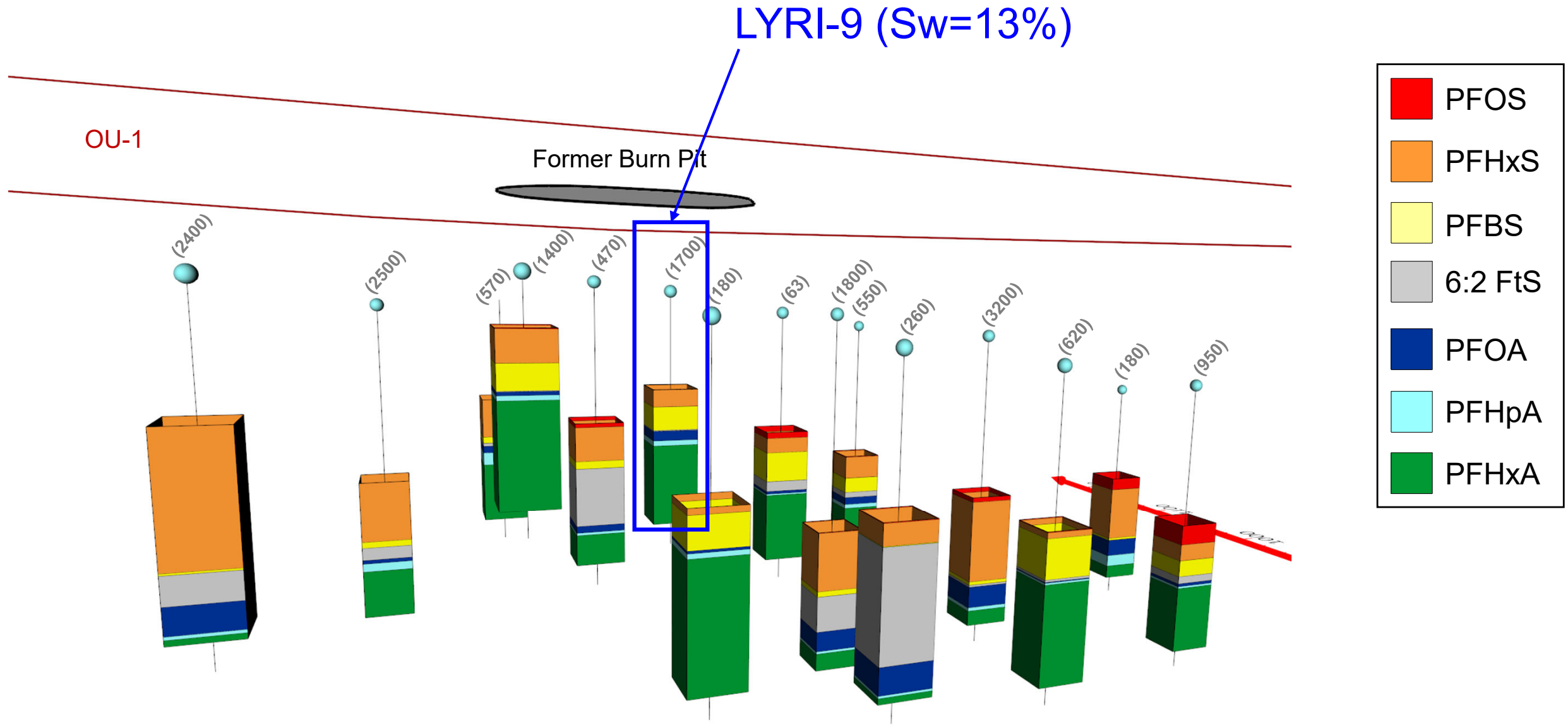


Gravimetric moisture content results are freely available at every soil sample location

PFAS Composition at LYRI-9: Porewater vs Soil



3-D Stacked Bars (Porewater at Deep Lysimeters)



Are Porewater Samples Representative?

Multiple Lines of Evidence

- Porewater reproducibility between monitoring events?
- Vertical attenuation - Porewater versus soil samples
- Influence of S_w on PFAS composition
- Factors influencing M_{d-vz} :
 - Deeper clay layer
 - Low water saturation at depth

PFAS Retention in Shallow Soil at Ellsworth AFB

Carey et al. (2026a)

Remediation Journal

WILEY

RESEARCH ARTICLE OPEN ACCESS

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Correspondence: Grant R. Carey (gcarey@porewater.com)

Received: 3 November 2025 | Revised: 2 January 2026 | Accepted: 7 January 2026

Keywords: AFFF | air-water interface | mass discharge | PFAS | vadose zone

ABSTRACT

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The use of AFFF in former fire training areas (FFTAs) typically involved the spraying of diluted AFFF products into burn pits to put out fires on a regular basis. Prior to the 1990s, these burn

pits were typically unlined. Carey et al. (2025) discuss the challenges associated with analyzing comprehensive PFAS data sets collected at AFFF-impacted sites. The utility of radial diagrams for differentiating between AFFF product uses and for evaluating ratios indicative of precursor biotransformation was demonstrated with a case study at Ellsworth Air Force Base (Ellsworth AFB) in South Dakota by Carey et al. (2025).

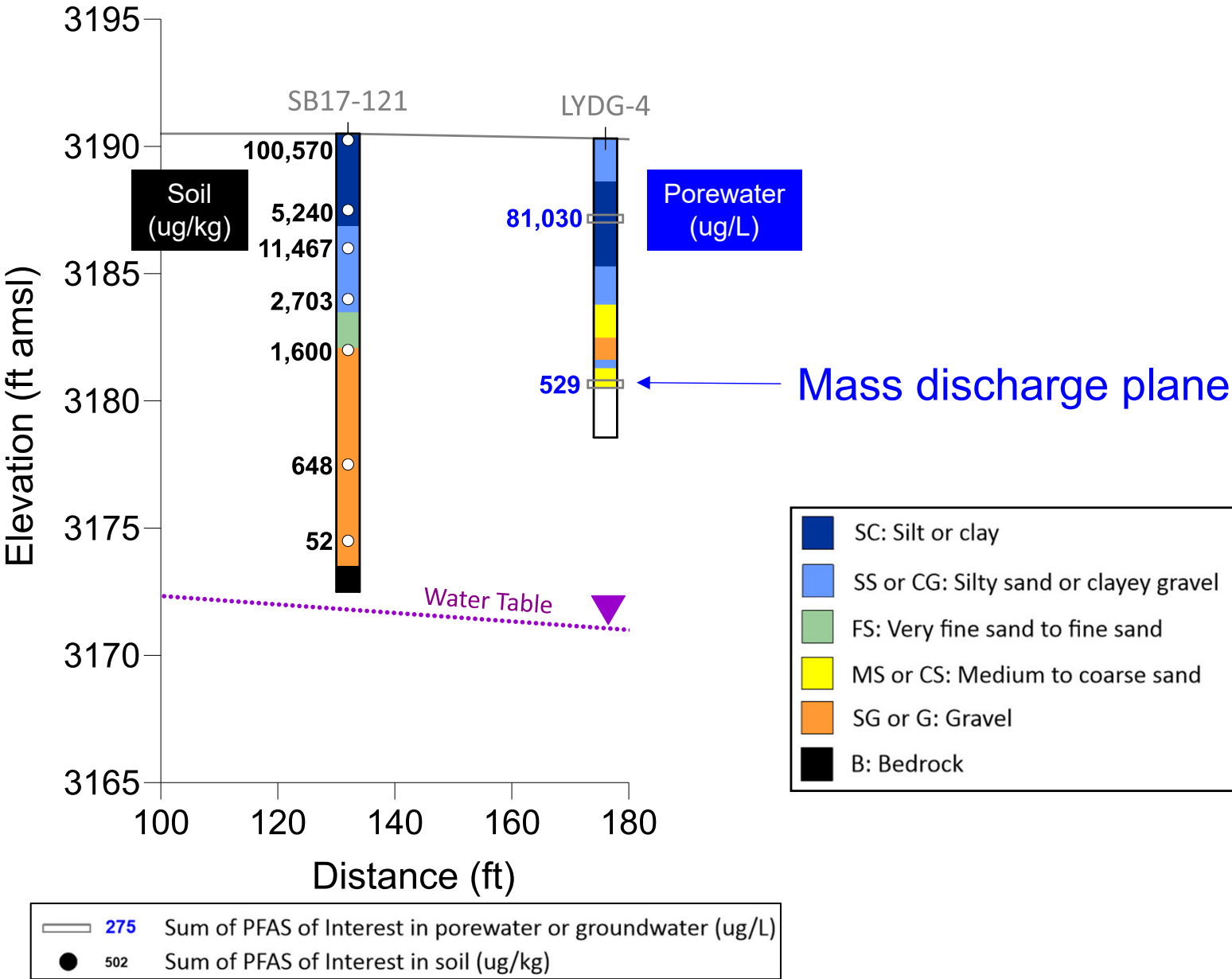
The surfactant qualities associated with PFAS cause many of these chemicals to adsorb to air-water interfaces, which will

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Remediation Journal, 2026; 36:e70058
<https://doi.org/10.1002/rem.70058>

1 of 16



Zero-Flux Plane at Another Semi-Arid Site

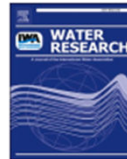
Wallis et al. (2022)



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Water Research

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Model-based identification of vadose zone controls on PFAS mobility under semi-arid climate conditions

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^b CSIRO Land and Water, Wembley, Western Australia 6014, Australia

^c CSIRO Land and Water, Glen Osmond, South Australia 5064, Australia

^d School of Earth Sciences, University of Western Australia, Crawley, Western Australia 6913, Australia

ARTICLE INFO

Keywords:

PFAS
Leaching
Vadose zone
Sorption
Air-water-interface
Numerical modelling

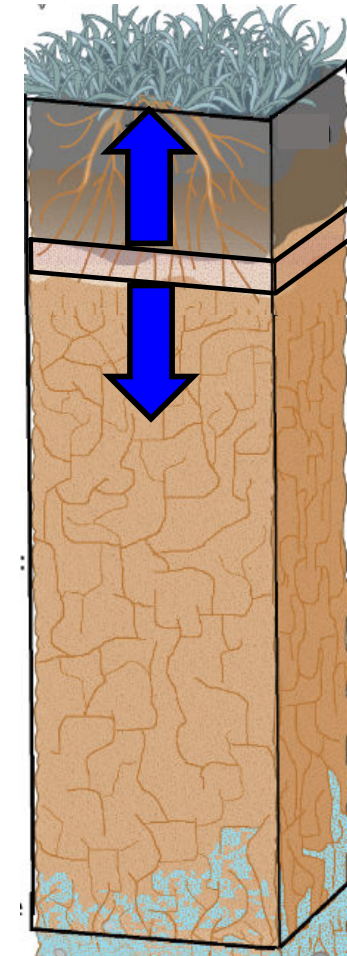
ABSTRACT

Contamination through per-and poly-fluoroalkyl substances (PFAS) have occurred globally in soil and ground-water systems at military, airport and industrial sites due to the often decades-long periodic application of firefighting foams. At PFAS contaminated sites, the unsaturated soil horizon often serves as a long-term source for sustained PFAS contamination for both groundwater and surface water runoff. An understanding of the processes controlling future mass loading rates to the saturated zone from these source zones is imperative to design efficient remediation measures. In the present study, hydrochemical data from a site where PFAS transport was observed as a result of the decades-long application of AFFF were used to develop and evaluate conceptual and numerical models that determine PFAS mobility across the vadose zone under realistic field-scale conditions. The simulation results demonstrate that the climate-driven physical flow processes within the vadose zone exert a dominating control on the retention of PFAS. Prolonged periods of evapotranspiration exceeding rainfall under the semi-arid conditions trigger periods of upward flux and evapoconcentration, leading to the observed persistence of PFAS compounds in the upper ca. 2 metres of the vadose zone, despite cessation of AFFF application to soils since more than a decade. Physico-chemical retention mechanisms, namely sorption to the air-water interface (AWI) and sediment surfaces, contribute further to PFAS retention. The simulations demonstrate how PFAS downward transport is effectively confined to short periods following discrete rain events when soils display a high degree of saturation. During these periods, AWI sorption is at a minimum. In addition, high PFAS concentrations measured and simulated below the source zone reduce the effect of the AWI further due to a decrease in surface tension associated with elevated PFAS concentrations. Consequently, time-integrated PFAS migration and retardation illuminates that the field-relevant PFAS transport rates are predominantly controlled by the physical flow processes with a lower relative importance of AWI and sediment sorption adding to PFAS retention.

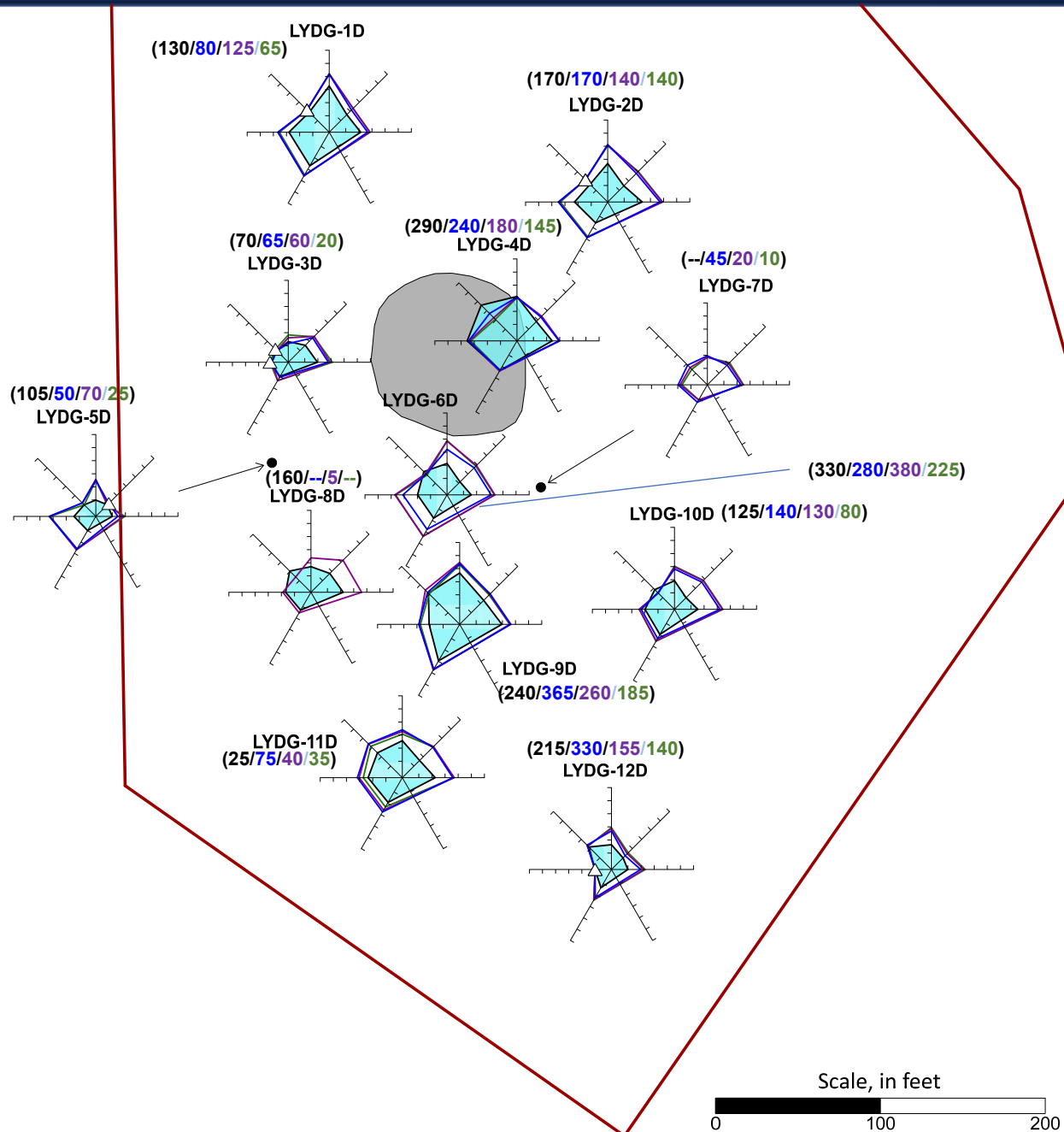
Adamson and Newell (2026): EREL-0101 e-Learning Module

Zero-flux plane

Water table

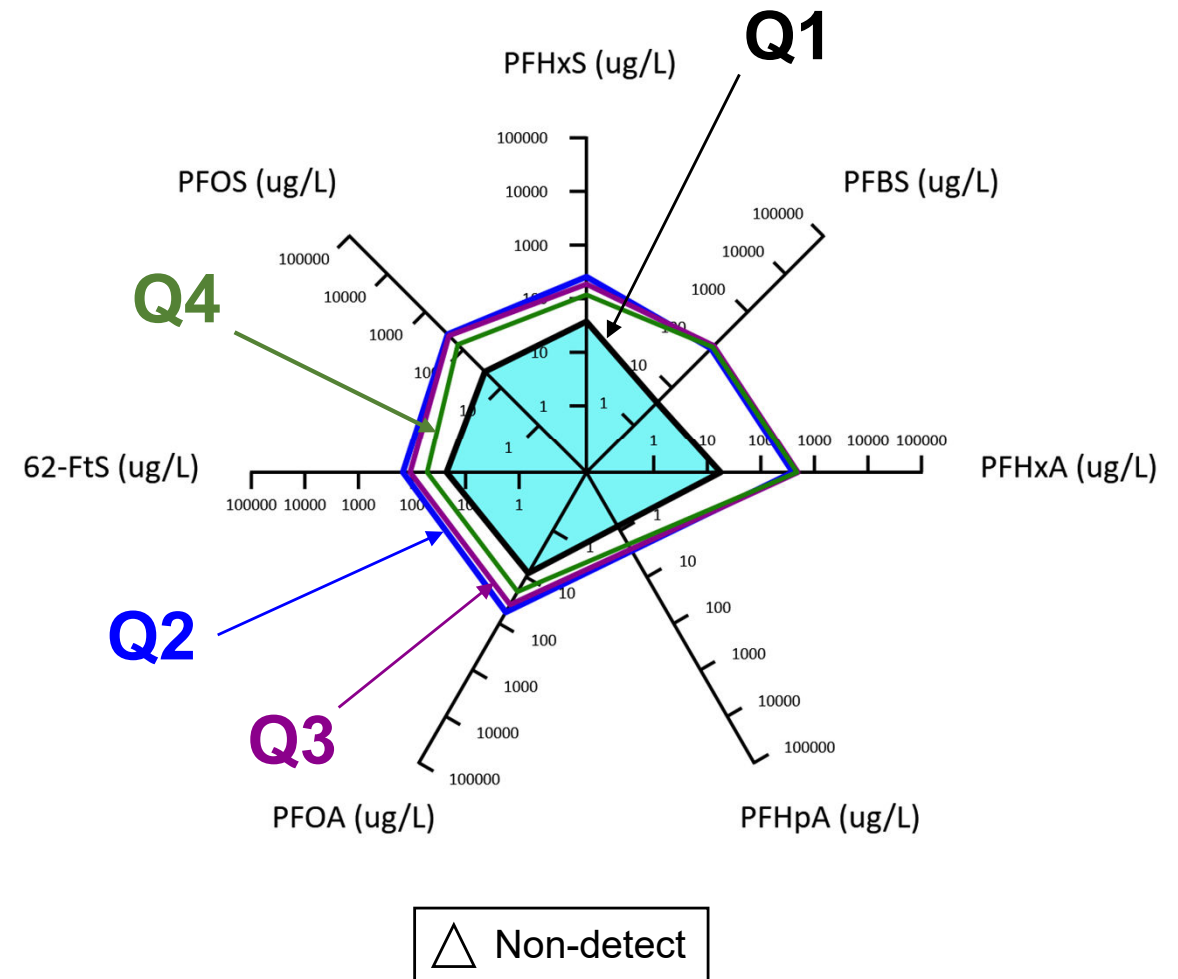


Checking Porewater Sample Reproducibility

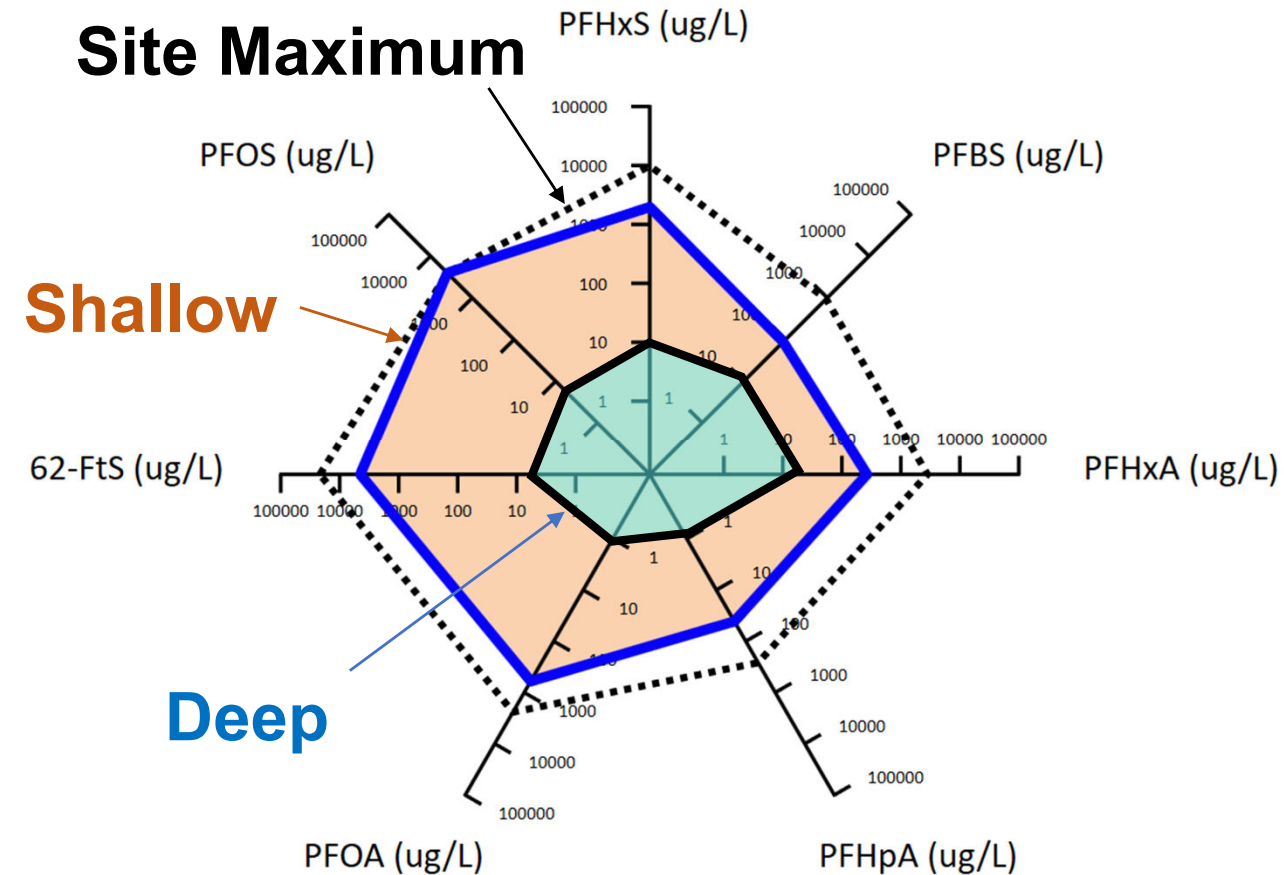
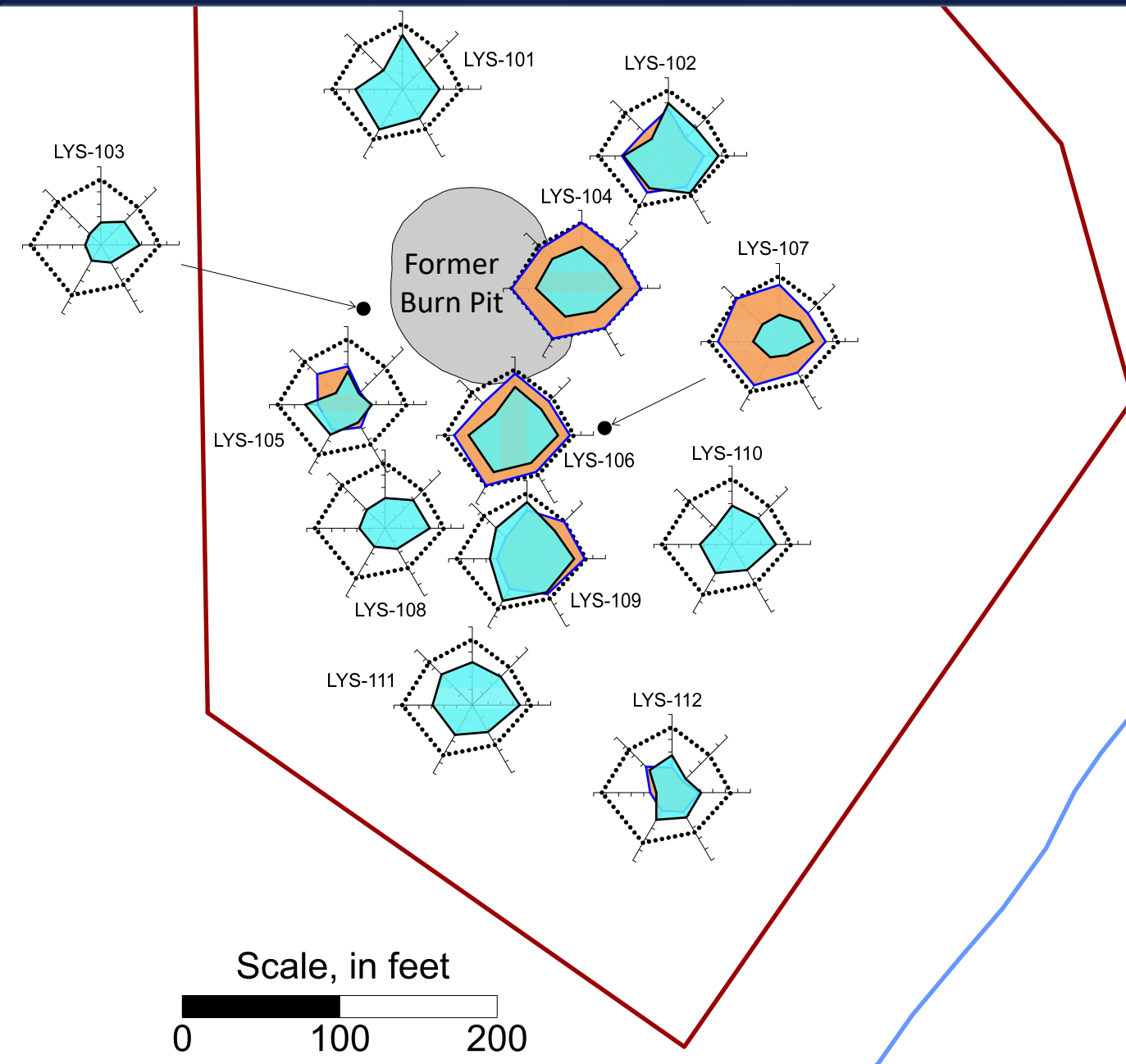


Sample yields (mL) by event:
(25/75/40/35)

-- Insufficient sample volumetric yield

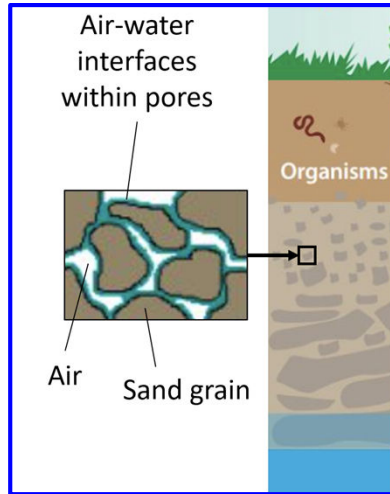


Shallow versus Deep Porewater Concentrations



Data from Anderson et al. (2022)

SPLP Tests: 20x Mass Ratio (Liquid-Solid)



4 Tablespoons of soil
(0.1 kg ~ 0.06 L)



Mixed with 2 liters of water



S_w	V_{PW} (Liters)	Dilution Factor, $LLDF$
15%	0.004	530
50%	0.012	160

$$\rho_b = 1.6 \text{ kg/L}$$

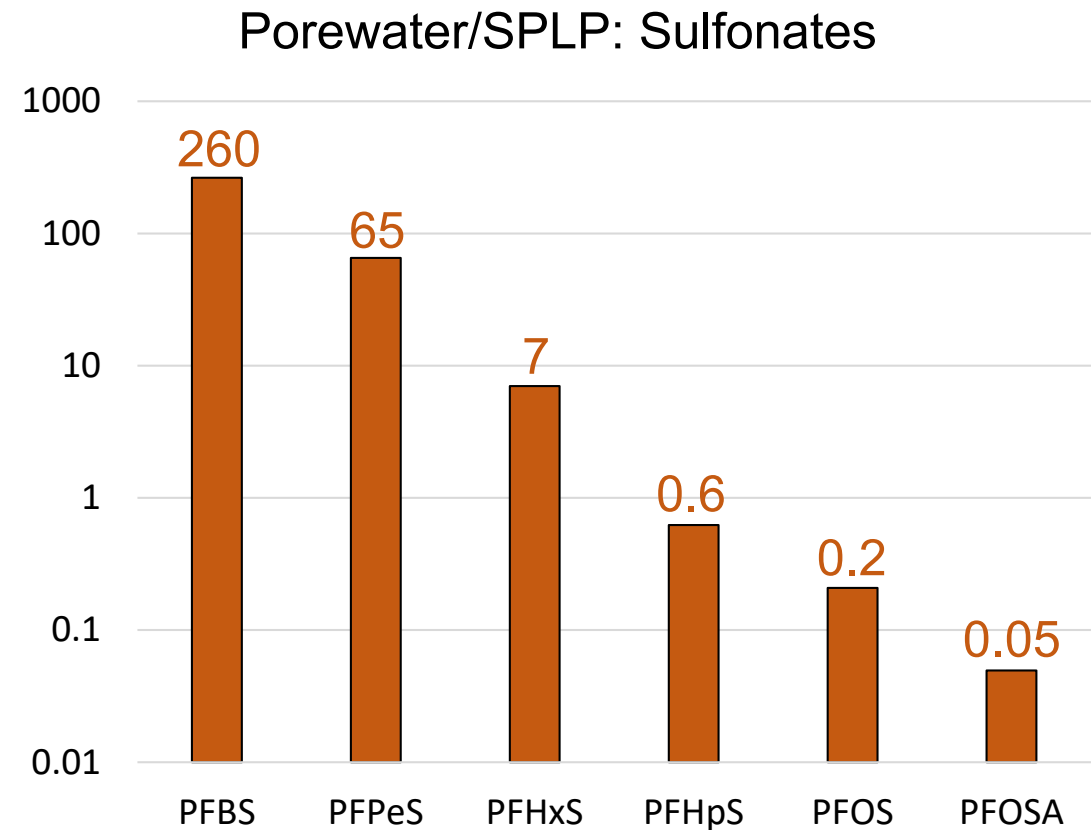
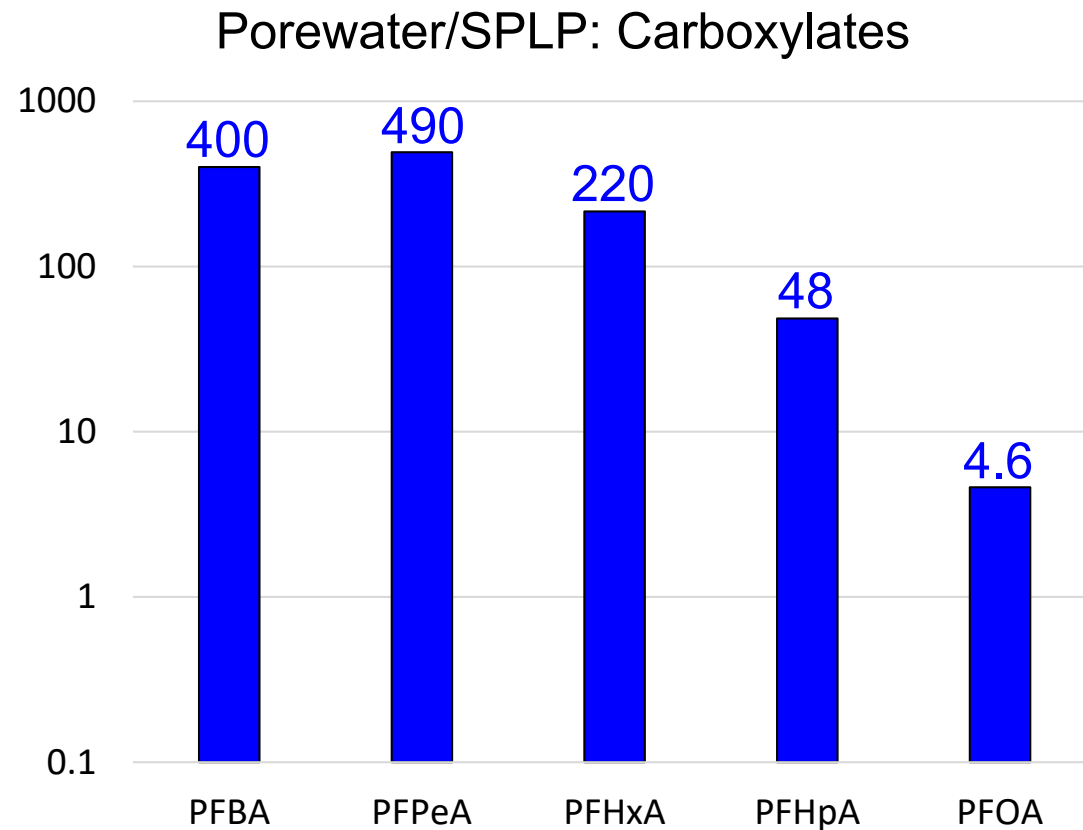
$$\theta_t = 0.40 \text{ L/L}$$

$$LLDF = \frac{(20 \text{ L/kg}) \rho_b}{S_w \theta_t}$$

where $LLDF$ = liquid-to-liquid dilution factor (dimensionless);
 ρ_b = soil dry bulk density (kg/L);
 S_w = water saturation (%); and
 θ_t = total porosity (L/L).

Ratio of Porewater to SPLP Leachate

LYRI-9: $S_w = 13\%$



Carey et al. (2026b)

$$C_{SPLP} = C_p \left(\frac{\frac{\theta_w}{\rho_b} \left(1 + K_d \frac{\rho_b}{\theta_w} + \frac{K_{aw} a_{aw}}{\theta_w} \right)}{(K_d + 20 \text{ L/kg})} \right)$$

Conclusions

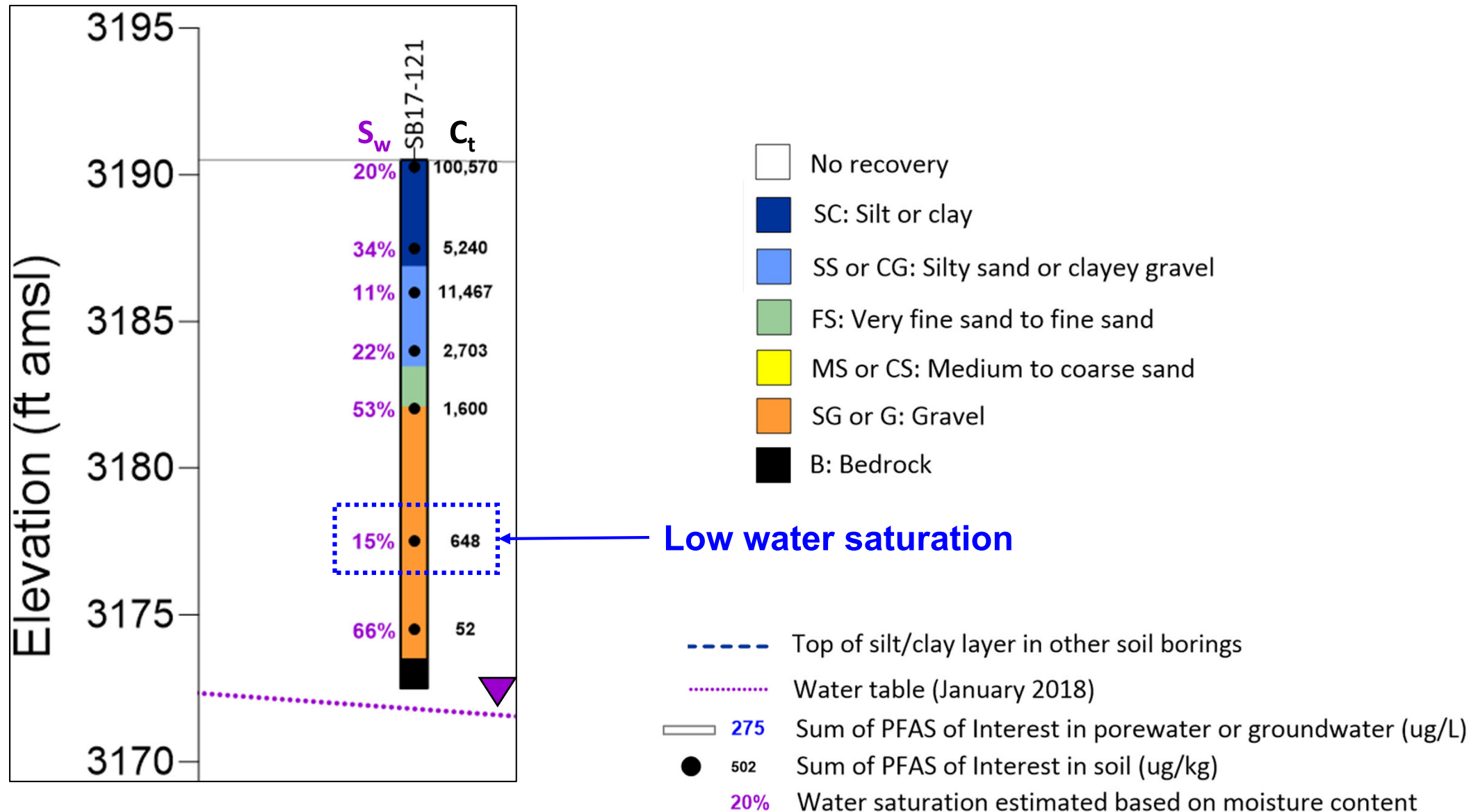
- Porewater samples are reproducible and representative
 - May be used for remedial decision-making (e.g., Mass discharge)
- SPLP was not representative of PFAS in porewater
 - Large LLDF
 - Adsorption at air-water interface affects PW but not SPLP
- SPLP may overestimate short-chain K_d
 - May need longer SPLP tests to improve K_d estimates (TBD)

Recommendations

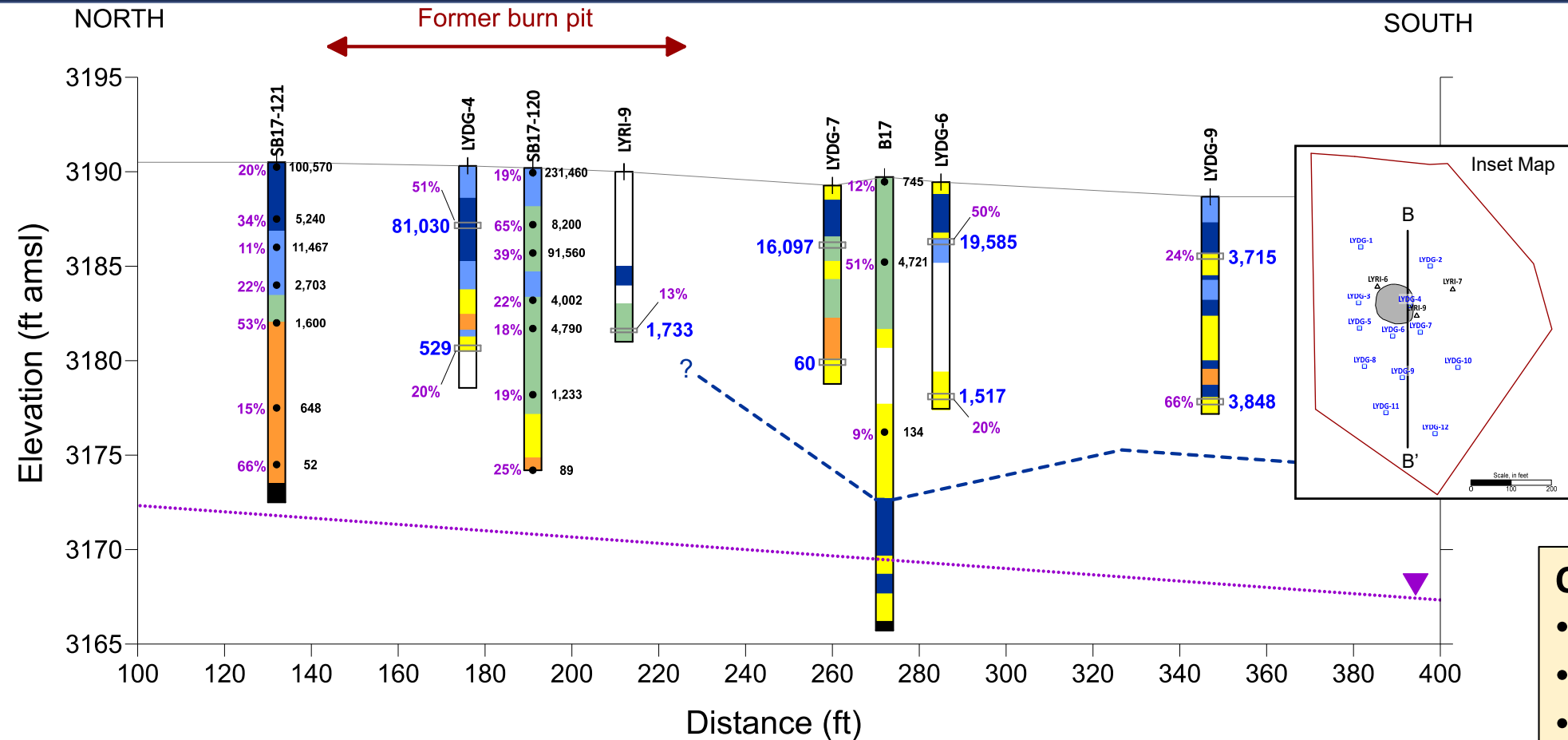
- Mine your laboratory analytical reports for moisture content data
 - Critical for vadose zone assessments
- Soil samples vs. depth to confirm vertical PFAS attenuation
- Check influence of SPLP test duration (18 h) on K_d estimates
- CSM improved with lines-of-evidence approach
- PFAS LEACH model for SSLs and mass discharge estimates

Extra Slides

PFAS Attenuation in Soil



FFTA Cross-Section



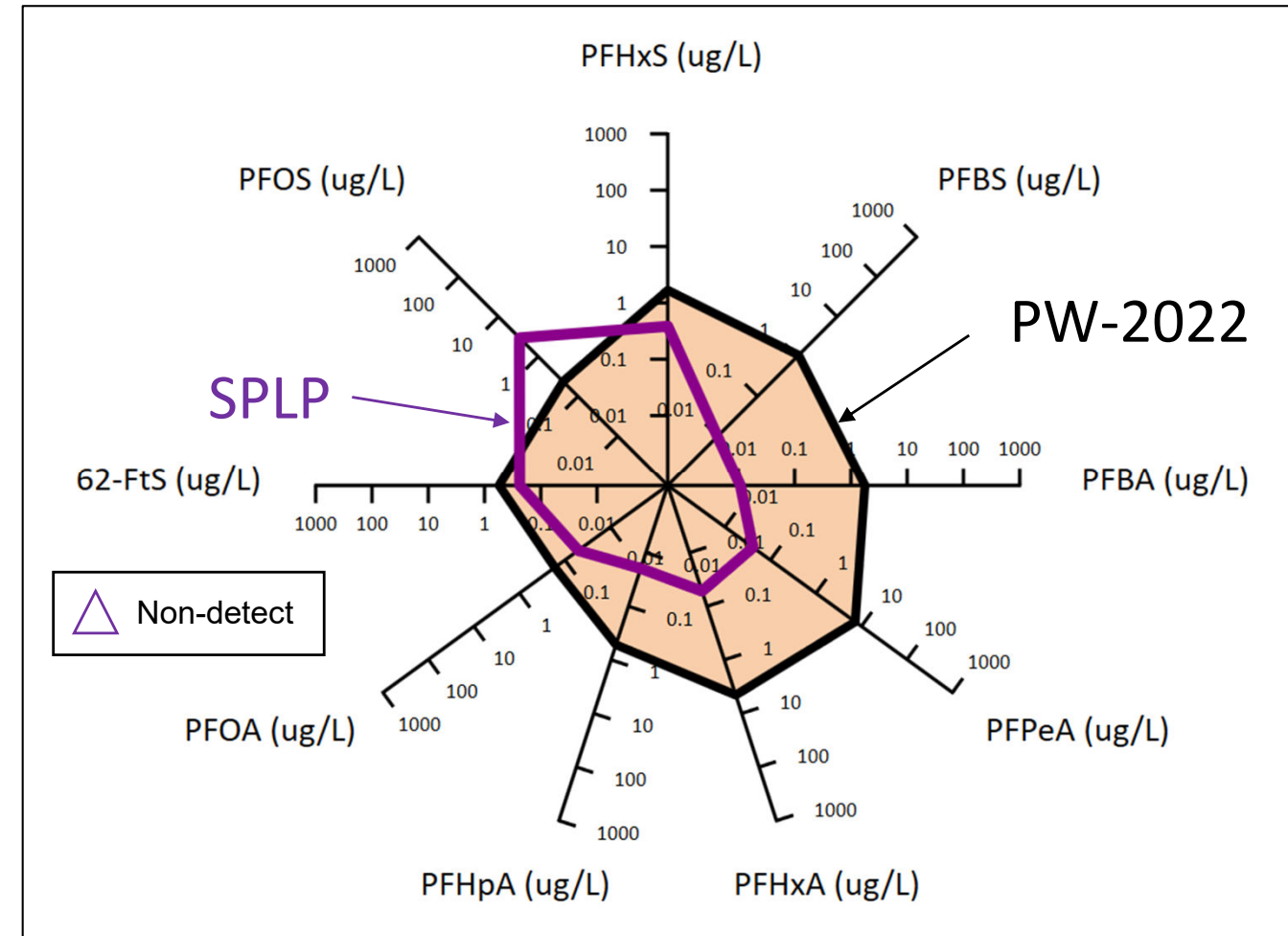
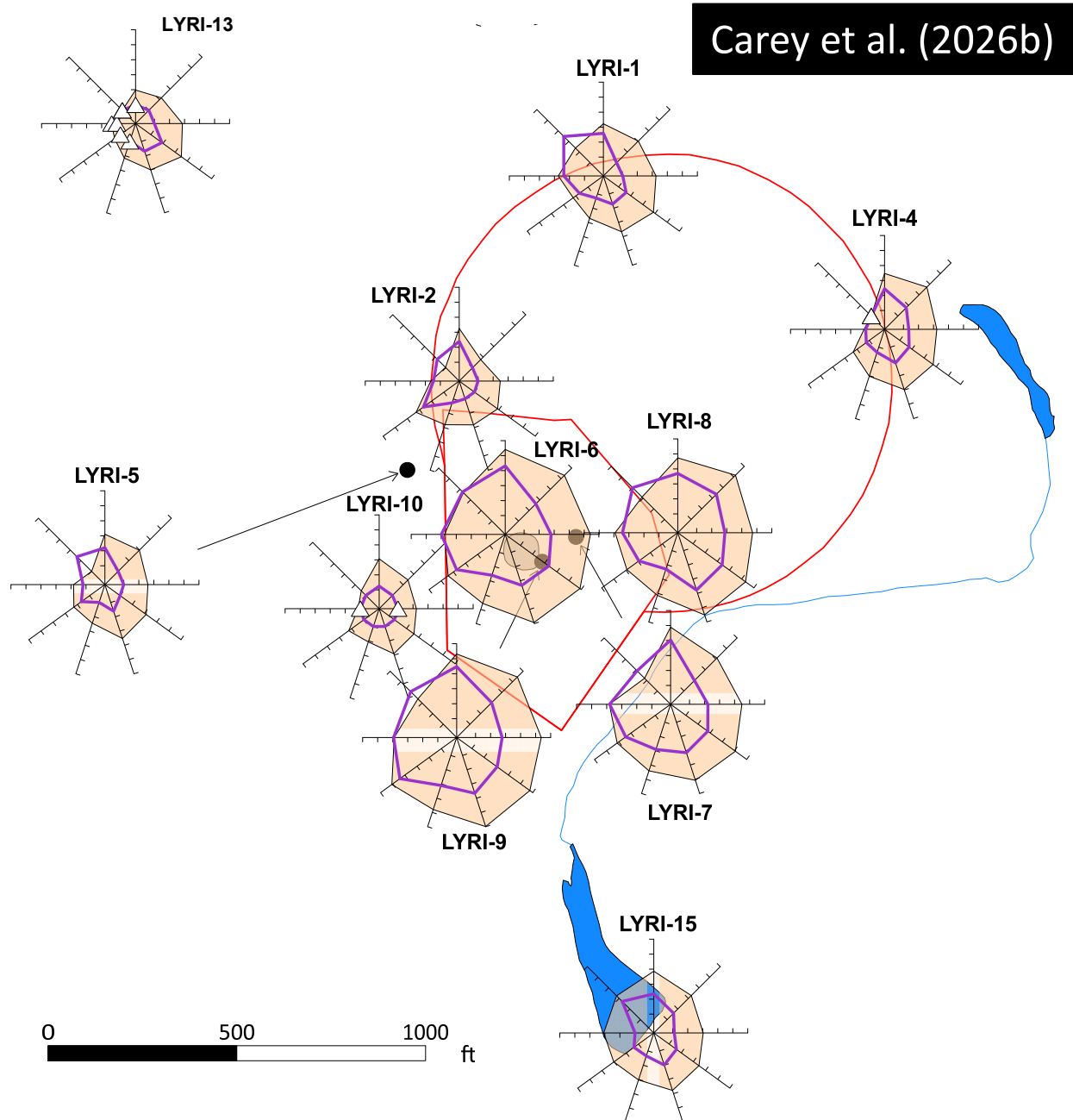
Cross-Section Data

- Geology
- Soil concentrations
- Porewater concentrations
- Water saturation, Sw
- Semi-continuous clay layer
- Water table surface

LEGEND

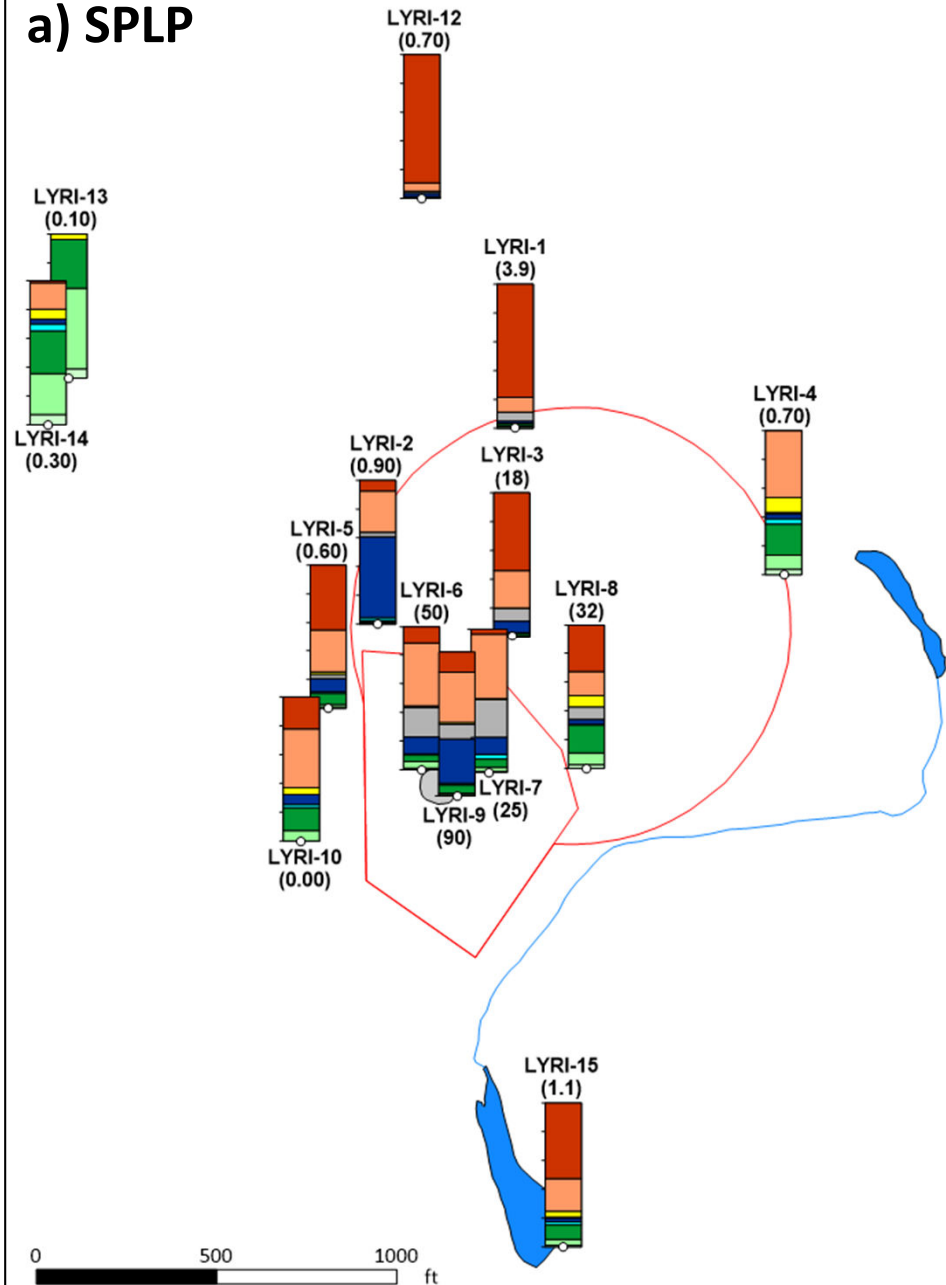
- | | | |
|--|---|---|
| SC: Silt or clay | FS: Very fine sand to fine sand | SG or G: Gravel |
| SS or CG: Silty sand or clayey gravel | MS or CS: Medium to coarse sand | B: Bedrock |
| No recovery | | |
| ---- Top of silt/clay layer in other soil borings | 275 Sum of PFAS of Interest in porewater or groundwater (ug/L) | |
| Water table (January 2018) | ● 502 Sum of PFAS of Interest in soil (ug/kg) | |
| | 20% Water saturation estimated based on moisture content | |

SPLP versus Porewater Concentrations

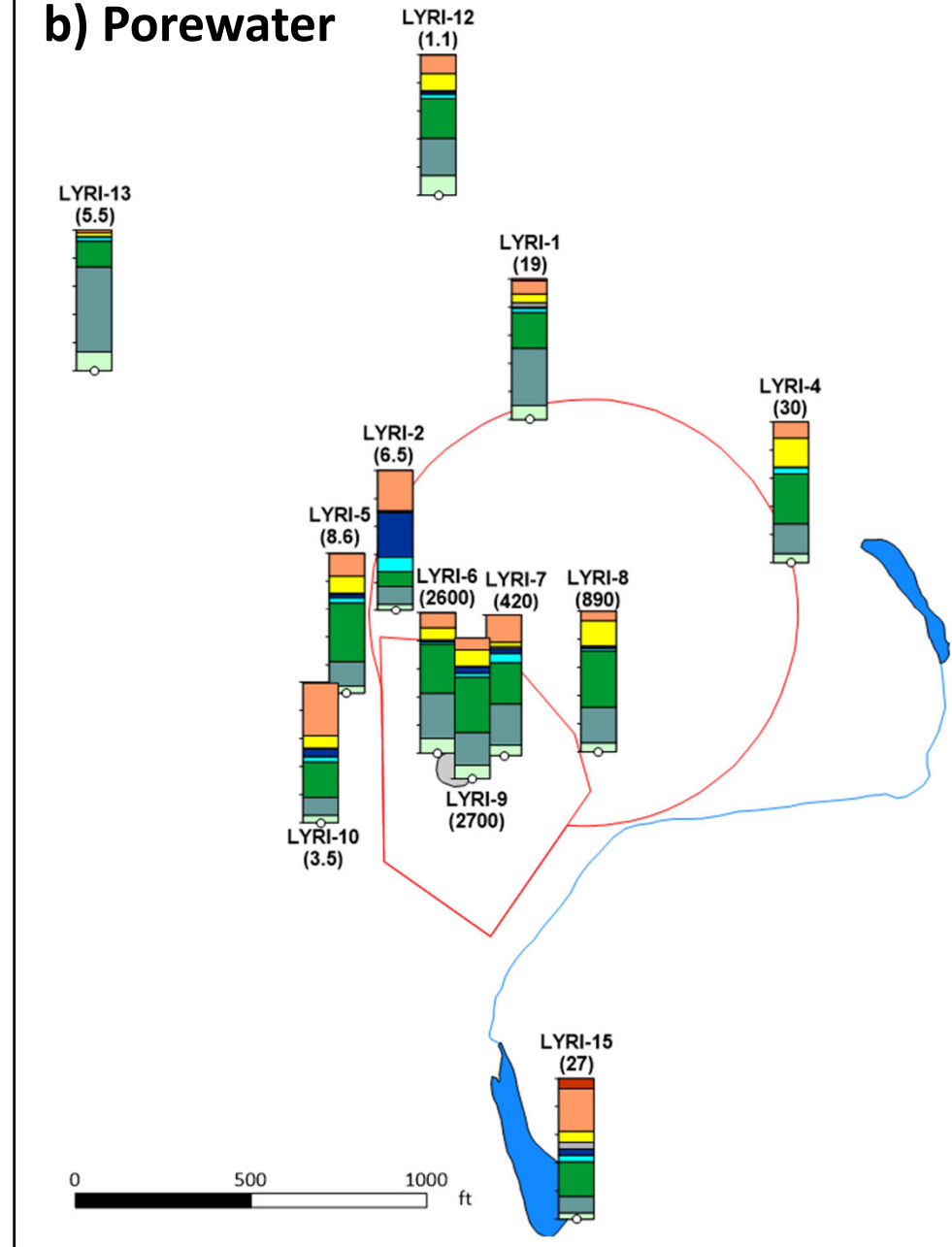


PFAS Composition: SPLP versus Porewater

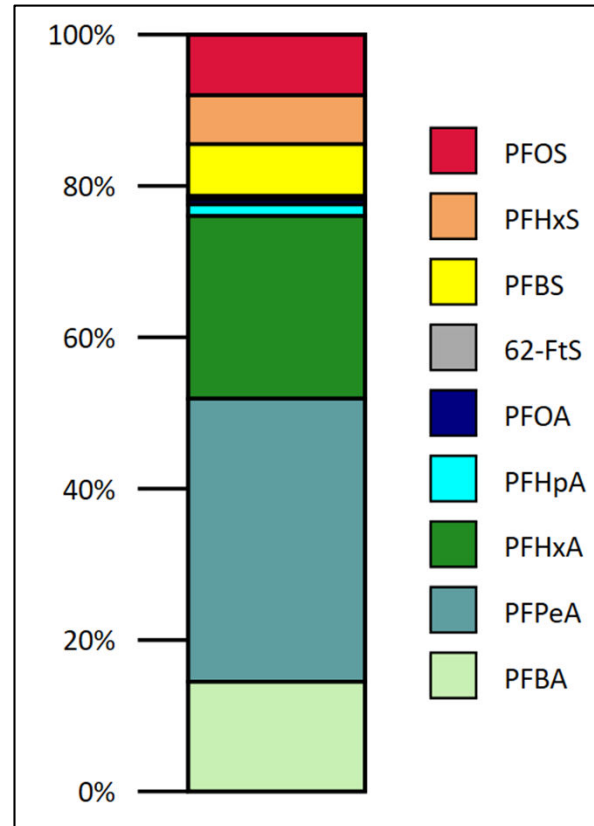
a) SPLP



b) Porewater



Carey et al. (2026b)



PFAS Leach: Mass Discharge at Former Burn Pit

Computed Results from PFAS-LEACH-Analytical

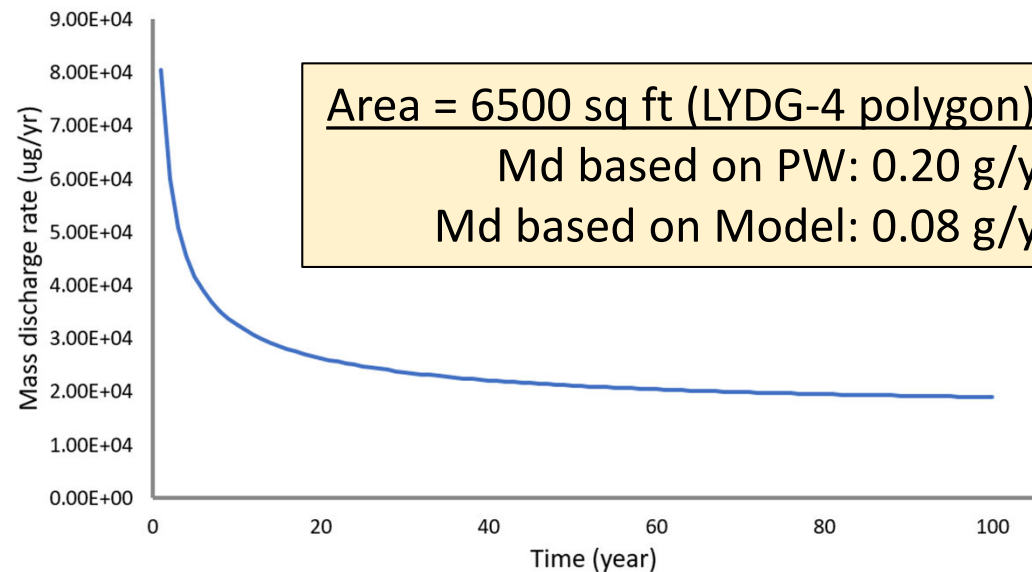
Select what to plot



Vadose-zone mass discharge rate

Download data

Vadose-zone mass discharge rate (PFOA)



Development and Demonstration of PFAS-LEACH—A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

ER21-5041

POINT OF CONTACT

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Principal Investigator

University of Arizona

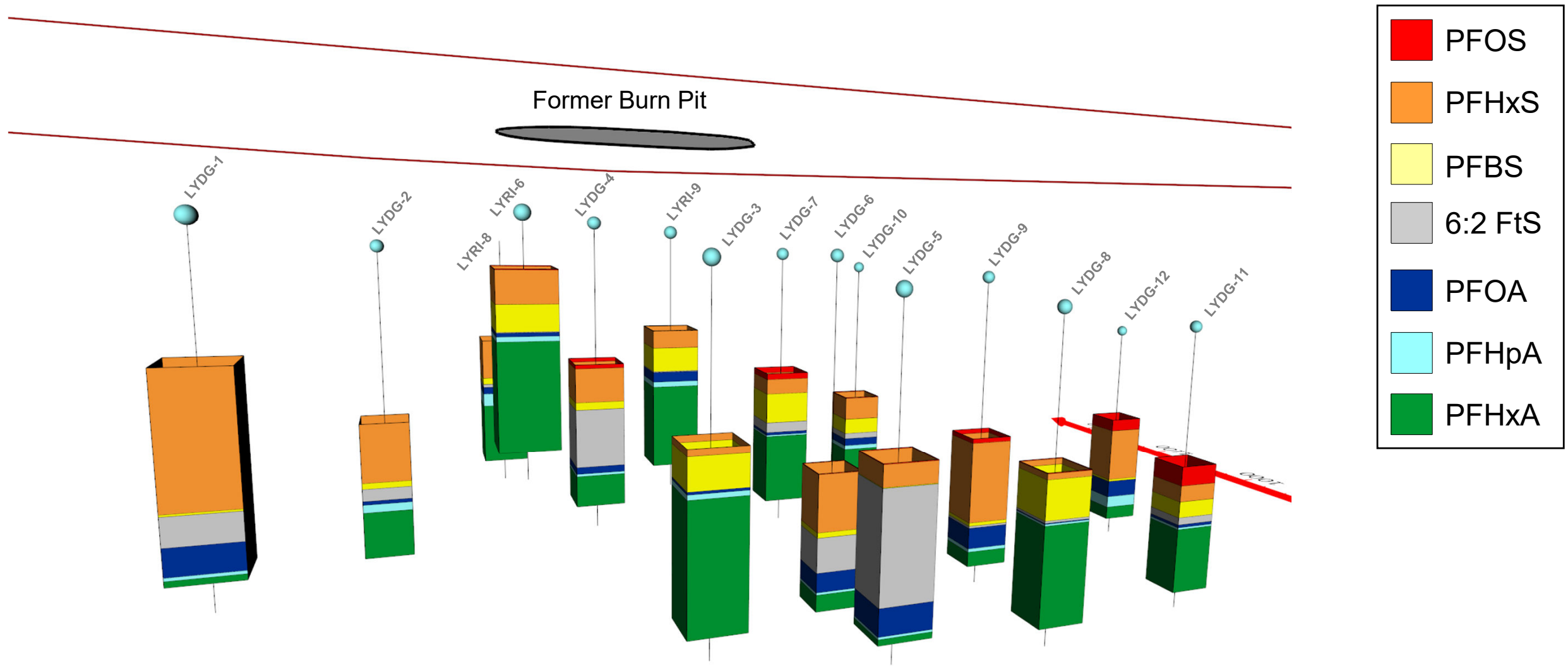
Phone: (520) 626-9971



<https://github.com/GuoSFPLab/PFAS-LEACH-Tier-3-4>

3-D Stacked Bars (Porewater at Deep Lysimeters)

OU-1



RI Lysimeters

