



Examining the Carbon Implications of Legacy Sediment Removal in Pennsylvania Watersheds

From deep in the past to the present

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Restoration Implications for the Carbon Cycle

Well documented aims of restoration *via* legacy sediment removal such as:

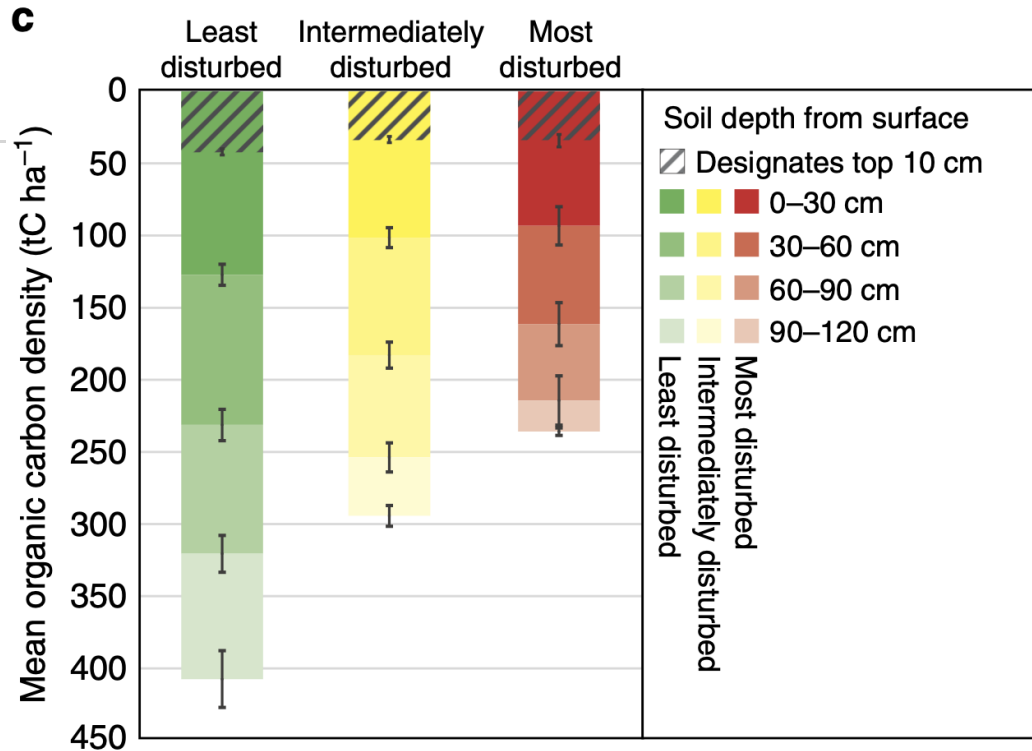
- Enhance groundwater recharge, suspended sediment reduction, nitrogen and phosphorus load reduction
- To achieve these aims, wetland restoration practices focus on modifications of the site hydrology and reestablishment of wetland vegetation
- **These actions have direct implications for the wetland C cycle.**



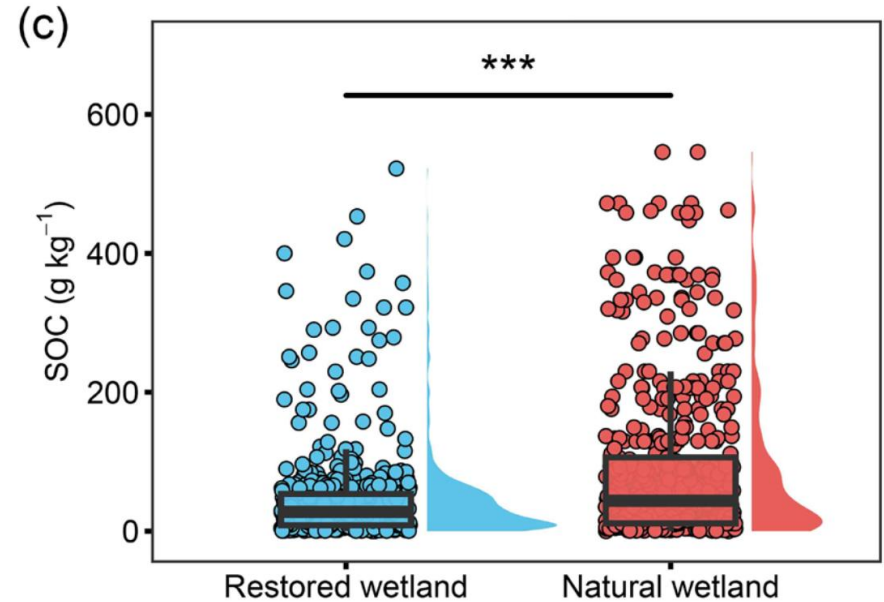
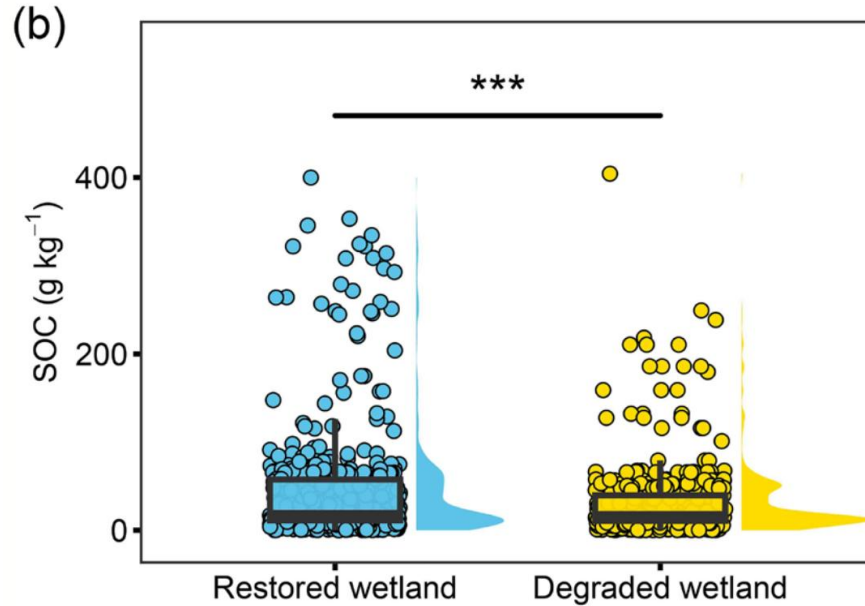
Wetland Carbon Processes Drive Many Ecosystem Services

Carbon Cycle Process / Soil Condition	Ecosystem Service
Carbon sequestration through growth of wetland vegetation	Fish & wildlife habitat, soil stabilization, plant products
Carbon accumulation in wetland soil	Reduction in atmospheric carbon dioxide
Anaerobic soils promote slow decomposition and microbially mediated processes for nutrient retention and removal (e.g., denitrification).	Water quality improvement, climate change regulation.
Soil and sediment accretion	Water quality improvement

Disturbance is related to reduced soil carbon stocks in US wetlands



On the other hand: restoration has the potential to increase soil carbon stocks



Legacy Sediment Removal and Carbon Cycling

How does reconnection of streams to their floodplains via legacy sediment removal alter floodplain carbon cycling:

- Soil gas flux (CO_2 , CH_4 , N_2O)
 - *Which ones, when and where?*
- Buried relict hydric soil stability?
 - *What happens when it's exposed?*
- Soil organic matter accumulation and soil health
 - *How much and at what rate?*
 - *For how long?*



Reading the Buried Archive

What buried floodplain sediments reveal about the pre-disturbance wetland conditions at the LCC



Ecosystem Processes

What those buried soils tell us about & ecosystem ecological processes

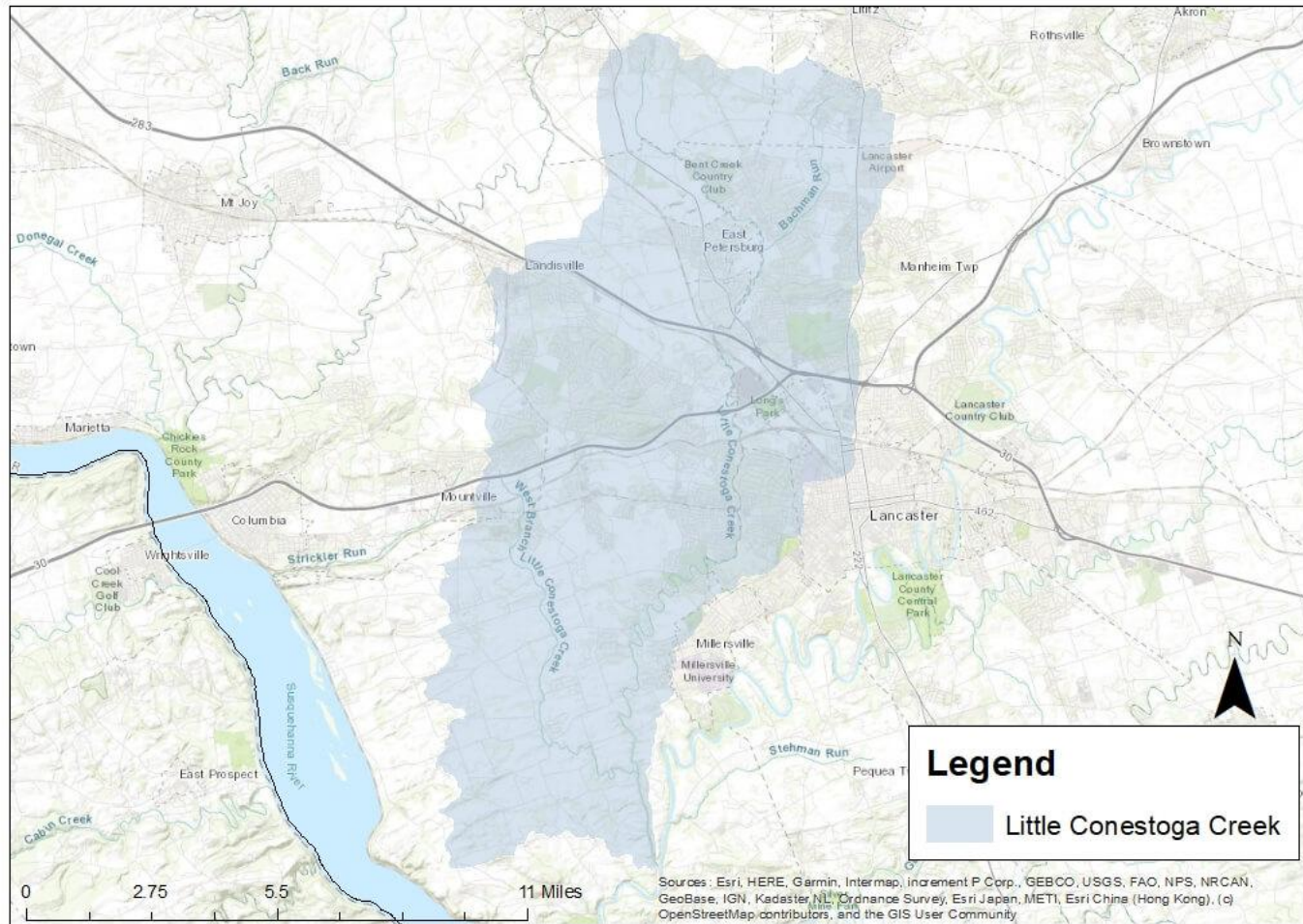


Measuring Restoration Outcomes

How we can document carbon accumulation, soil gas flux, and soil health

Reading the Buried Archive

Little Conestoga Creek, Lancaster, PA



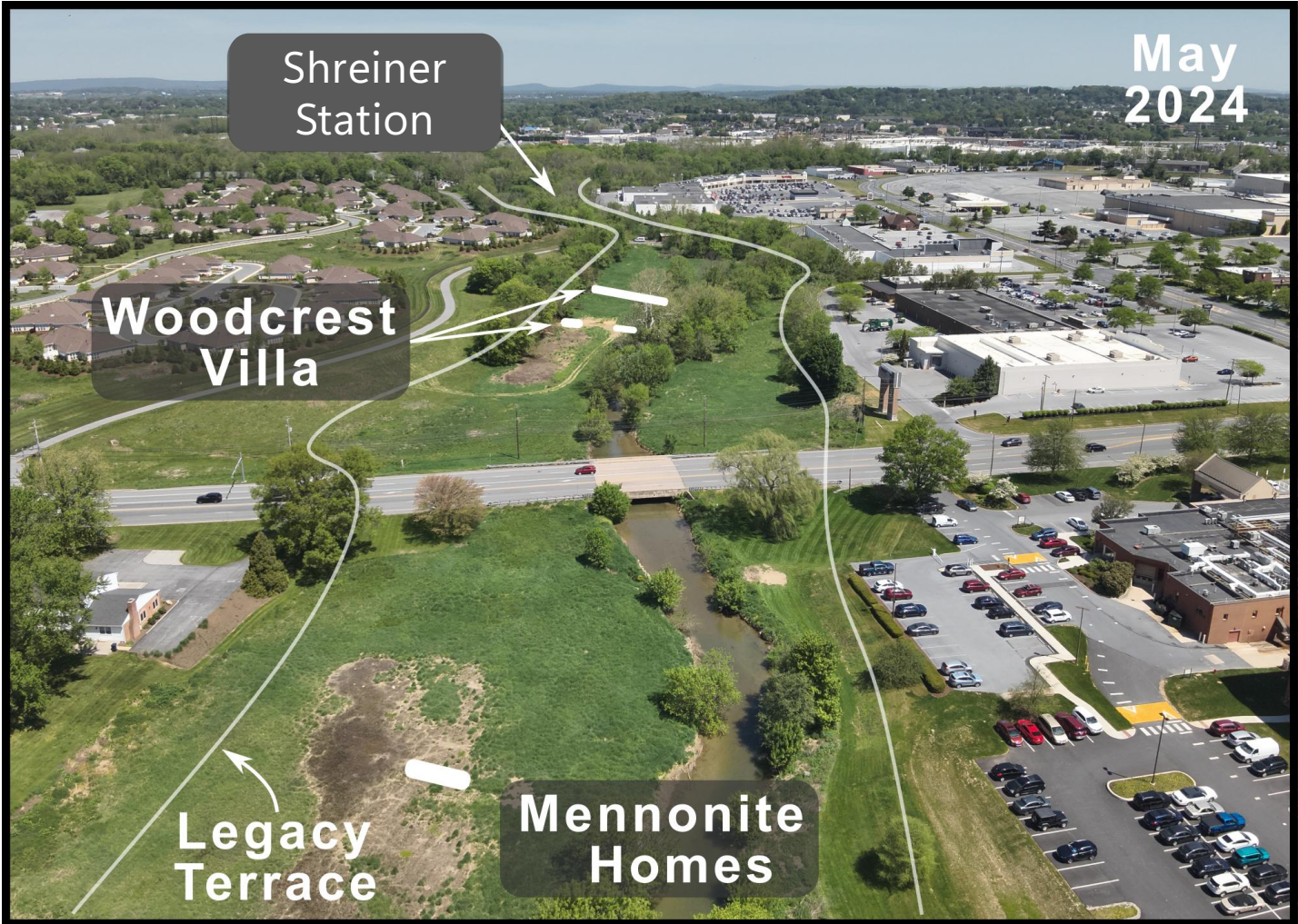
May
2024

Shreiner
Station

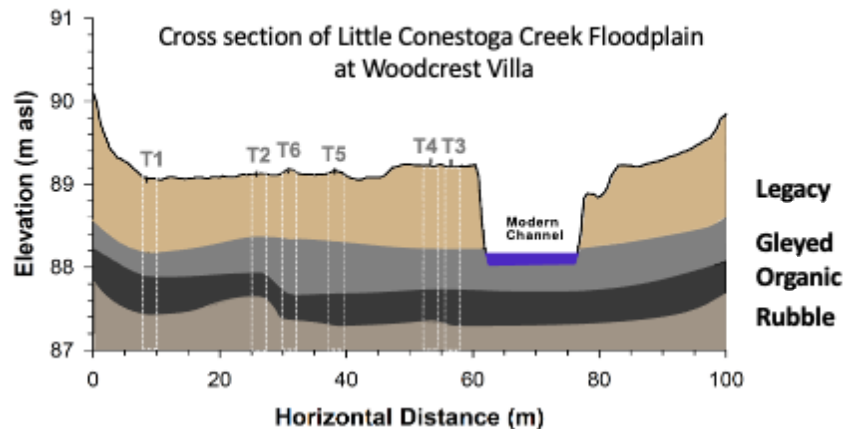
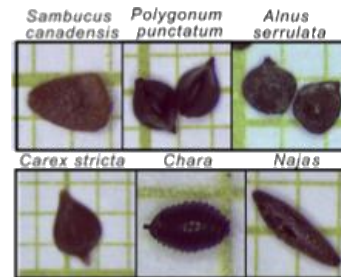
Woodcrest
Villa

Legacy
Terrace

Mennonite
Homes



Reading the Buried Archive



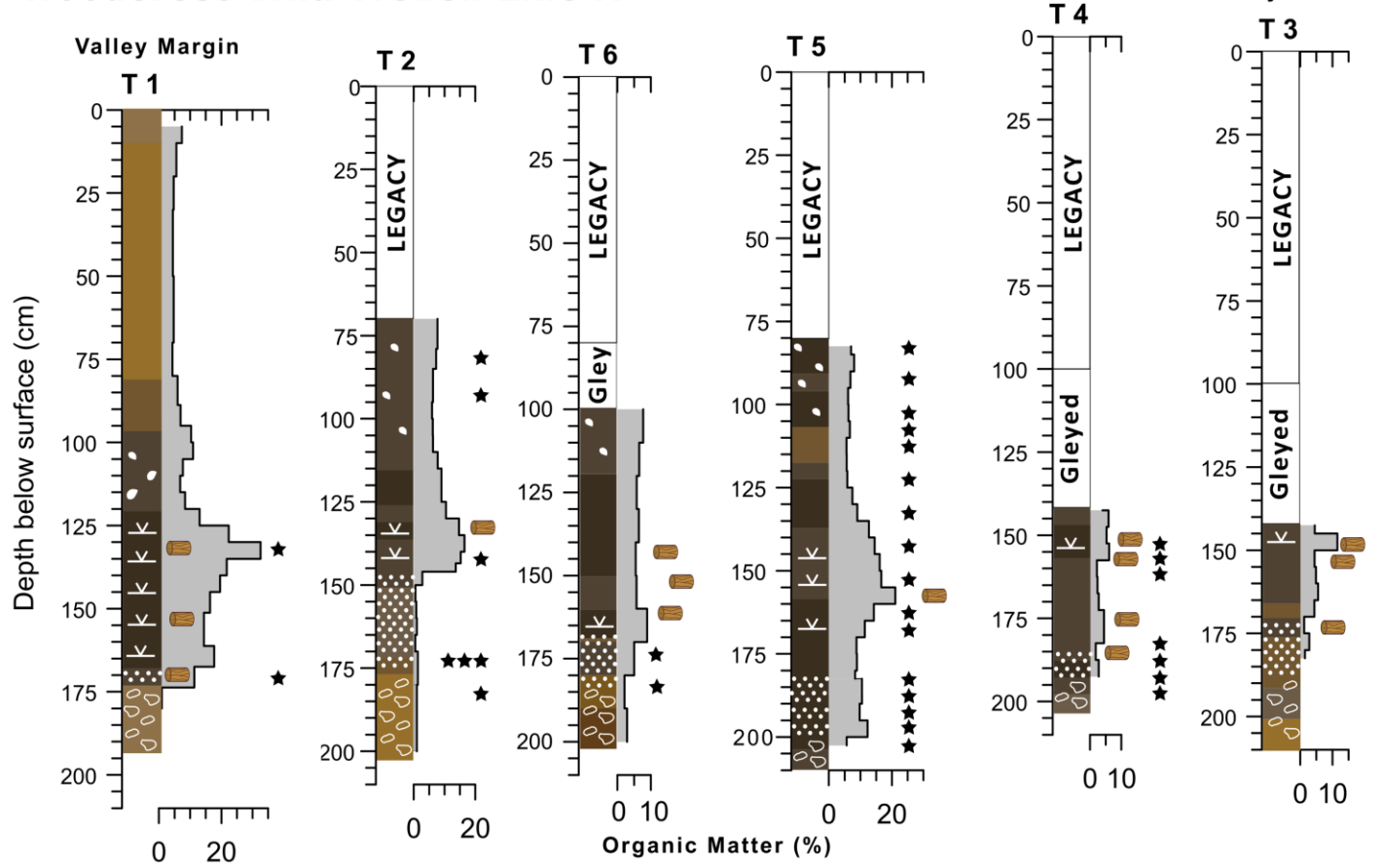
Reading the Buried Archive - *How big is the archive?*

Woodcrest Villa Trench Line A

Spatially variable paleoenvironment across the valley bottom (~50m)

- Highest Soil Organic Matter (SOM) toward valley margin
Hillslope seeps/springs?
- Lowest in valley center

Rubble -> Organic -> Gleyed -> Legacy



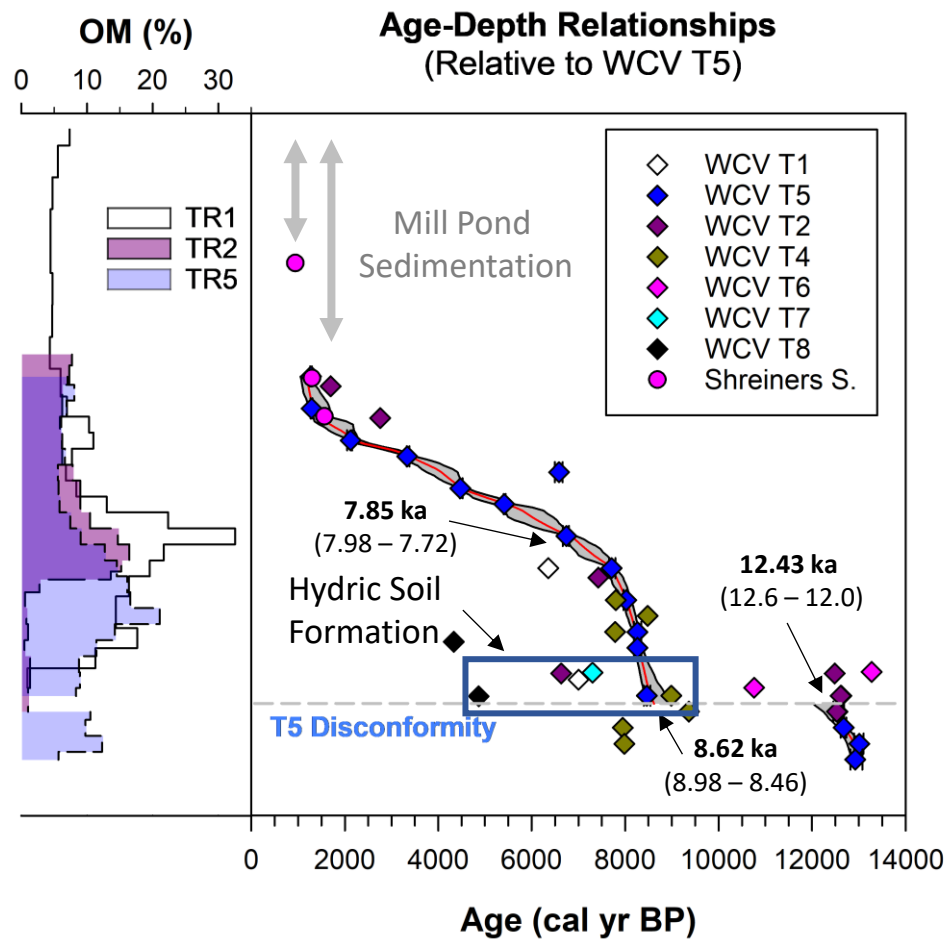
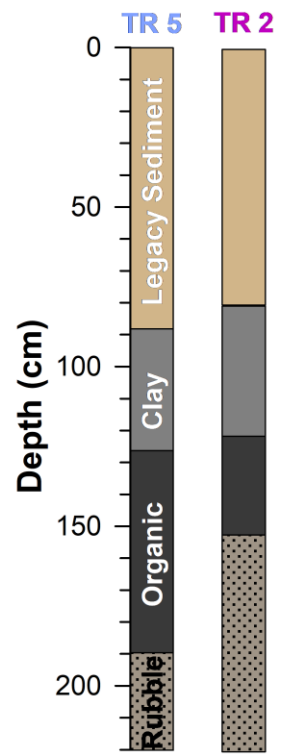
Reading the Buried Archive – *What volume, chapter, or page are we reading?*

Sequence of Wetland Formation

Gleyed Soil ages:
7.85 ka – 4.5 ka

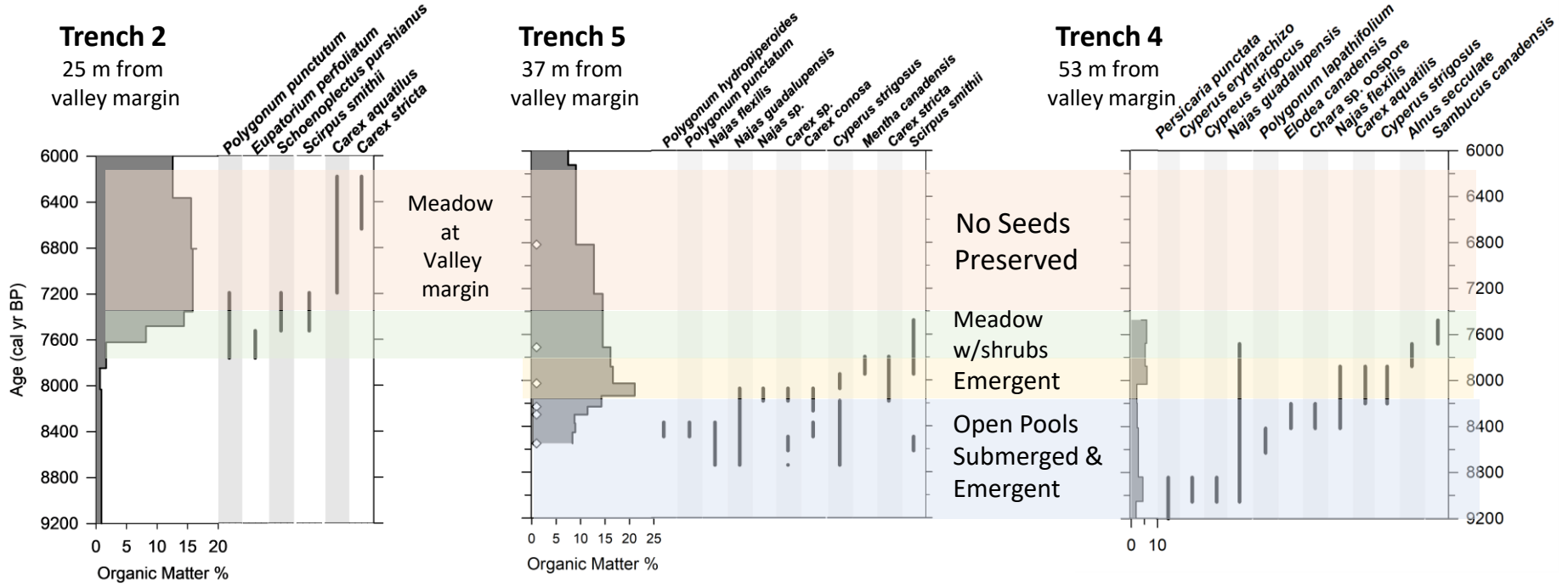
Organic soil ages:
9.23 – 6.0 ka

Top of “Rubble” age:
12.43 - 12.49 ka



Reading the Buried Archive – *Who are the main characters?*

Tracking the growth and expansion of the floodplain wetland



Reading the Buried Archive

What buried floodplain sediments reveal about the pre-disturbance wetland conditions at the LCC



Ecosystem Processes

What those buried soils tell us about the past ecosystem & ecological processes



Measuring Restoration Outcomes

How we can document carbon accumulation, soil gas flux, and soil health

Ecosystem Processes – *Wetland Succession*

Macrofossil Evidence for Wetland Plant Succession

Trench 2



Trench 5



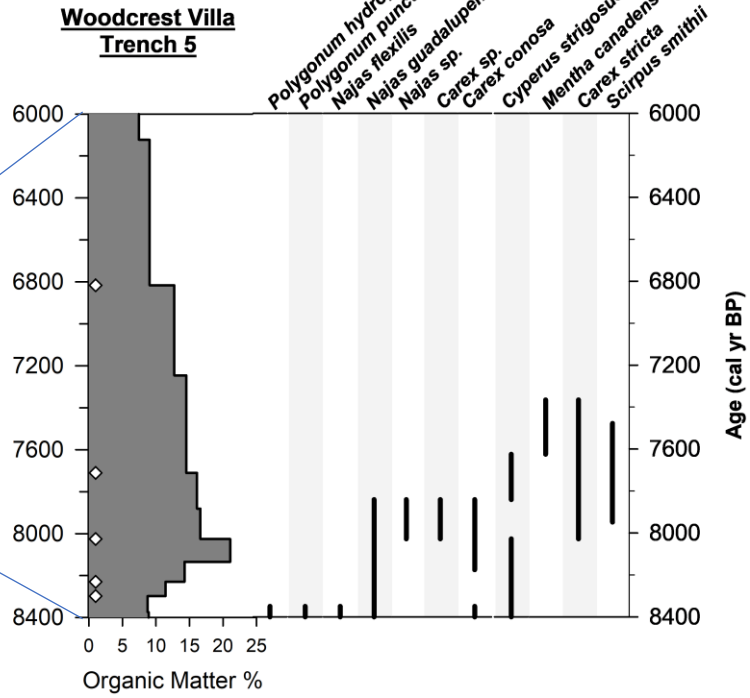
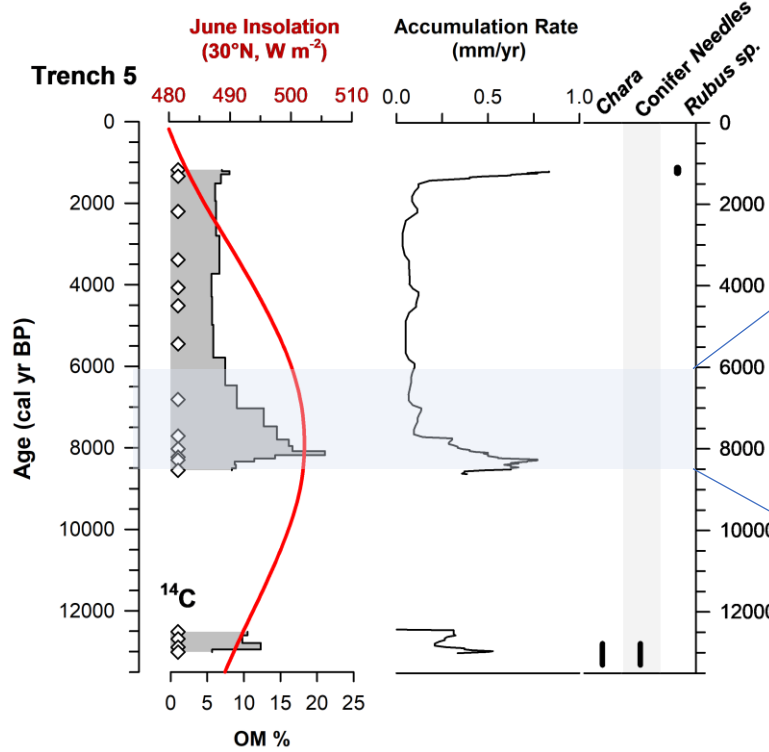
Trench 4



Ecosystem Processes – *Soil organic matter accumulation rates*

High organic deposition at Woodcrest Villa occurred rapidly and ended quickly

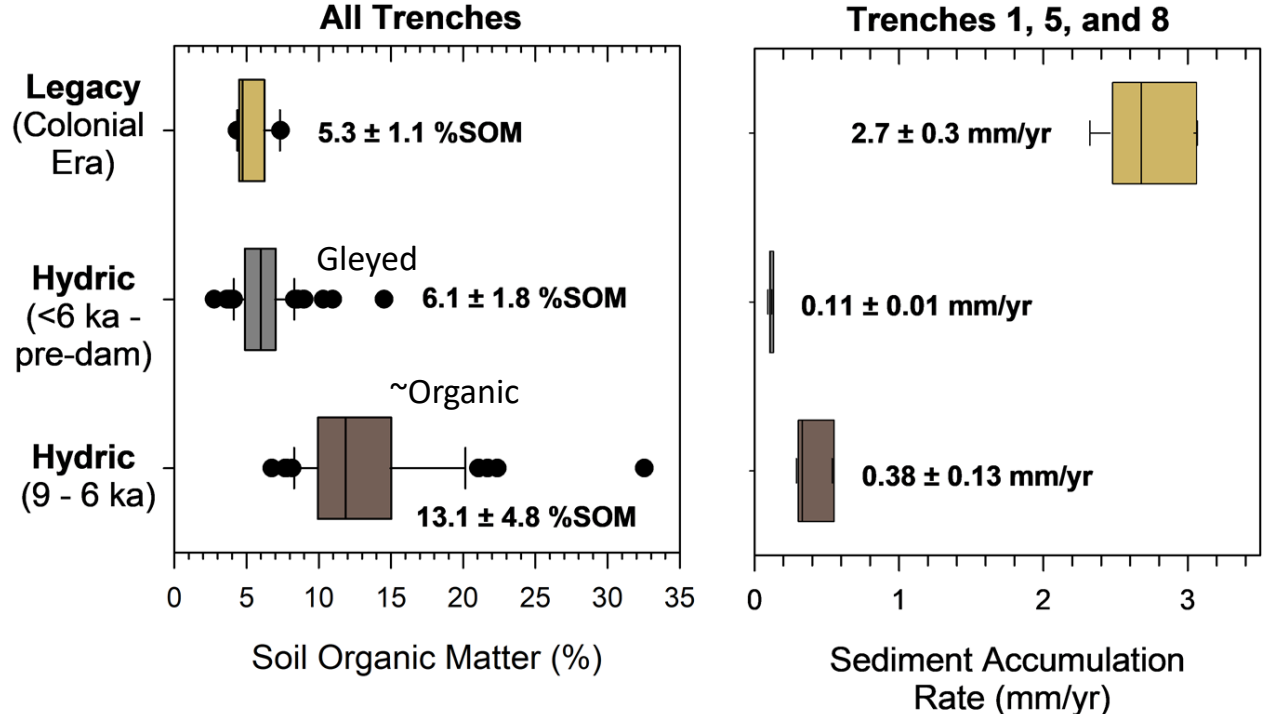
Organic soil accumulation: ~800 – 1,800 year duration



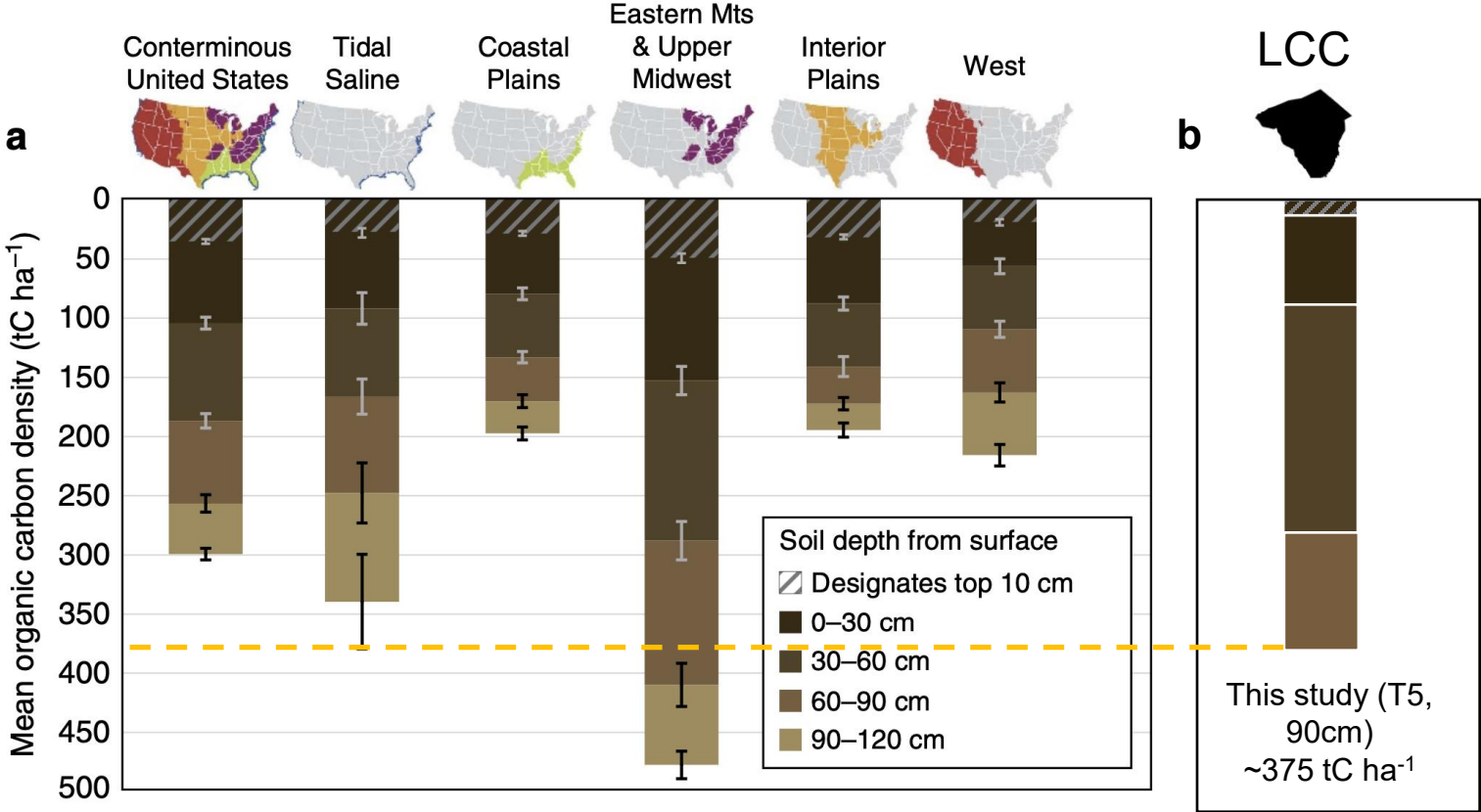
Organic Matter and Accumulation rates in Sediment Facies

- Wood, charcoal, and plant fragments are major components of organic soils
- Legacy Sediments have comparable SOM values to gleyed soils

Little Conestoga Creek



Ecosystem Processes – Soil carbon stocks – How do the buried soils compare to modern US wetland soil carbon stocks?



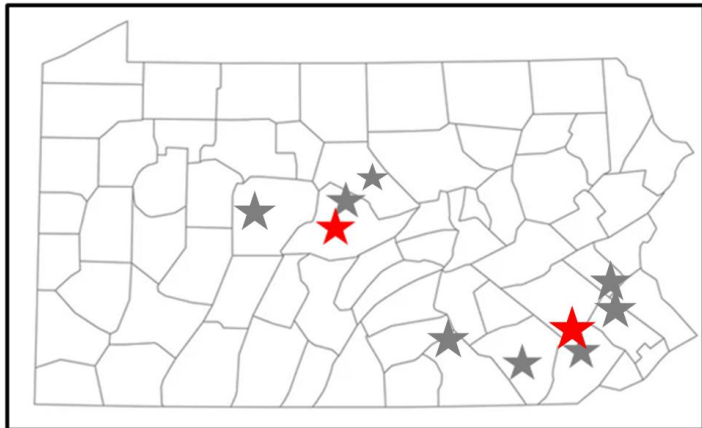
^a From Nahlik & Fennessy (2015) DOI: 10.1038/ncomms13835 ^b Buried wetland soils - Little Conestoga Creek

Ecosystem Processes – *LCC buried soils compared to regional wetland profiles*

Regional Wetland Soil Carbon

Ongoing project to characterize unglaciated wetland soils throughout PA

Open vegetation fens have highest SOM other than Peat Bogs

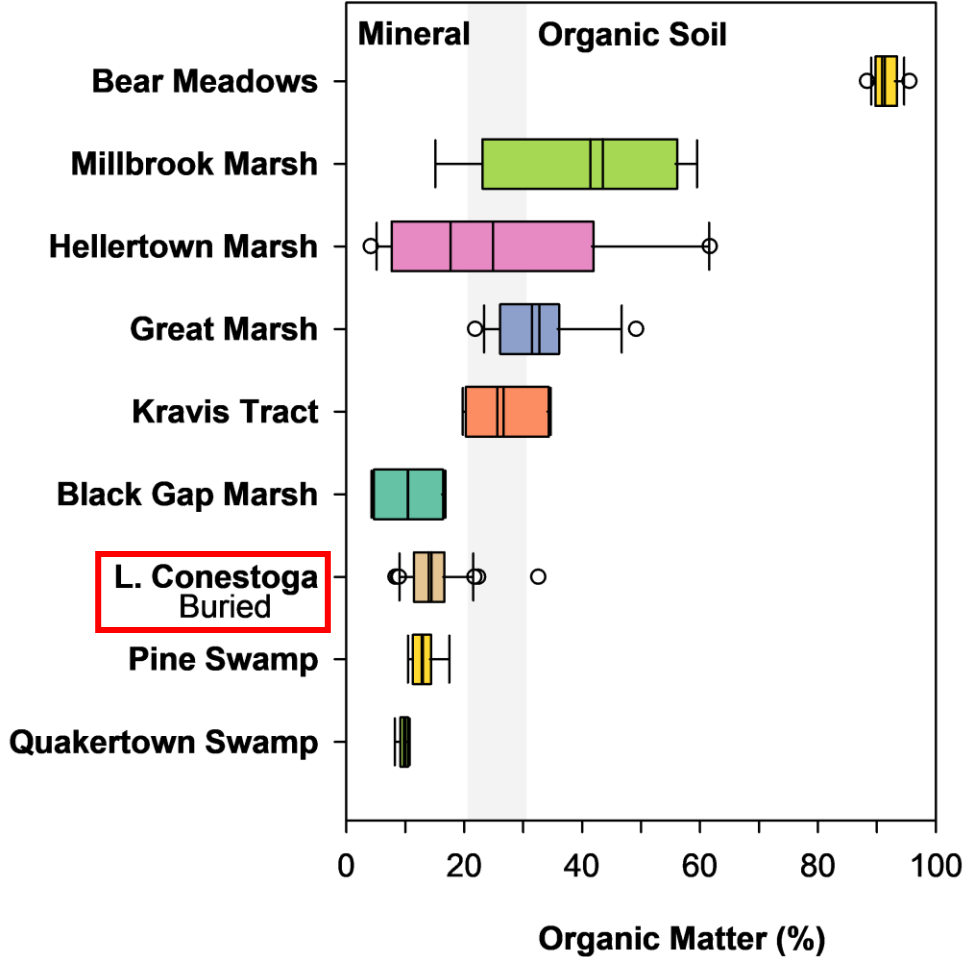


Sphagnum
Peat Bog

Open
Meadows

Forested
Swamp

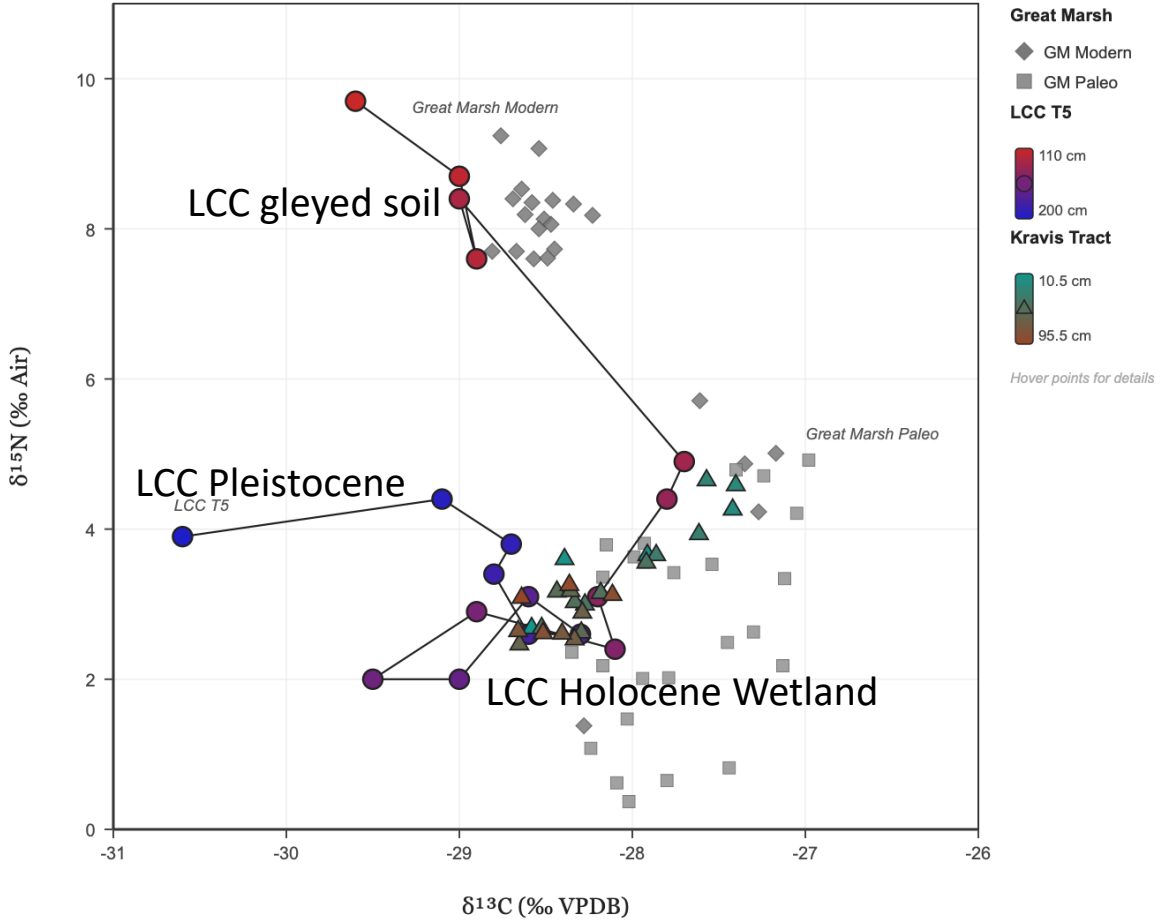
Surface Soil Organic Matter (0 - 40 cm depth below surface)



Ecosystem Processes – *LCC buried soils compared to regional wetland profiles*

Stable C & N isotopic indicators of soil organic matter origin (botanical source) and environmental conditions

LCC buried soil is remarkably similar to other regional analog sites.



Reading the Buried Archive

What buried floodplain sediments reveal about the pre-disturbance wetland conditions at the LCC



Ecosystem Processes

What those buried soils tell us about ecosystem & ecological processes



Measuring Restoration Outcomes

How we can document carbon accumulation, soil gas flux, and soil health

Three questions targeting *three different stages of the carbon cycle*

1. How does legacy sediment removal affect soil greenhouse gas emission?

HYPOTHESIS

Restored wetlands will show higher CH₄ and lower CO₂ emissions compared to pre-restoration sites impaired by legacy sediment

WHY IT MATTERS

Carbon sequestration and reduced CO₂ are significant restoration benefits - but there is a **potential methane trade-off** that needs to be quantified

2. How does legacy sediment removal affect buried relict hydric soils?

HYPOTHESIS

Relict hydric soils are characterized by low microbial activity and will remain stable when exposed

WHY IT MATTERS

Depending on how relict soil is exposed, it might mineralize both **carbon and nutrients currently sequestered**

3. How much and how rapidly are restored wetlands accumulating soil carbon?

HYPOTHESIS

Restored wetlands will rapidly accumulate soil organic carbon driven by plant productivity, slow decomposition, and flood-derived inputs

WHY IT MATTERS

Wetlands are among the most efficient carbon stores on Earth - **soil organic matter is a key indicator of improving ecosystem function**

Emissions

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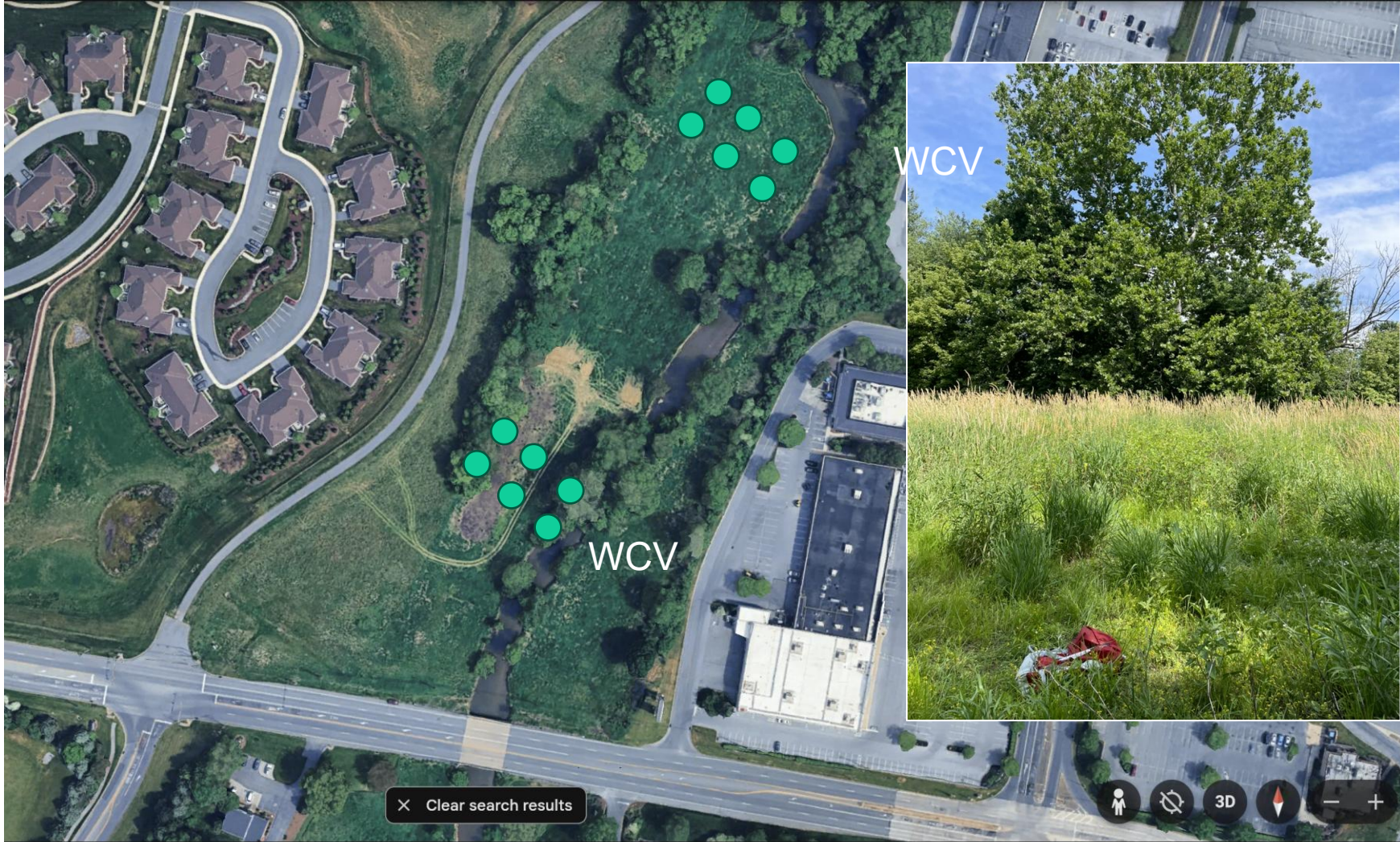
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Little Conestoga Creek Study Area Lancaster County, Pennsylvania

- 1.3 stream miles along a 3 mile corridor
- 25 acres of floodplain-wetland restoration

- Unrestored
- Restored
- Surface Sample





✕ Clear search results

WCV

WCV

PWZ

Little Conestoga Creek

FP







Soil Gas Flux Measurements

Biweekly to monthly *in situ* static chamber measurement of CO₂ and CH₄ soil emissions.

Initial Goal: Characterize the changes in soil trace gas emissions before and after restoration across the LCC corridor.

Longer term – understand changes in the key drivers (water level, substrate availability, carbon quality, soil and water temperature, veg.)

Restoration reduces CO₂ — *but increases CH₄*

Greenhouse gas flux across three site types · Little Conestoga Creek corridor

CARBON DIOXIDE (CO₂)

g C / m² / day · lower is better

Pre-restoration
floodplain



Post-restoration
floodplain



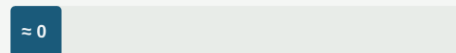
Post-restoration
pocket wetland



METHANE (CH₄)

mg C / m² / day · anaerobic conditions drive increase

Pre-restoration
floodplain



Post-restoration
floodplain



Post-restoration
pocket wetland



Wetter, more anaerobic pocket wetlands show the strongest CO₂ reduction — but also the highest CH₄ production. **Restoration design shapes the carbon trade-off.**

Comparative Data

Comparing site measurements against published literature on restored and unrestored riverine wetlands

Category / Site	CO ₂ -C (g m ⁻² d ⁻¹)	CH ₄ -C (mg m ⁻² d ⁻¹)
Lancaster – Pre-Restoration Floodplain	5.35	-0.7
Lancaster – Post Restoration Floodplain	4.43	2.8
Lancaster – Post Restoration Depressional Wetland	2.46	30.5
Unrestored riverine wetlands (6 sites, 3 studies)	3.10	-0.9
Restored riverine wetlands (4 sites, 3 studies)	2.25	84.6

Stability of buried stocks

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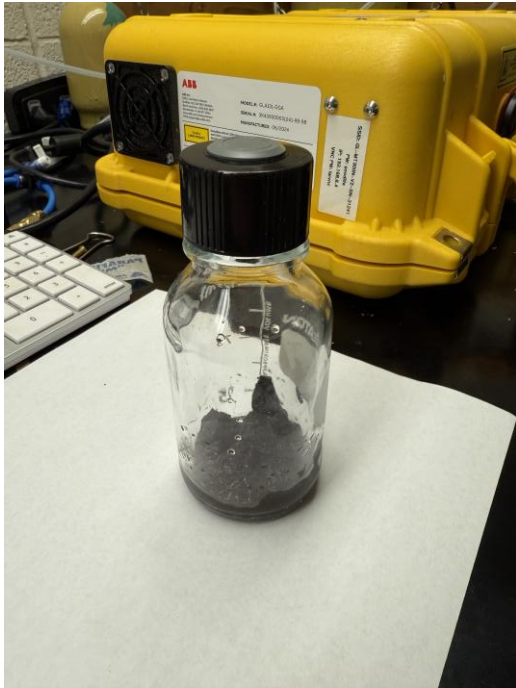
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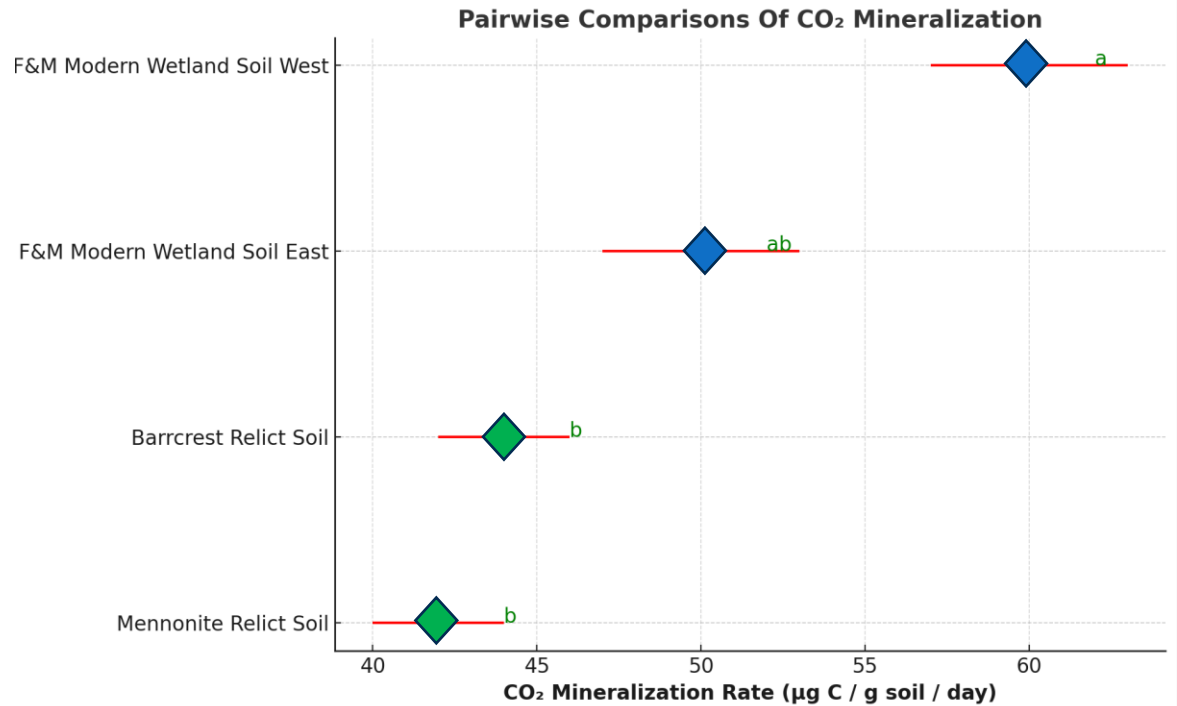
How labile are the buried hydric soils?

- Weitzman et al. 2014 found the relict hydric soil at BSR to have low microbial activity as measured by *in vitro* aerobic incubations jar incubations.
- Similar findings related to microbial nitrogen mineralization recently published by Yaculak et al. 2025 for relict hydric soil in Maryland.





LCC Relict Hydric Soils



Buried relict soils from 2 different LCC sites have lower aerobic microbial respiration rates than surface soils from an 11-year-old wetland creation site.

This contrast persists for CH₄ in anoxic incubations as well

New accumulation

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Systematic
sampling of soil
carbon across the
pre- and post
restoration sites
along the LCC





Short-term soil carbon accumulation rates

For the Barrcrest floodplain (~3 years old) we have a provisional value of soil carbon accumulation at a rate of:

478 g C /m² /yr



Short-term carbon accumulation rates

- Barrcrest Floodplain (@ 3 yrs)
 - 478 g C /m²/yr
- Big Spring Run (@ 12 yrs)
 - 400 g C /m²/yr

Literature values – Temperate Wetlands

140-317 g C /m²/yr

– Bernal & Mitsch 2011

144-235 g C /m²/yr

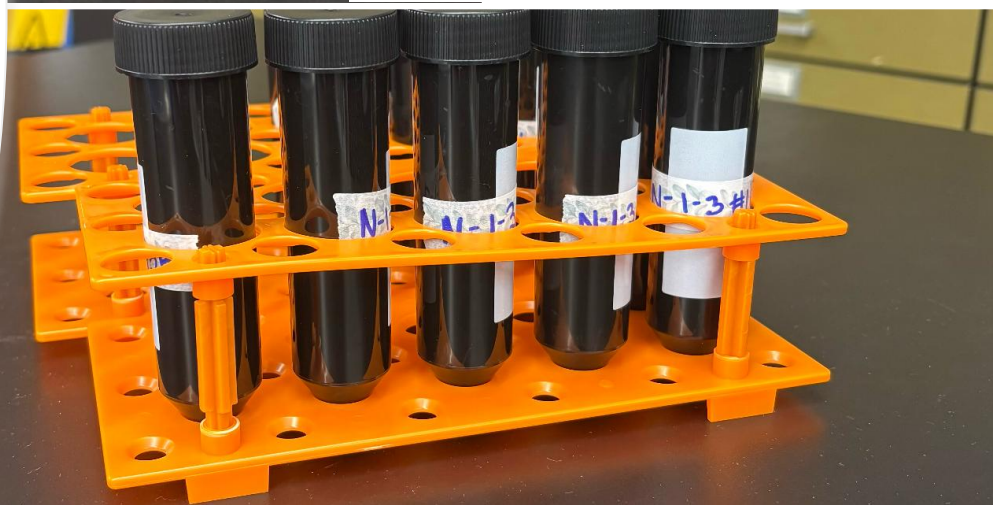
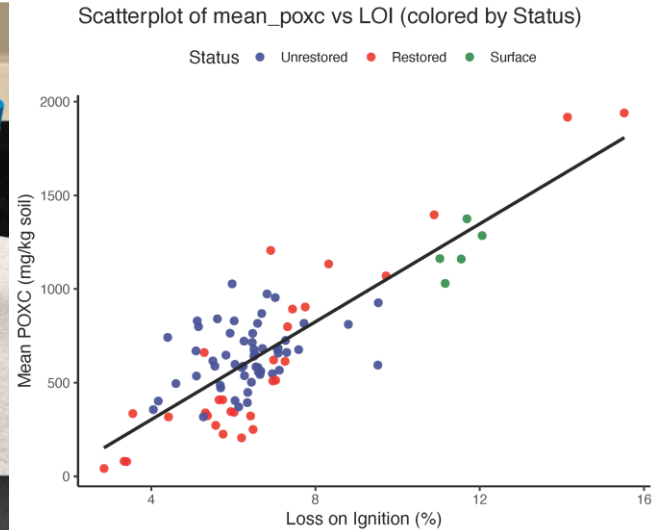
– Loder et al. 2024

49-88 g C /m²/yr – Craft et
al. 2008 -peatlands

We are on the high end of short-term accumulation rates

Soil Health – PoxC Permanganate- Oxidizable Carbon

POxC is significantly related to particulate organic carbon, soil microbial biomass carbon, and soil organic carbon in wetland soil (Chambers et al. 2024)

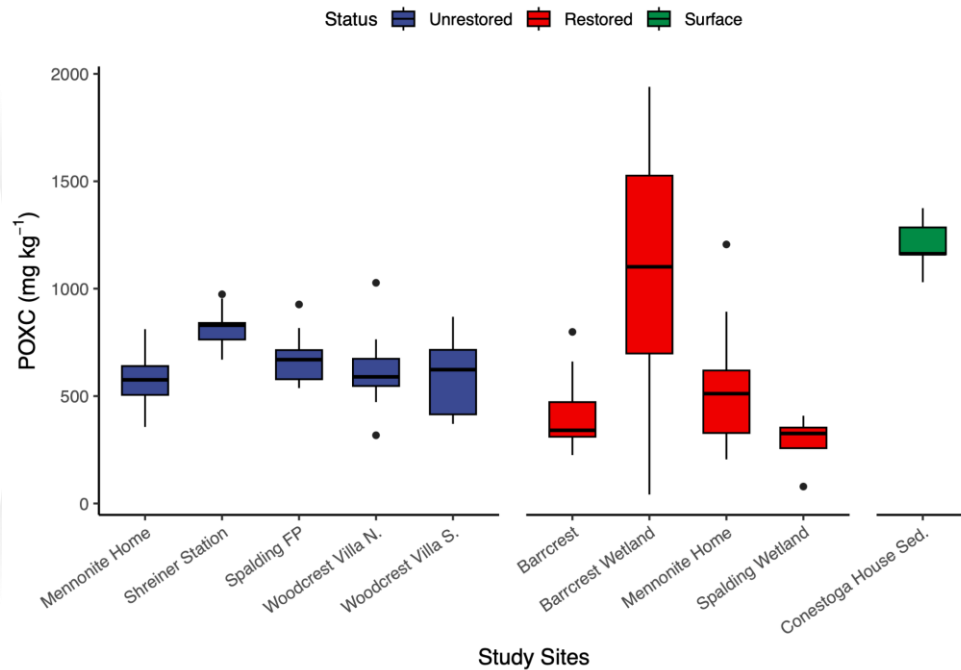


Soil Health – PoxC

Permanganate-Oxidizable Carbon

Site Type	PoxC mg /kg soil	
LCC Pre-restoration floodplain soils	664 (410-770)	This Study
LCC Post-restoration floodplain soils	616 (42-1898)	This Study
129 Ag Soils from the USA	300 - 800	Culman et al. 2012, Hurisso et al. 2016
Freshwater wetlands in FL	21.7-29.5	Chambers et al. 2024

Distribution of POXC by Site



Early results *support* our hypotheses

1. Greenhouse gas emission?

HYPOTHESIS

Restored wetlands will show higher CH_4 and lower CO_2 emissions compared to pre-restoration sites impaired by legacy sediment

✓ Supported

↓ **54%** CO_2 flux reduction in the deeper wetlands

↑ **29x** CH_4 increase in deepest wetlands vs. pre-restoration

2. Buried Soil Stability

HYPOTHESIS

Relict hydric soils are characterized by low microbial activity and will remain stable when exposed

✓ Supported

↓ **15-20%** Lower CO_2 mineralization in buried hydric soils vs modern wetland surface soils

Low carbon loss expected upon exposure. Stability!

3. Carbon Accumulation and Soil Health?

HYPOTHESIS

Restored wetlands will rapidly accumulate soil organic carbon driven by plant productivity, slow decomposition, and flood-derived inputs

✓ Supported

400 g C m⁻² yr⁻¹ at two legacy sediment removal sites -- Literature range 140-317

PoxC shows a wide range in nascent restoration sites highly correlated with soil organic matter content



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- R.K. Mellon Foundation
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- Franklin & Marshall College



PWZ

Little Conestoga Creek

FP

