October 23, 2025

Assessing the Environmental Impacts of Scaling Plant-Based Protein Production in the Northeast

International Soil and Water Assessment Tool Conference

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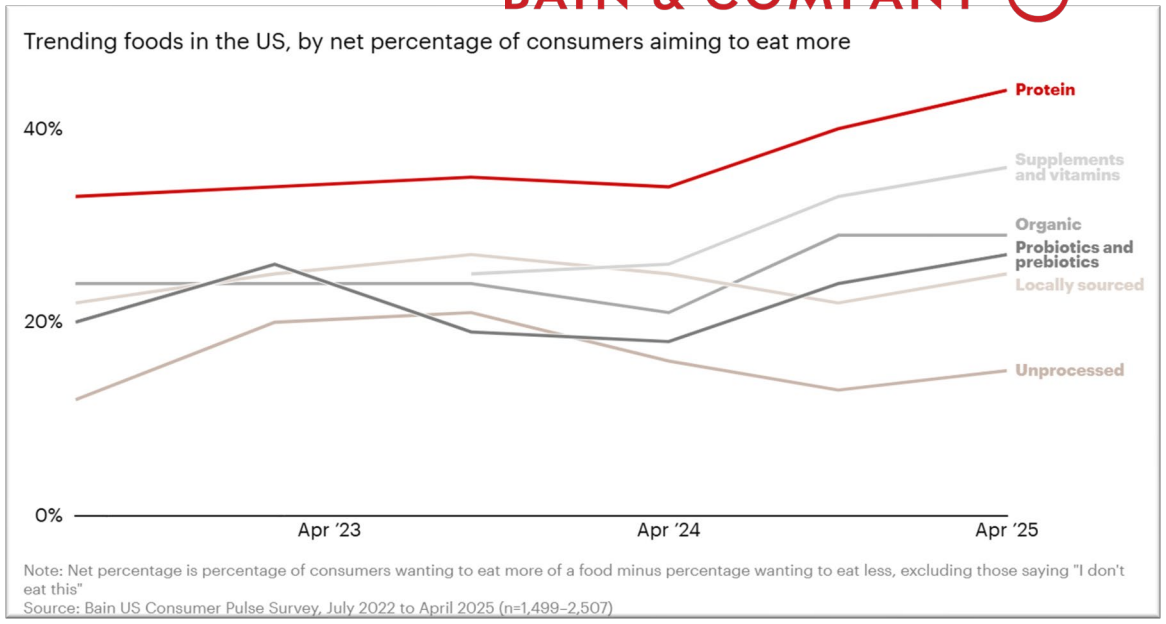
American's want more protein, …

1

Population growth and **rising protein demand** places rising pressure on food systems to meet nutritional needs sustainably

BAIN & COMPANY



IFIC 2024 IFIC Food & Health SURVEY

The number of consumers trying to consume protein continues to rise: 59% in 2022, 67% in 2023, to 71% in 2024.

Consumers are Seeking More Protein for Health and Taste in 2025

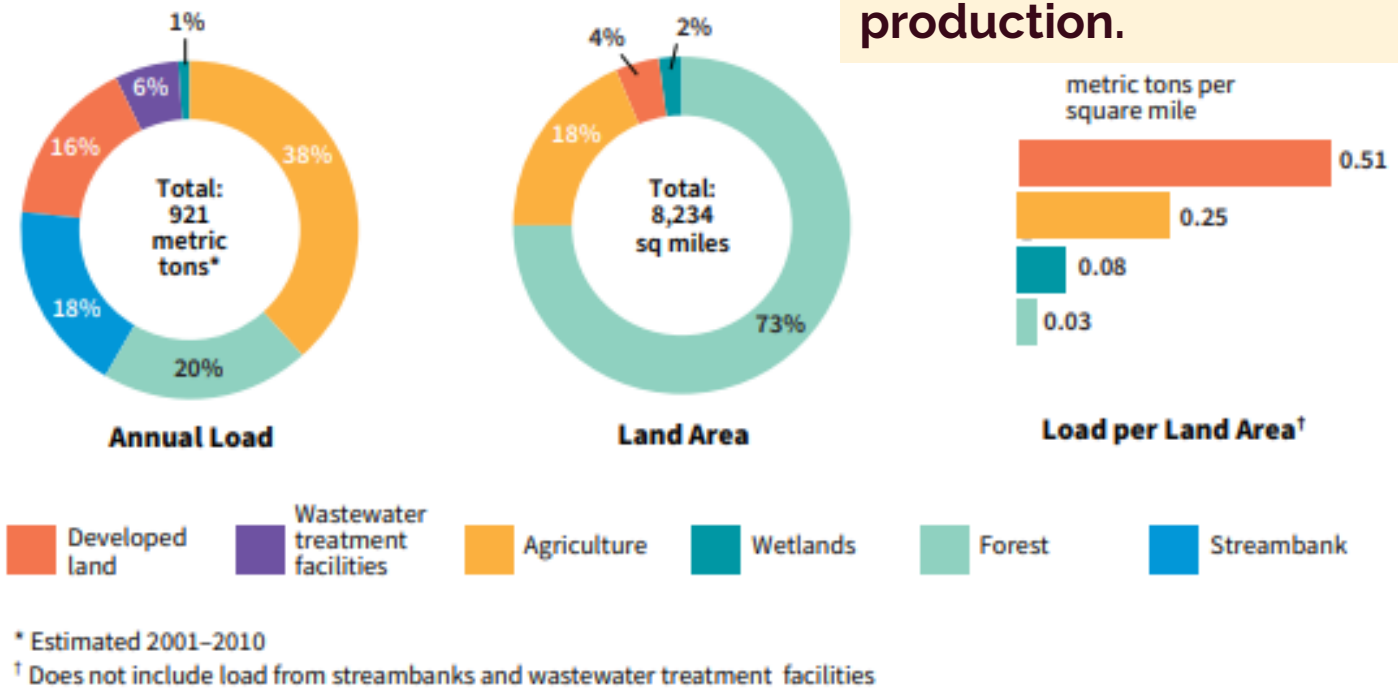
Cargill's 2025 Protein Profile finds 61% of consumers report increasing their protein intake in 2024, up from 48% from 2019

But animal-based protein comes at an environmental cost.

2

Animal-based production dominates Vermont agriculture, contributing to GHG emissions and phosphorus pollution

In 2024, dairy represented **70% of agriculture products sold in Vermont.** As of the 2022 USDA Ag Census **78% of cropland is in forage production.**



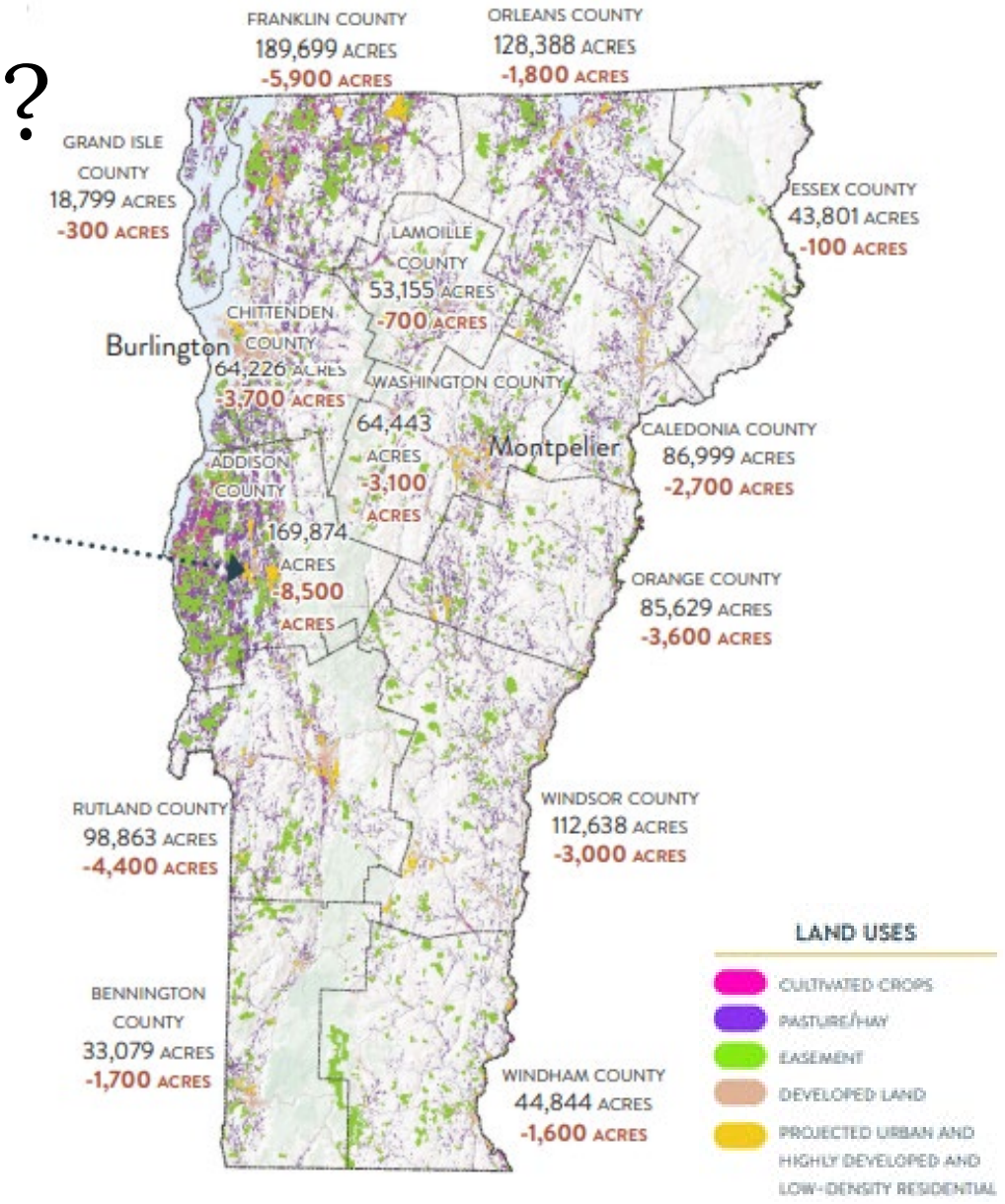
Source: 2016 Phosphorus Total Maximum Daily Load Phosphorus for Vermont Segments of Lake Champlain

So, how do we feed more with less agriculture land?

3

Dairy farms are declining, and farmland is increasingly converted to development or conservation

By 2040, Vermont could lose an additional **41,200 – 61,800 acres of agriculture land** of 1.1 M acres currently in use



Source: American Farmland Trust, Farms Under Threat Choosing an Abundant Future

So, how about beans?!

1

Population growth and **rising protein demand** places rising pressure on food systems to meet nutritional needs sustainably

2

Animal-based production dominates Vermont agriculture, contributing to GHG emissions and **phosphorus pollution**

3

Dairy farms are declining, and **farmland is increasingly converted to development or conservation**

+ Expanding plant-based market (Ron et al., 2022)

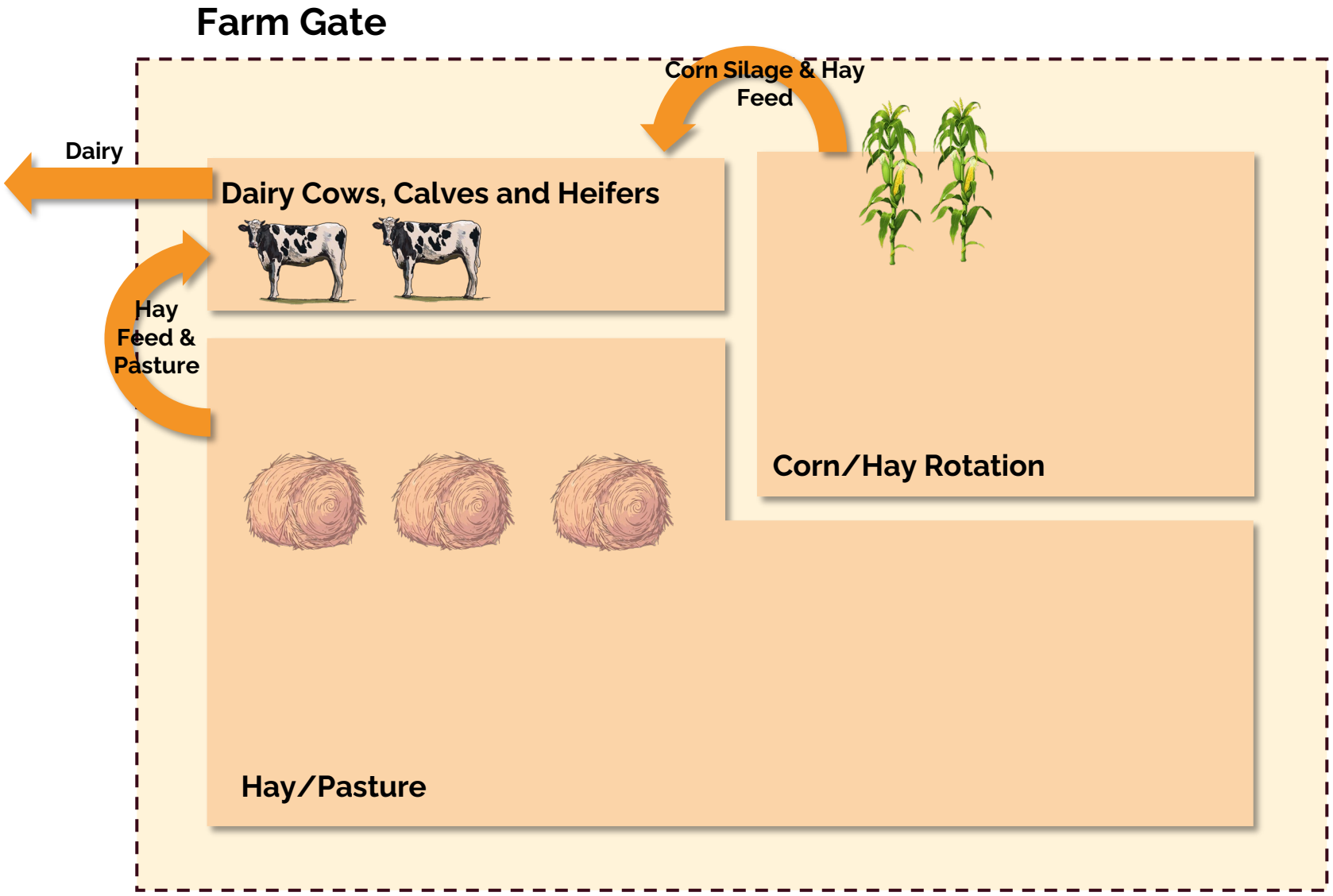
+ Expected lower environmental burden (Willet, 2019)

+ Greater land use efficiency (human-edible protein per acre) (Mottet et al., 2017)

Research question

How does the environmental impact change if **croplands growing corn silage are converted to soybean and black bean production** for human consumption?

Nutrient balance in a dairy operation

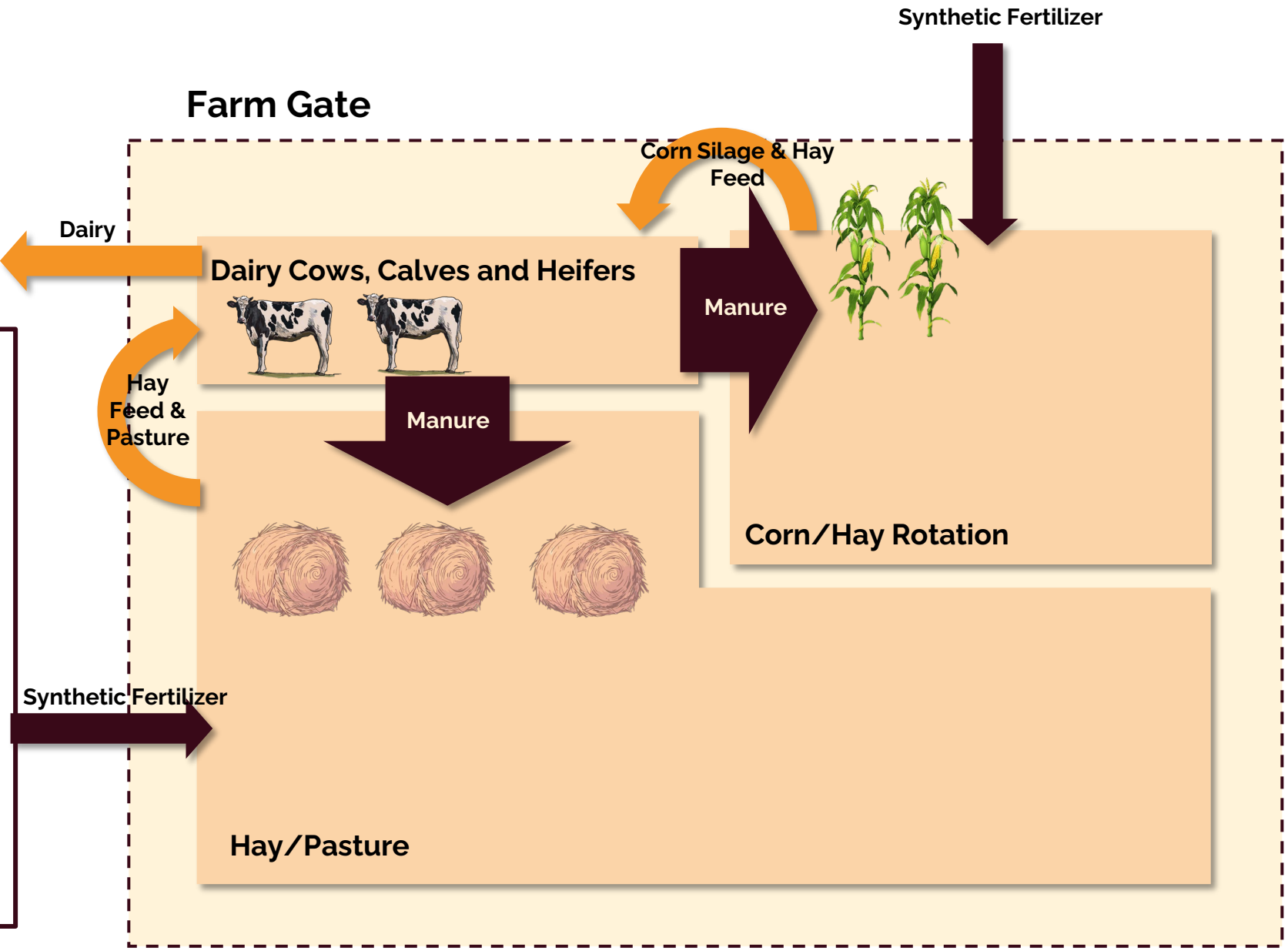


Nutrient balance in a dairy operation

Primary data sources

Manure nutrient content: UVM extension Ag & Enviro Testing Lab manure samples from 2016 – 2024

Application rates: UVM extension recommended management routines
- 60% injection method
- well-drained v.s. poorly drained



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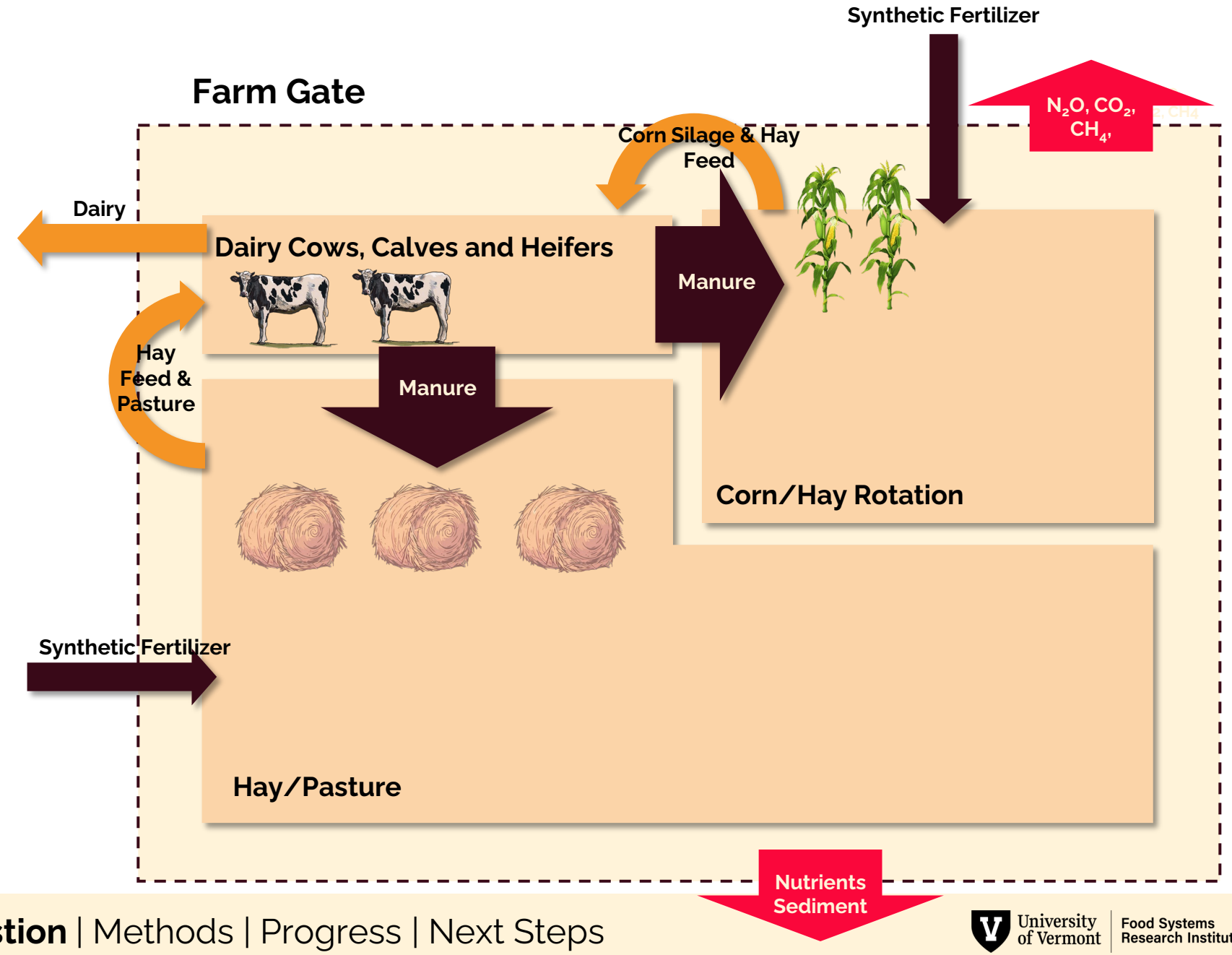


Nutrient balance in a dairy operation

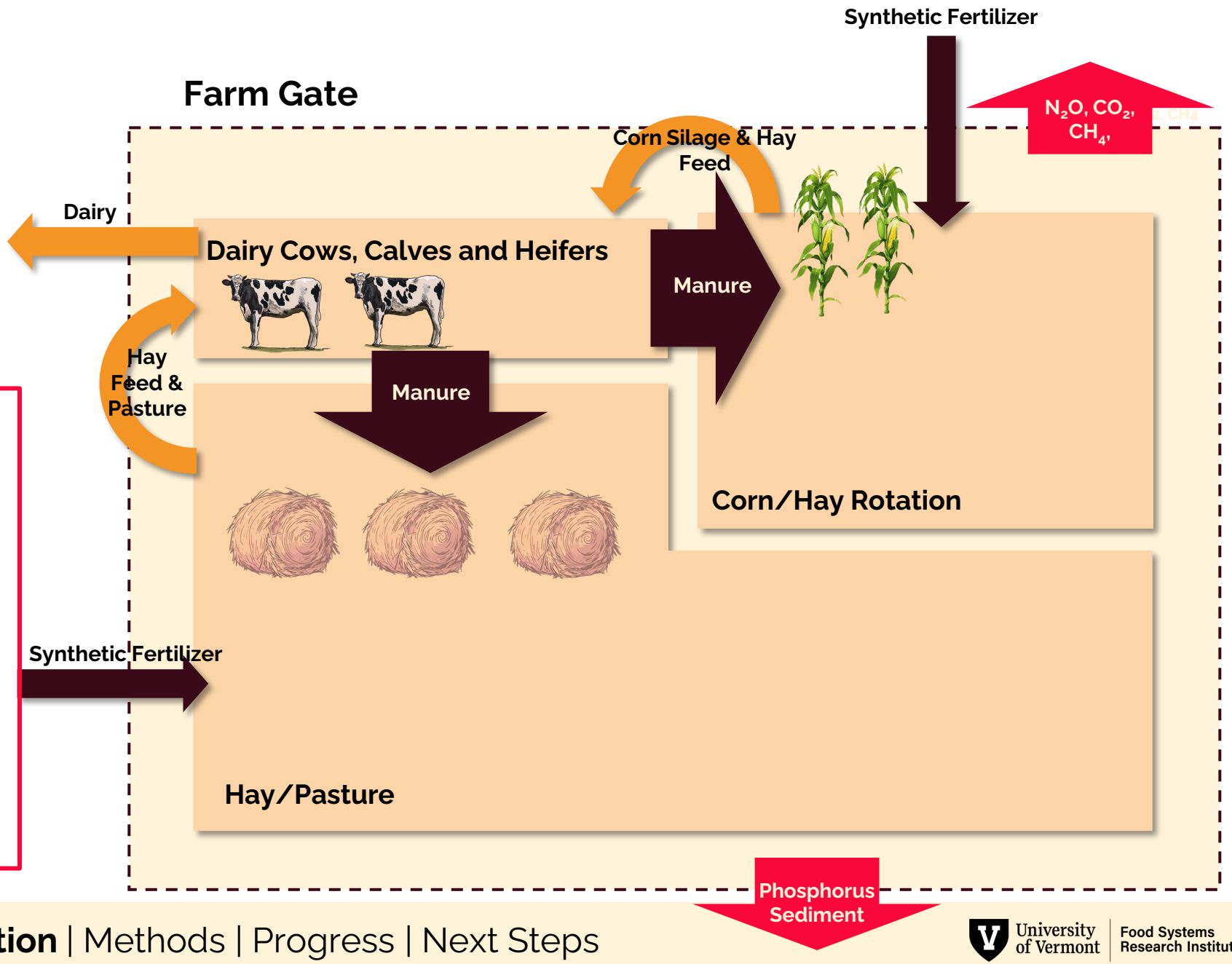
Focus on this portion of the study is on phosphorus and sediment loads

Soluble P

Sediment-bound P

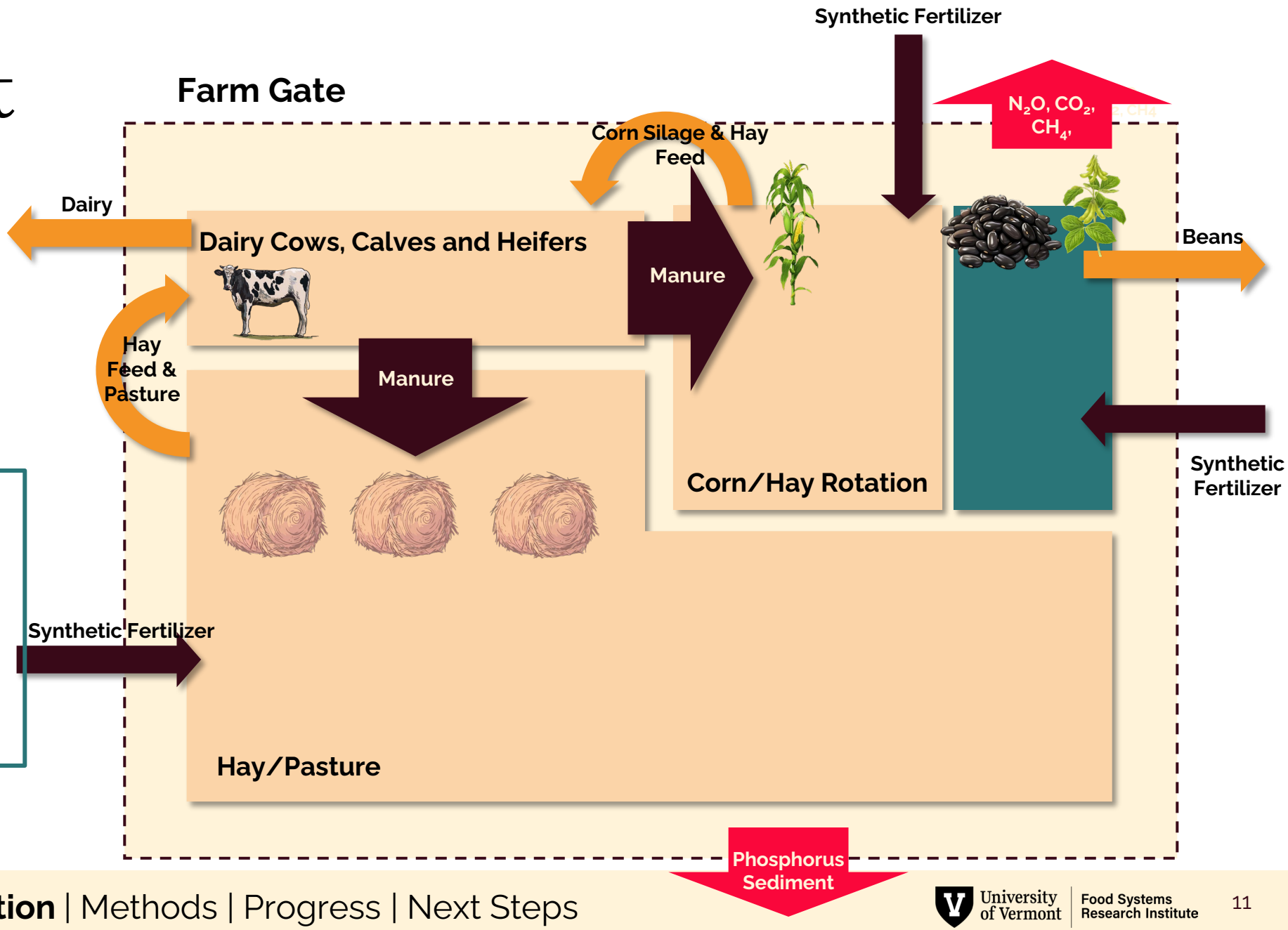
Organic P

Sediment



Shift in management routines – adoption of plant-based proteins

- \+ More beans
- \- Less feed
- \- Smaller herd, less dairy
- \- Less manure
- \+ Potential for more synthetic fertilizer



Research questions

How does the environmental impact change if **croplands growing corn silage are converted to soybean and black bean production** for human consumption?

Environmental Metrics:

Phosphorus runoff and sediment loss **-> SWAT+**
Greenhouse gas emissions **–> COMET-Farm**
Applied nutrients **–> County-level nutrient balance**

Crop conversion scenarios

Enterprise diversification

Dairy farms growing feed in excess convert land to conventional soybean or black bean production, likely conventional.

Maintain herd size

Considerations: Most realistic, smallest potential environmental benefit

Partial transition: crop & livestock integrated system

Dairy farms reduce herd size to grow black beans or soybeans, considering organic and conventional operations.

25%, 50%, 75% transition

Considerations: Determine optimal distribution between animal-based and plant-based considering tradeoffs

Full transition

Dairy farms fully transition to plant-based protein production for human consumption, likely organic.

No manure production

Considerations: Least realistic but helpful to understand the extreme if beans became the primary crop

Land management scenarios

	Corn/Hay Rotation	Plant-based protein
Baseline	100%	-
Enterprise diversification	95%	5%
Crop & livestock integrated scenarios	75%	25%
	50%	50%
	25%	75%
Full Transition	-	100%

Changes in Modeled Management Practices

Manure fertilization
Synthetic fertilization
Cultivation

Modeled management schedules

		Manure applied (kg manure/ha)	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Cultivation
		dairy_addison	elem_n	elem_p	
Corn/Hay Rotation	4 yrs Corn	1620	200	20	chisel x1 disk x1
	4 yrs Hay	3000	100	-	
Permanent Hay		3000	200	-	
Soybean		-	-	20	disk x1
Black Beans			45	20	disk x1
Organic Black Beans		30*	-	-	disk x1 culti-weed x3

* chicken manure

Modeled management schedules

	Manure applied (kg manure/ha)	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Cultiva...
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Soybean	-	-	20	disk x1
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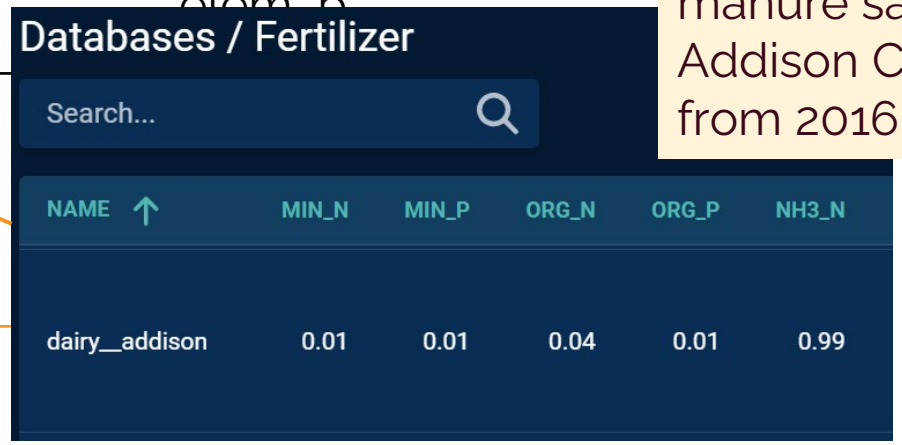
Custom manure fertilizer based on manure samples from Addison County, VT, from 2016 - 2024



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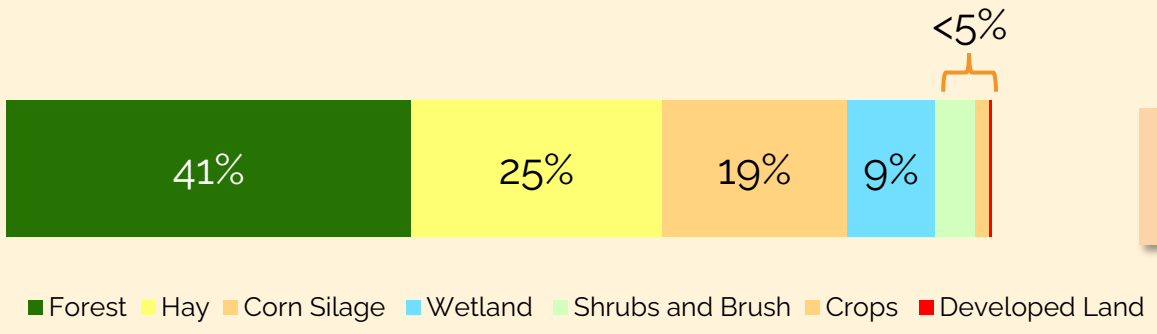
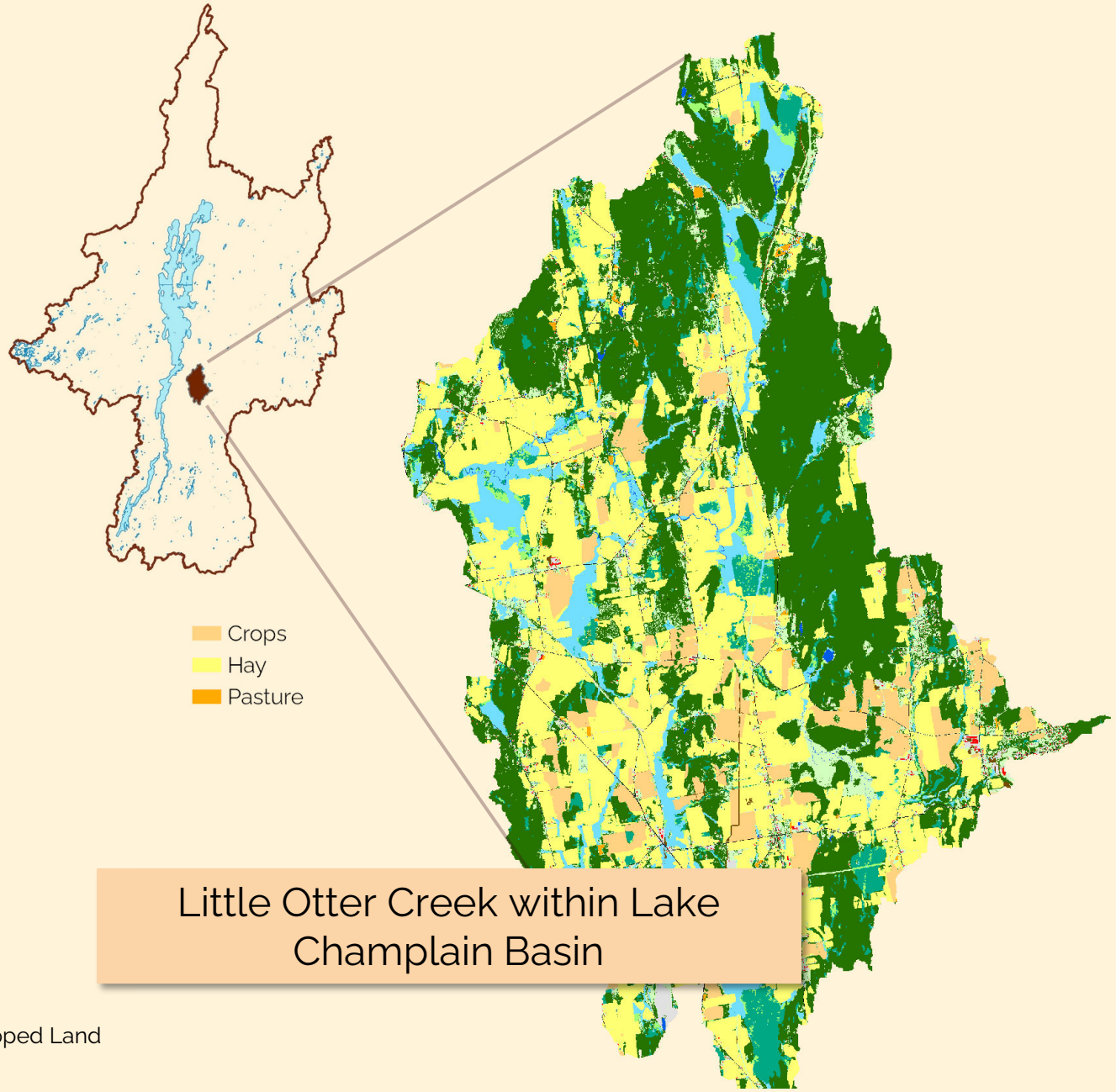
Study area – Little Otter Creek

- Subbasin of the Lake Champlain Basin
  - 15,800 ha/158 km²
  - Addison County, the second-largest dairy-producing county in VT
  - Two USGS monitoring stations
  - Tile drainage
  - Land use distribution:

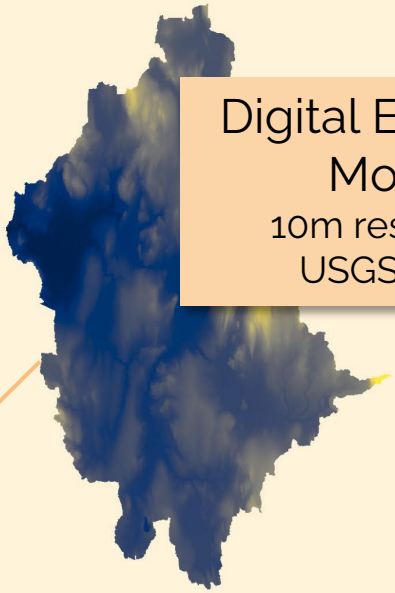




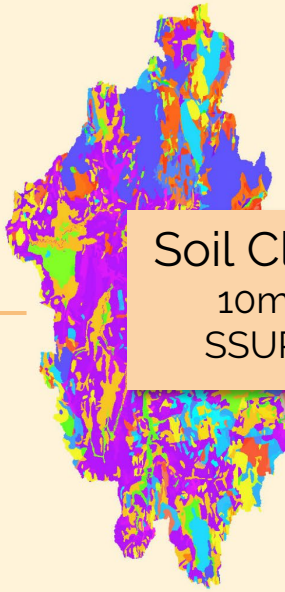
Little Otter Creek within Lake Champlain Basin

Data sources for watershed initialization

- SWAT+ v61.0.1
- SWAT+ Toolbox v3.1.0

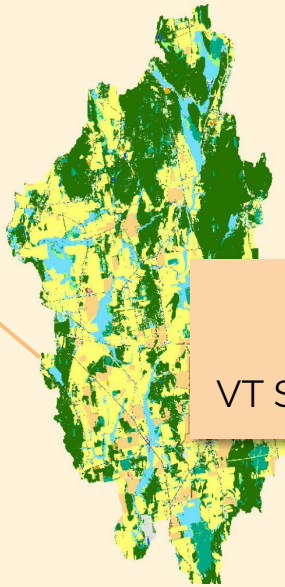


Digital Elevation Model
10m resolution
USGS, 2019



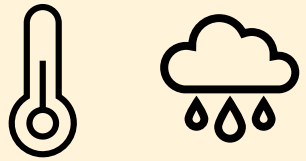
Soil Classification
10m resolution
SSURGGO, 2020

SWAT+
SOIL & WATER ASSESSMENT TOOL



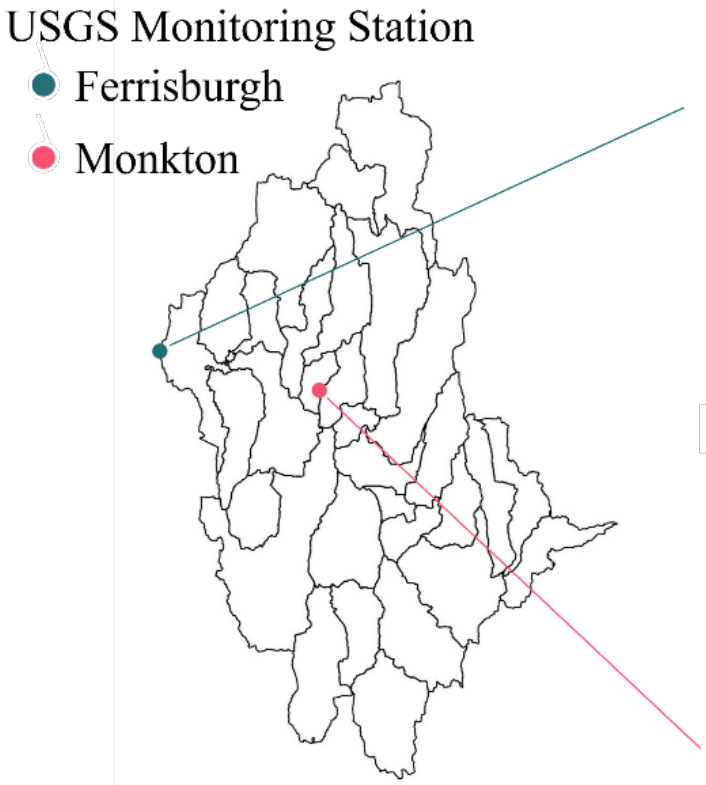
Land Use
10m resolution
VT Spatial Analysis Lab, 2024

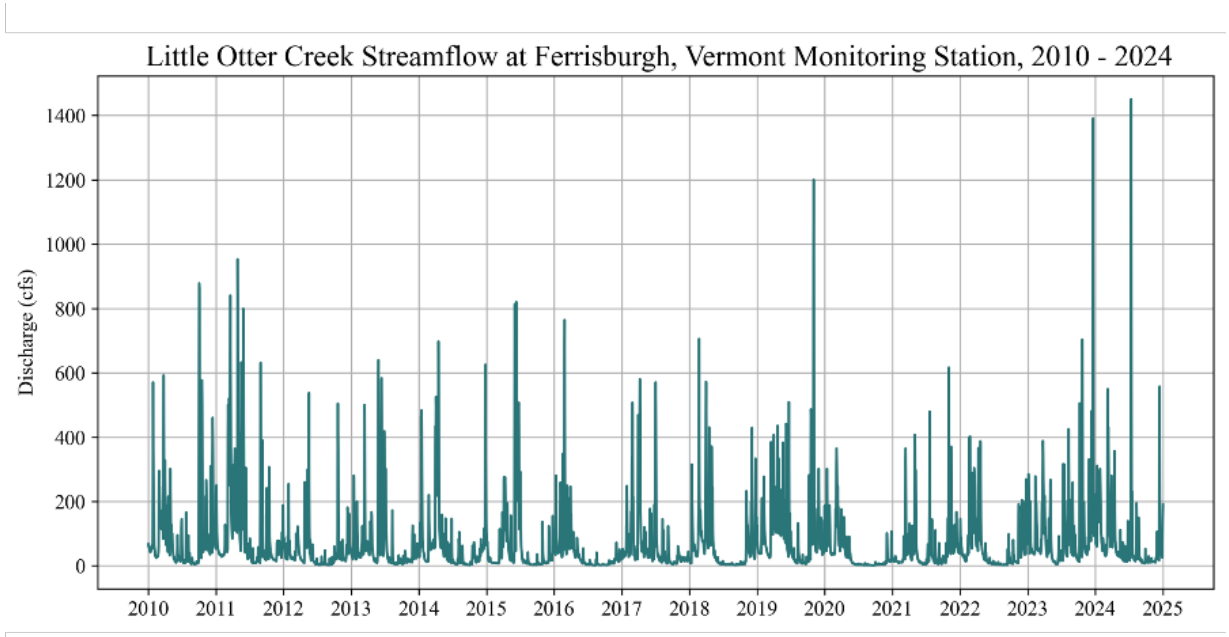
Weather
NOAA

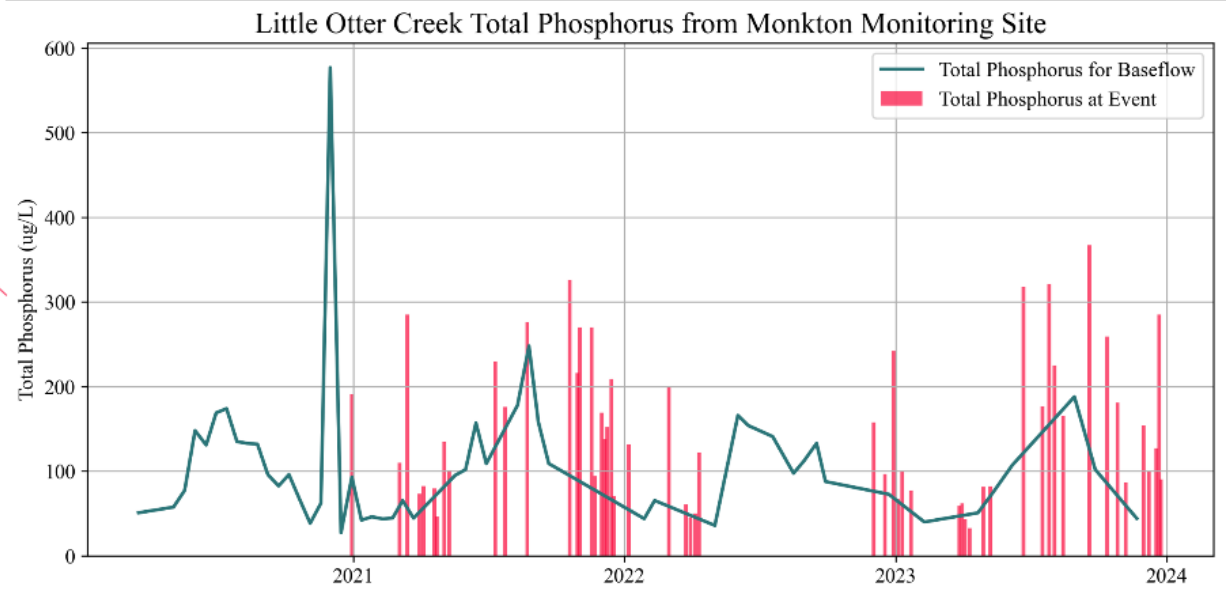


Management Practices
UVM Extension

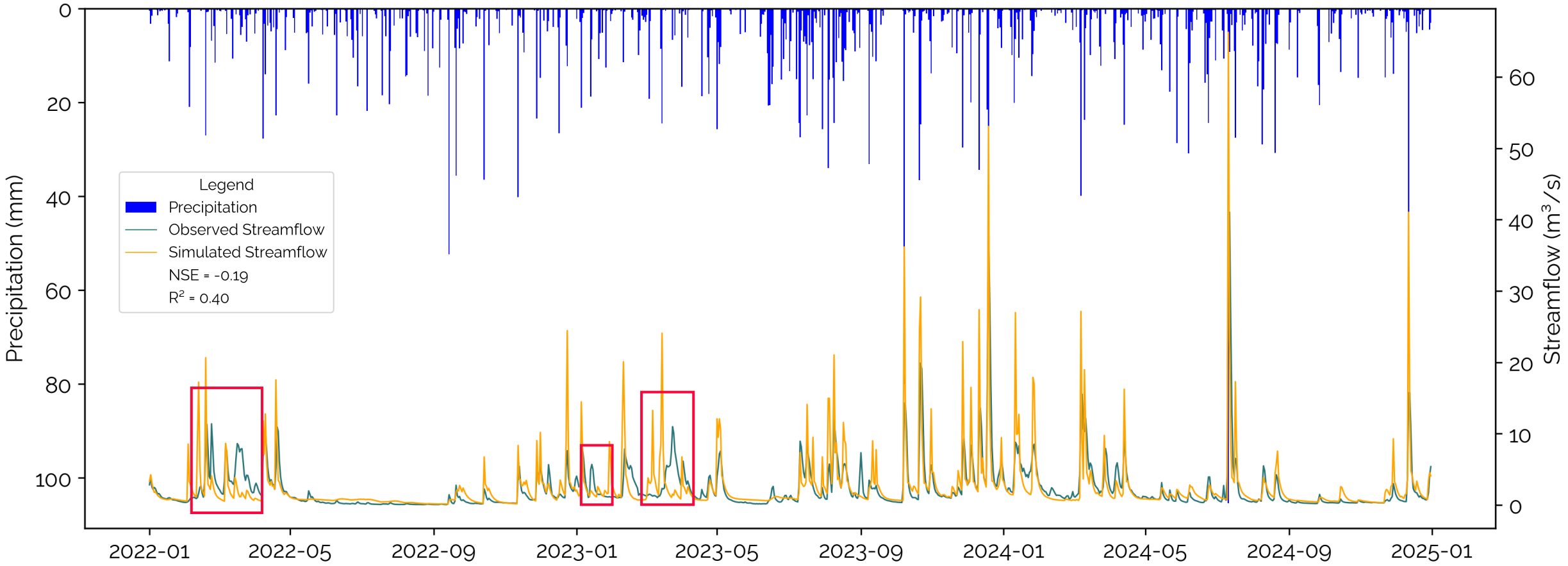
Observed streamflow and phosphorus loads





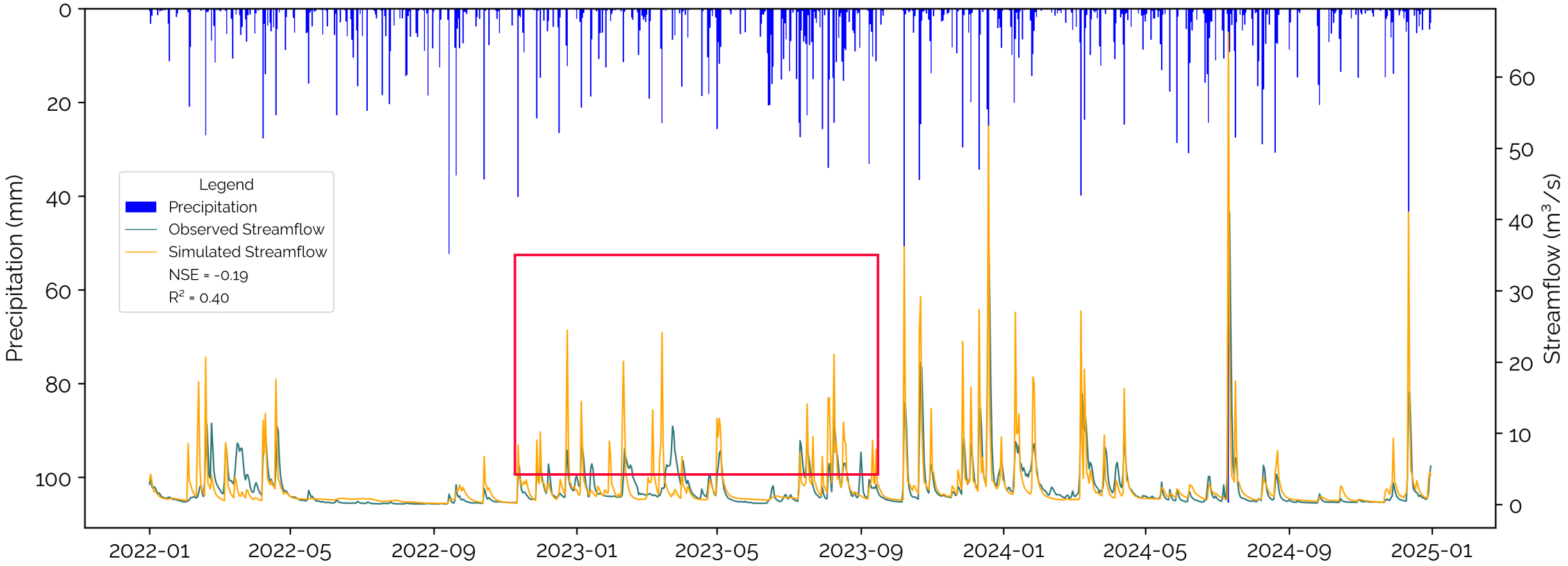


Pre-calibration observed vs. simulated



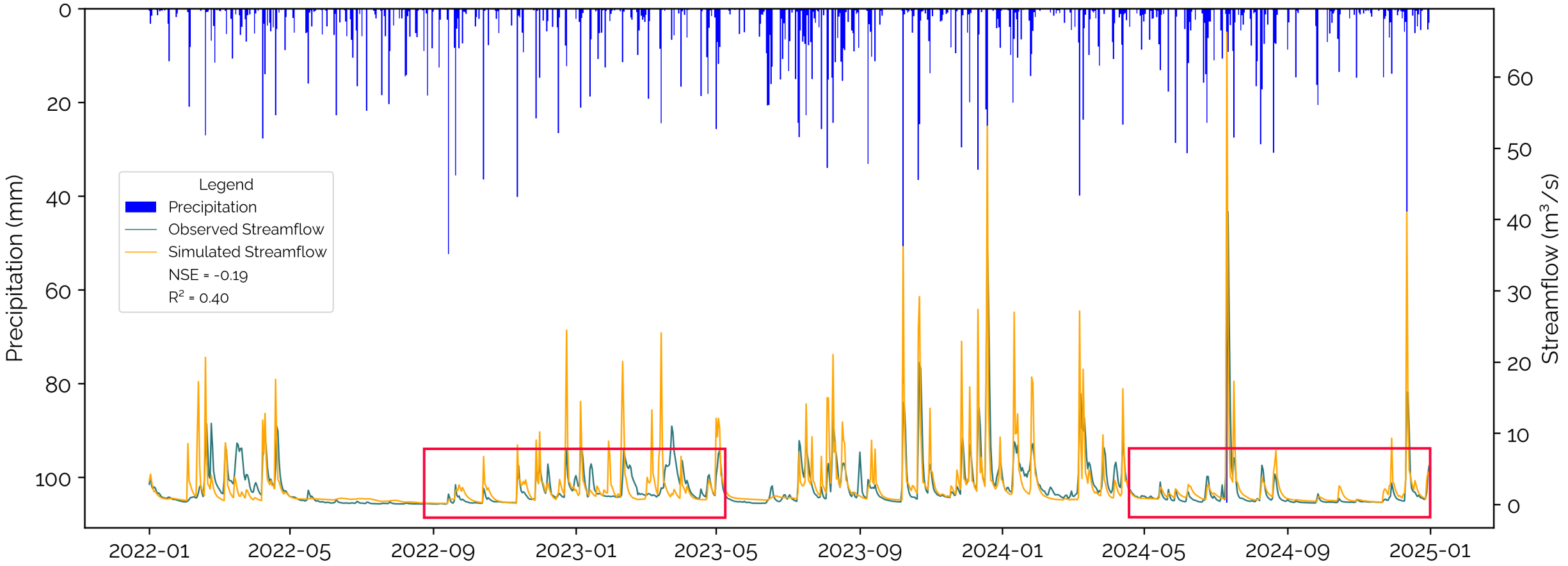
*** The simulation misses the early spring peak, likely due to inadequate representation of snowmelt processes.**

Pre-calibration observed vs. simulated



*** The simulation overpredicts peak flows, suggesting the model is overestimating surface runoff.**

Pre-calibration observed vs. simulated



*** Recession curve has a slower decline than observed data, indicating the model underestimates groundwater drainage or baseflow recession**

Parameters

Name	Group	Change Type	Minimum	Maximum
cn2	hru	Percent	-20.00000	20.00000
esco	hru	Replace	0.00000	1.00000
epco	hru	Percent	0.00000	1.00000
canmx	hru	Replace	1.00000	100.00000
perco	hru	Replace	0.00000	1.00000
lat_ttime	hru	Percent	-10.00000	20.00000
cn3_swf	hru	Replace	0.00000	1.00000
alpha	aqu	Replace	0.01000	0.90000
flo_min	aqu	Percent	0.00000	20.00000
revap_co	aqu	Replace	0.02000	0.20000
revap_min	aqu	Replace	0.00000	50.00000
bf_max	aqu	Replace	0.10000	2.00000
awc	sol	Percent	-10.00000	10.00000
k	sol	Percent	-10.00000	20.00000
chk	rte	Percent	-20.00000	20.00000
snofall_tmp	hru	Replace	-5.00000	5.00000
snomelt_tmp	hru	Replace	-5.00000	5.00000
snomelt_max	hru	Replace	0.00000	10.00000
snomelt_min	hru	Replace	0.00000	10.00000

SWAT calibration methods

Tile drainage

Assume 25% of cropland with hydrologic class C &D, <5% slope contain tile drains

Streamflow calibration with SWAT+ Toolbox

Ferrisburgh daily Obs.
Sobol sensitivity analysis
Calibration with CALSI
NSE > 0.50

Repeat with Monkton monitoring station

Monkton daily Obs.
Sobol sensitivity analysis
Calibration with CALSI
NSE > 0.50

Update baseline scenario

Corn/Hay rotation
Manure application
Poor vs. well drained
+ Addison Country average manure nutrient content

Event-based total phosphorus calibration

Tune P sensitive parameters
Maximize NSE

Scenario Analysis

Soybean, black bean. organic black bean production

Compare final output of Sediment, SRP, TP, OrgP

Expected results

Identify the **optimal crop transition** from corn silage and hay to soybean or black bean production **to reduce sediment and phosphorus export** from agriculture lands.

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Identify the **optimal crop transition** from corn silage and hay to soybean or black bean production **to reduce sediment and phosphorus export** from agriculture lands.

+ Combine with farm-level analysis of GHG emissions and nutrient balance

+ Weave in with multi-disciplinary results, agronomic, economic, and social analysis exploring the dimensions of sustainability of beans in the Northeast

Thank You

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