LAKE CARMI WATERSHED PHOSPHORUS STUDY
FINAL REPORT

October 2021

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1. Nutrient Mass Balance

1.1. Methods

1.1.1. Watershed Nutrient Mass Balance

We conducted a nutrient mass balance analysis for agricultural land in the Lake Carmi watershed during the 2019 growing year (May 2019 – May 2020). Team members from University of Vermont Extension conducted farmer surveys to determine imports and exports of materials containing nitrogen (N), phosphorus (P) and potassium (K). NPK contents of materials were then determined using direct measurements from samples or standard calculations included in the Cornell Whole-Farm Nutrient Mass Balance Tool (Rasmussen et al., 2011). A key challenge that we navigated was the fact that the Lake Carmi Watershed boundary does not align with farm boundaries. There are numerous fields in the watershed managed by entities that do not own farmsteads within the watershed. Additionally, the three farmsteads with animals on-site that are located within the watershed boundary manage fields both inside and outside of the watershed boundary. We considered multiple approaches to resolve the discrepancy between watershed and farm boundaries and settled on the approach shown in Error! Reference source not found..

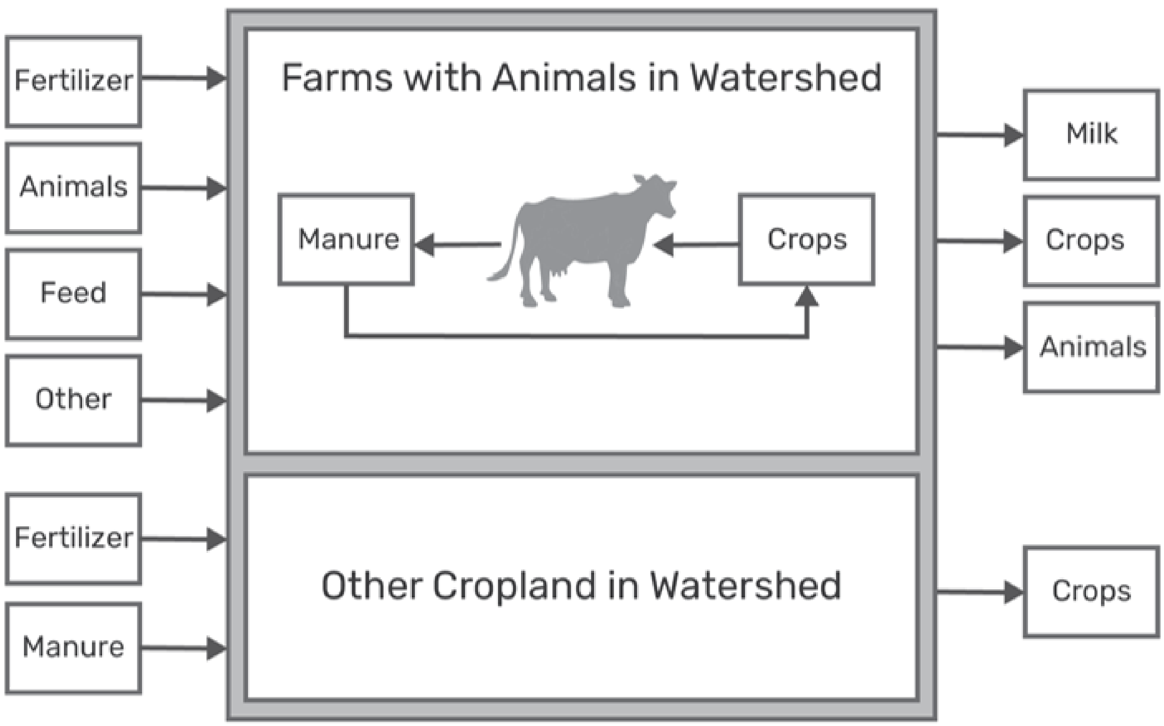

Figure 1. *Sources of nutrient imports and exports considered in the watershed mass balance.*

We calculated a whole watershed nutrient mass balance ($MB_{Watershed}$) by subtracting all nutrient exports from all nutrient imports:

$$MB_{Watershed} = I_{Fert} + I_{Manure} + I_{Feed} + I_{Animals} + I_{Other} - E_{Milk} - E_{Crops} - E_{Animals}$$

where, $\boldsymbol{I_{Fert}}$ = fertilizer inputs to fields within the watershed (including fields managed by the three farms within the watershed and all other fields in the watershed), $\boldsymbol{I_{Manure}}$ = manure inputs to the fields that are not part of the three farms within the watershed, $\boldsymbol{I_{Feed}}$ = all purchased feed inputs to the three farms in the watershed, $\boldsymbol{I_{Animals}}$ = all animal inputs to the three farms in the watershed, $\boldsymbol{I_{Other}}$ = other miscellaneous inputs to the three farms in the watershed (bedded pack, sawdust), $\boldsymbol{E_{Milk}}$ = milk exported from the watershed, $\boldsymbol{E_{Crops}}$ = all crops exported from the watershed (including fields managed by the three farms within the watershed and all other fields in the watershed), and $\boldsymbol{E_{Animals}}$ = animals exported from the watershed.

Assumptions and limitations associated with our method for whole watershed nutrient mass balance include:

- For the three farms within the watershed, we did not resolve the flows of manure to their fields outside of the watershed, nor the return of crops from those fields to the farmstead within the watershed. Implicit in this approach is the assumption that those nutrient flows largely cancel each other out and would have negligible impact on the overall watershed mass balance. Further study of the fields outside of the watershed could test this assumption.
- We only include agricultural land use in the watershed in this mass balance, ignoring all nutrient imports and exports associated with other land uses in the watershed.
- Our whole-watershed mass balance does not account for nutrients exported from the watershed to Lake Carmi via hydrologic processes (runoff, leaching, streamflow). It also does not consider atmospheric pathways (e.g., P deposition, reactive N deposition, N fixation, gaseous N emissions).
- There is substantial movement of animals into and out of the Lake Carmi watershed. This includes temporary boarding of pregnant animals undergoing weight gain. To account for this, we estimated the number of animals entering and exiting the watershed, mean initial weights of these animals, weight gain during boarding, and nutrient contents in animal biomass based on the Cornell Whole-Farm Nutrient Mass Balance Tool.

1.1.2. Cropland Nutrient Mass Balance

We see value in also presenting a cropland mass balance that only includes human-mediated nutrient inputs (manure, fertilizer) to and outputs (harvested crops) from all cropland fields in the watershed. This enables us to assess whether or not cropland soils in the watershed are currently receiving excess nutrients overall. We calculated the cropland mass balance ($MB_{Cropland}$) as:

$$MB_{Cropland} = I_{Fert} + I_{Manure} - O_{Crops}$$

where, $\boldsymbol{I_{Fert}}$ = fertilizer inputs to all fields within the watershed, $\boldsymbol{I_{Manure}}$ = manure inputs to all fields within the watershed, and $\boldsymbol{O_{Crops}}$ = crop harvest outputs from all fields within the watershed. All three terms include fields managed by the three farms within the watershed and all other fields in the watershed.

1.2. Results

1.2.1. Watershed Nutrient Mass Balance

We show the whole watershed mass balance results for N, P, and K in **Figures 2, 3, and 4**, respectively. As a reminder, this analysis only considers nutrient flows that cross the watershed boundary.

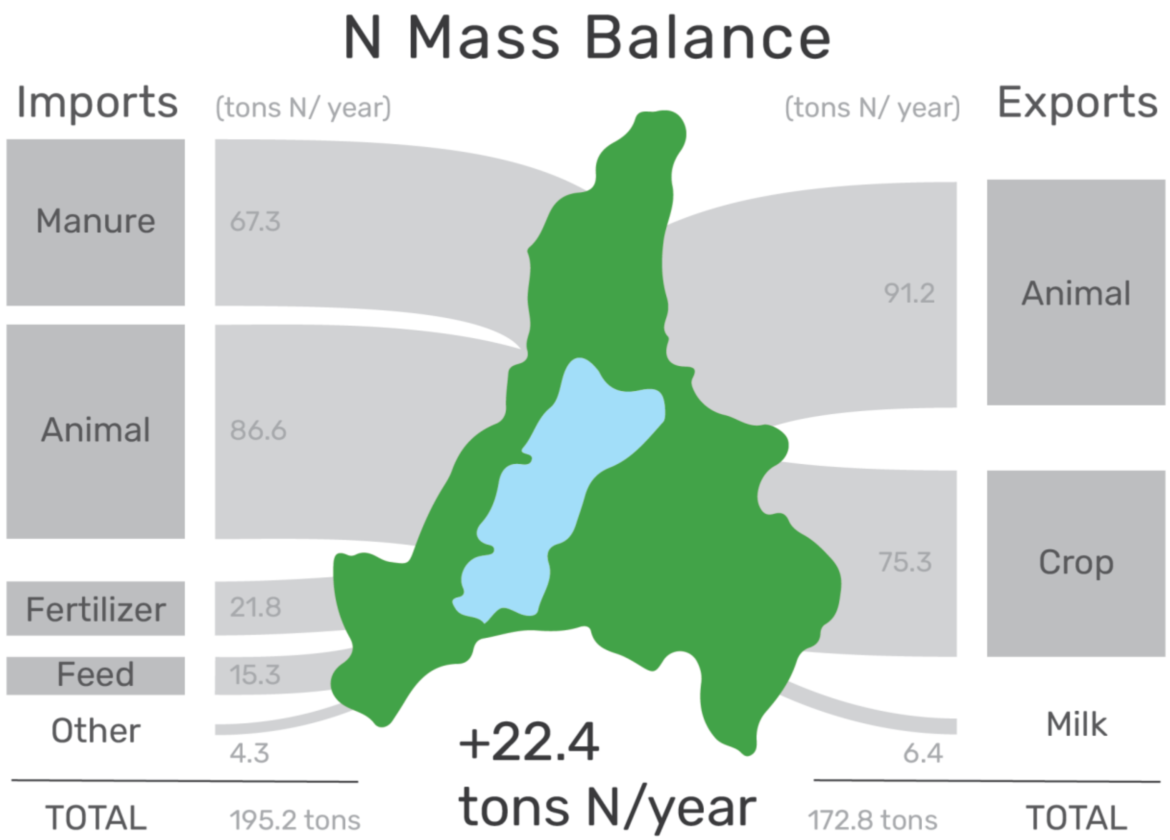

Figure 2. *Watershed nitrogen (N) mass balance for the Lake Carmi watershed (2019 growing year).*

For nitrogen, imports to the watershed were mostly in the form of animals (86.6 tons N/year) and manure (67.3 tons N/year), with lesser amounts imported as fertilizer (21.8 tons N/year), feed (15.3 tons N/year) and other materials (4.3 tons N/year). Nitrogen was exported from the watershed largely as animals (91.2 tons N/year) and crops (75.3 tons N/year), with an additional 6.4 tons N/year exported as milk. These flows result in a net watershed mass balance of +22.4 tons N/year (+27.6 lbs N per cropland acre per year).

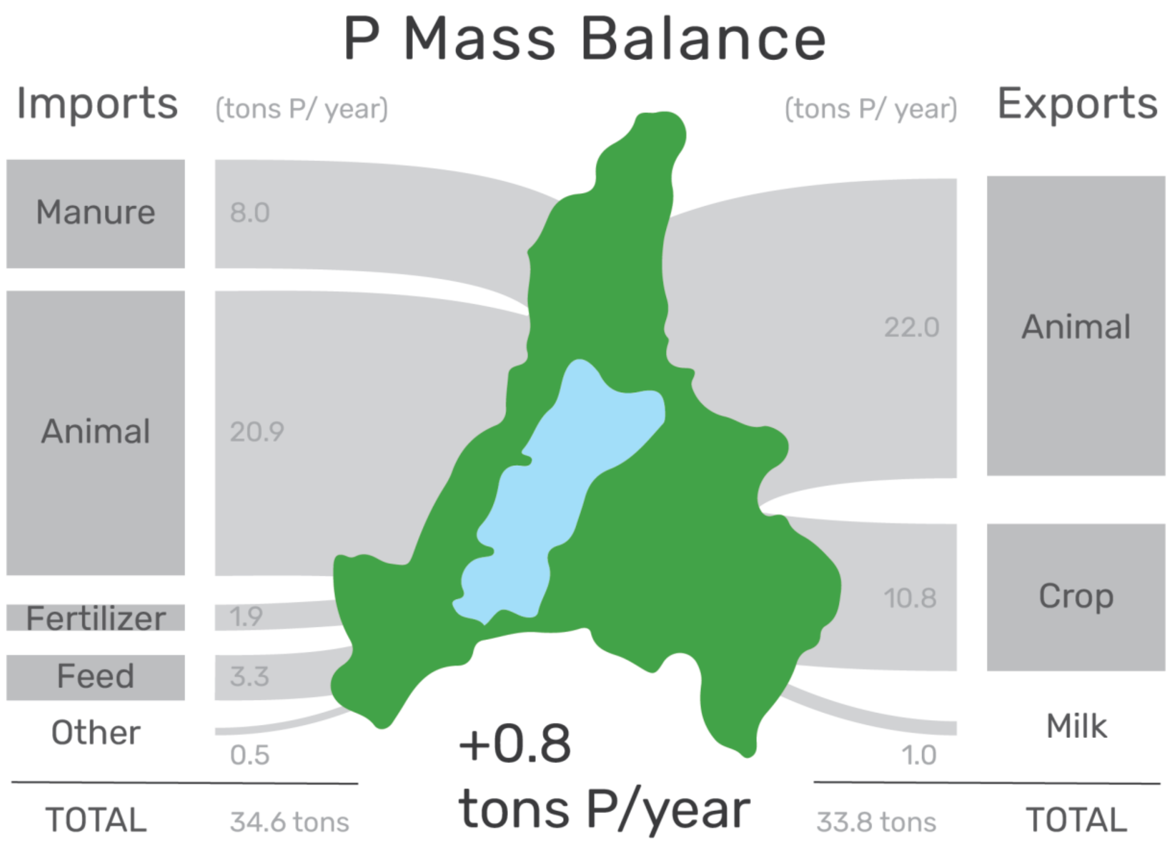

Figure 3. *Watershed phosphorus (P) mass balance for the Lake Carmi watershed (2019 growing year).*

For phosphorus, imports to the watershed were also mostly in the form of animals (20.9 tons P/year), with lesser amounts imported as manure (8.0 tons P/year), feed (3.3 tons P/year), fertilizer (1.9 tons P/year) and other materials (0.5 tons P/year). Phosphorus was exported from the watershed largely as animals (22.0 tons P/year) and crops (10.8 tons P/year), with an additional 1.0 tons P/year exported as milk. These flows result in a net watershed mass balance of +0.8 tons P/year (+1.0 lb P per cropland acre per year).

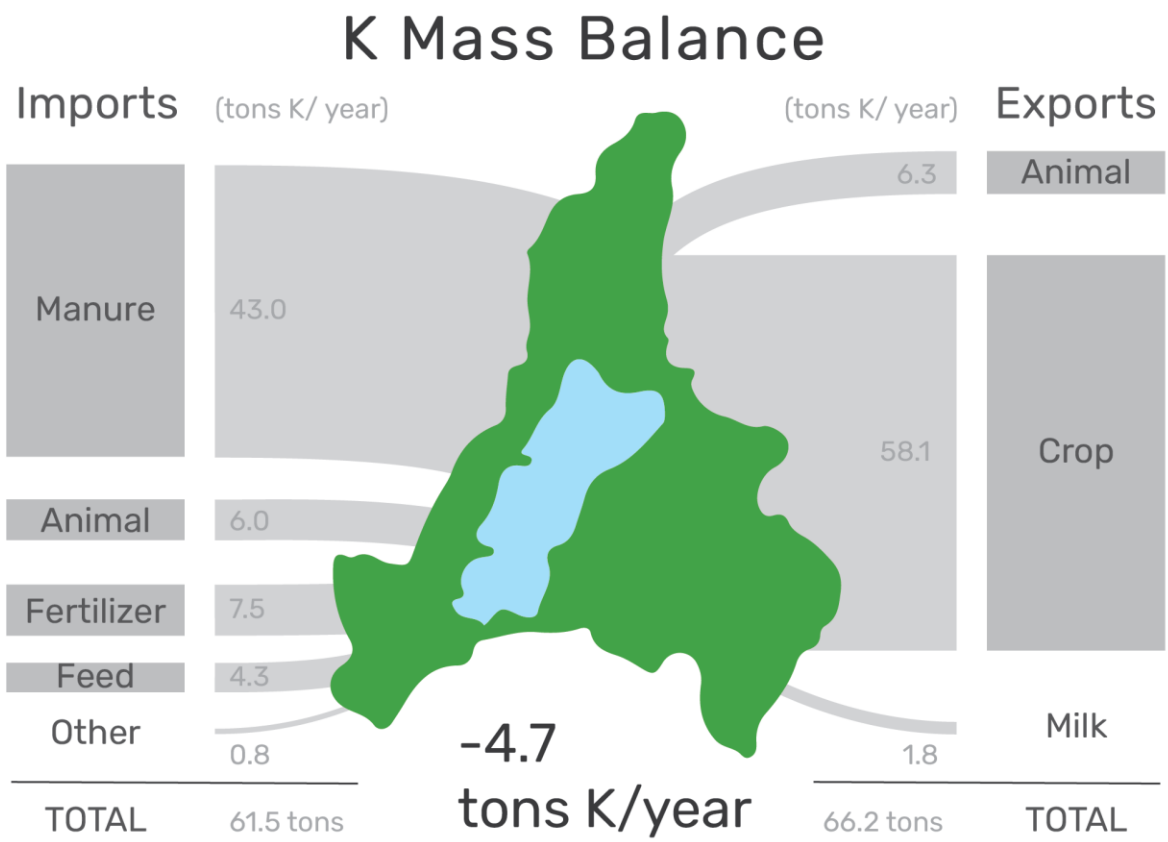

Figure 4. *Watershed potassium (K) mass balance for the Lake Carmi watershed (2019 growing year).*

For potassium, imports to the watershed were also mostly in the form of manure (43.0 tons K/year), with lesser amounts imported as fertilizer (7.5 tons K/year), animals (6.0 tons K/year), feed (4.3 tons K/year), and other materials (0.8 tons K/year). Potassium was exported from the watershed largely as crops (58.1 tons K/year), with additional exports of 6.3 and 1.8 tons K/year in animals and milk, respectively. These flows result in a net watershed mass balance of -4.7 tons K/year (-5.8 lbs K per cropland acre per year).

1.2.2. Cropland Nutrient Mass Balance

Table 1 shows human-mediated N, P, and K flows to and from all cropland soils in the watershed. As a reminder, these flows do not necessarily cross the watershed boundary. Our results show that N applied as fertilizer and manure exceeded the N harvested in crops, resulting in a positive net mass balance of +18.7 tons N/year, or +23.1 lbs N per acre per year on average. To the contrary, we found that farmers removed more P and K from cropland soils in the form of harvested crops than they added in fertilizer and manure during the 2019 growing year. This resulted in negative mass balances of -5.2 tons P/year (-6.4 lbs P per acre per year on average) and -28.3 tons K/year (-34.9 lbs K per acre per year on average).

Table 1. *Nitrogen (N), phosphorus (P) and potassium (K) mass balance for cropland in the Lake Carmi watershed in 2019.*

Nutrient	Applied as Fertilizer (tons/yr)	Applied as Manure (tons/yr)	Harvested as Crops (tons/yr)	Mass Balance (tons/yr)	Mass Balance (lbs $acre^{-1}$ yr^{-1})
Nitrogen (N)	21.8	123.4	126.5	+18.7	+23.1
Phosphorus (P)	1.9	13.0	20.0	-5.2	-6.4
Potassium (K)	7.5	75.4	111.2	-28.3	-34.9

The difference between the whole watershed mass balance and cropland mass balance is notable for P (+0.8 tons P/year for the whole watershed mass balance compared to -5.2 tons P/year for the cropland mass balance). This suggests that while farmers added less P to cropland soils than they harvested in crops (which should result in decreasing soil P levels over time), P accumulated elsewhere on the three farms in the watershed to a degree that caused the overall watershed mass balance to be positive. Possible explanations for this include stored feed, growing animals, or stored manure. Additional data collection is needed to tease apart these possible storages of surplus P. We therefore recommend that nutrient management efforts in the Lake Carmi watershed place emphasis on best management practices in the farmstead areas where feed, animals, and manure are stored to limit P losses to water, alongside continued efforts to use P efficiently on croplands.

1.2.3. Comparison with Previous Studies and Databases

Table 2 on the next page shows prior nutrient mass balance results per cropland acre for different spatial scales in Vermont and New York, putting our findings into a broader context. Data available in previous works are ≥5 years old (2012-2016 for Vermont, 2006 for New York dairy farms), but still provide useful comparisons. Our estimated N mass balances for the Lake Carmi watershed and cropland are lower than 2013 and 2014 estimates in the The Fertilizer Institute (TFI) NuGIS database for Franklin County cropland, but greater than the most recent estimates at the state-level for Vermont (TFI, 2021; **Table 2**). Our estimated P mass balances for cropland stands out as the lowest P balance value in **Table 2**, indicating net P mining from cropland soils within the watershed. The Lake Carmi watershed balance per cropland acre was lower than past estimates in the TFI NuGIS database for Franklin County cropland, and also lower than the state-level estimates for Vermont cropland (TFI, 2021; **Table 2**). We observed a negative K mass balance for the Lake Carmi watershed and cropland, indicating net K export from the watershed due to agricultural activities. Compared to farm-level nutrient mass balances for New York dairy farms in 2006 (Cela et al., 2014), our whole-farm mass balances for the three farms having farmsteads within the Lake Carmi watershed indicate better than average performance. Note that NuGIS data referenced in this final report differ somewhat from those listed in the interim report because the NuGIS methodology was updated in 2021 as the database was moved to The Fertilizer Institute.

Table 2. *Annual nitrogen (N), phosphorus (P) and potassium (K) mass balances per cropland acre at multiple spatial scales in Vermont and New York according to previous studies and this study of the Lake Carmi Watershed in 2019.*

Location/Spatial Scale	Year	Citation	N mass balance (lbs N/acre)	P mass balance (lbs P/acre)	K mass balance (lbs K/acre)
State-level					
Vermont	2012	TFI (2021)	-8.1	+2.7	-38.3
Vermont	2012	Wironen et al. (2018)	N/A	+7.4	N/A
Vermont	2013	TFI (2021)	+3.2	+4.0	-31.2
Vermont	2014	TFI (2021)	-0.7	+3.0	-35.9
Vermont	2015	TFI (2021)	+29.5	+4.7	-25.7
Vermont	2016	TFI (2021)	+22.5	+5.1	-25.2
County-level					
Franklin County	2012	TFI (2021)	+29.0	+11.7	-25.6
Franklin County	2012	Wironen et al. (2018)	N/A	+13.4	N/A
Franklin County	2013	TFI (2021)	+53.4	+13.0	-13.1
Franklin County	2014	TFI (2021)	+48.5	+10.8	-21.5
Franklin County	2015	TFI (2021)	+105.7	+11.9	-5.7
Franklin County	2016	TFI (2021)	+66.8	+12.3	-7.2
Watershed-level					
Lake Carmi Watershed (mass balance of all farm flows, divided by cropland acres)	2019	This study (Figs. 2-4, on per cropland acre basis)	+27.6†	+1.0	-5.8
Lake Carmi Cropland (mass balance of cropland flows only, divided by cropland acres)	2019	This study (Table 1)	+23.1†	-6.4	-34.9
Farm-level					
102 Dairy Farms in New York (mean ± std. dev.)	2006	Cela et al. (2014)	+66 ± 55†	+9 ± 7	+26 ± 29
3 Farms that Contain Land within the Lake Carmi Watershed (range)	2019	This study	-59 to +23†	-5.3 to +4.8	-72 to +10

†excludes N fixation by legumes

1.3. References

Cela, S., Ketterings, Q. M., Czymmek, K., Soberon, M., & Rasmussen, C. (2014). Characterization of nitrogen, phosphorus, and potassium mass balances of dairy farms in New York State. Journal of Dairy Science, 97(12), 7614-7632.

Rasmussen, C.N., P.L Ristow, and Q.M. Ketterings (2011). Whole Farm Nutrient Balance Calculator; User's Manual. Department of Animal Science. Cornell University, Ithaca NY.

TFI (The Fertilizer Institute). 2021. A Nutrient Use Information System (NuGIS) for the U.S. https://nugis.tfi.org/. Accessed in Fall 2021.

Wironen, M. B., Bennett, E. M., & Erickson, J. D. (2018). Phosphorus flows and legacy accumulation in an animal-dominated agricultural region from 1925 to 2012. Global Environmental Change, 50, 88-99.

2. Demonstrate Farm-PREP Model

Supplemental data for three farms in the Lake Carmi watershed were collected and entered into Farm-PREP. Assessments were then run for 30, 40, 50 and 60% P reduction on all three farms. Methods and results are shown below, along with a description of the challenges encountered.

2.1. General Methods

We ran 30, 40, 50 and 60% P reduction assessments using crop, manure, fertilizer, and soil test P data provided by UVM Extension Team Members. We used the default BMP prioritization settings in Farm-PREP (**Table 3**). We did not have sufficient data to include the optional *Precision Feeding* or *Manure Technologies* data entry fields (**Figure 5**) in our analysis.

Table 3. *Default Farm BMP Prioritizations*

Prioritization Level	**Best Management Practices**
Priority 1	Manure Injection, No-till, Reduced till
Priority 2	Cover crop early plant (9/15), Cover crop, Inter-seeded, Cover crop late plant (10/15), cover crop Mid-plant (10/1)
Priority 3	Buffer-10 ft, Buffer-25 ft, Grass waterway-30 ft, Grass waterway-50 ft
Excluded	None

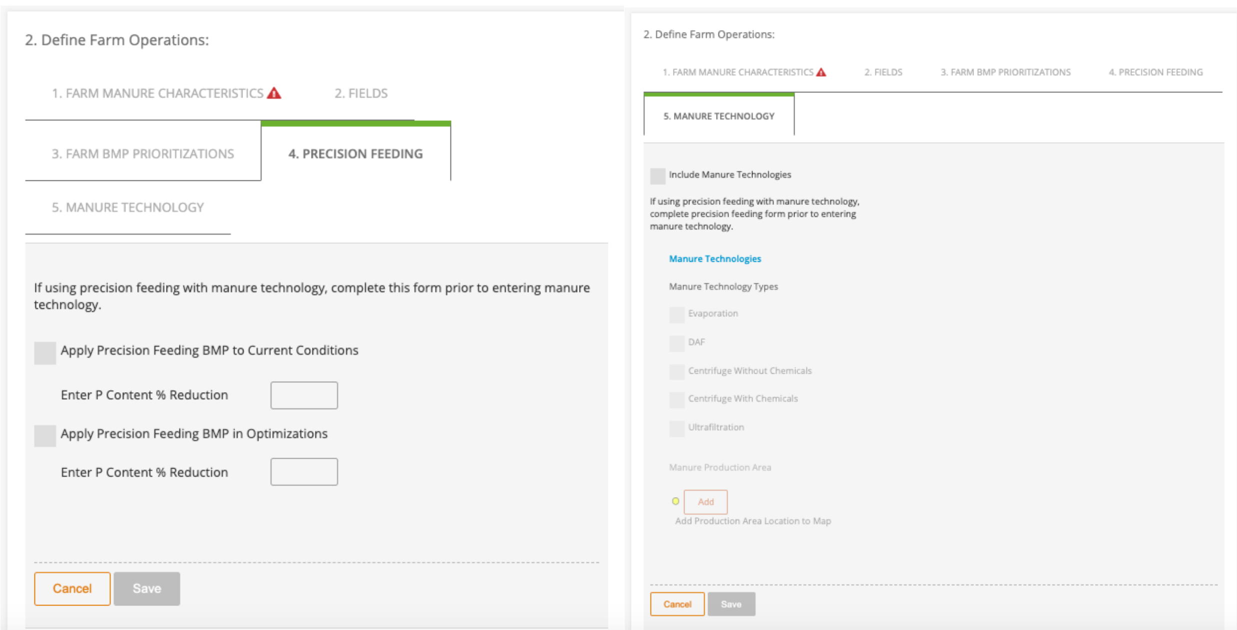

Figure 5. *Precision Feeding and Manure Technology data entry fields.*

2.2. Assumptions and Limitations

General assumptions and limitations are summarized in **Table 4** and farm-specific assumptions and limitations are summarized in **Table 5**.

Table 4. *Important notes on issues encountered in the Farm-PREP modeling, including details on limitations of the model during testing and default model assumptions. We also provide updates to describe how challenges were resolved following consultation with Stone Environmental.*

Issue	**Description**	**Update**
	General	
Large farms	Farm-PREP stalled for ~34 seconds whenever we made a change to a field in Farm 11. This was the largest farm modelled, with 71 fields total. Our attempts to run model assessments for Farm 11 were unsuccessful for several months. In all cases, the model run continued indefinitely with no results. We relayed this information to Stone Environmental and they worked on a solution.	Following updates by Stone Environmental, we have been able to successfully run all target reduction assessments for Farm 11.
	Soils	
Soil Test P	The default soil test P started as 5 ppm in every field modeled. Actual soil test P across the 3 farms modeled ranged from 1 – 29.5 ppm. We used the actual values for all fields but one in this testing.	This is an inherent challenge with modeling. Future users of FarmPREP should always use site-specific soil test P data.
	Crop/Tillage/Manure Information	
Grazing	The "grazing" option was absent for the duration of our analysis, though it was available in earlier versions of Farm-PREP. We excluded 5 fields designated as "pasture" from our analysis because there is no option for "0 cuts" in Farm-PREP, so there was no way to model these fields.	The grazing option is still unavailable which makes it necessary to exclude certain fields from the analysis.
	Best Management Practices	
Buffers	UVM Extension provided buffer widths where applicable, but Farm-PREP also requires you to enter a buffer length. After consulting with Stone Environmental, we settled on the following method for estimating buffer length. For fields directly adjacent to surface waters (as determined by visual inspection of a streams layer from the VT Natural Resource Atlas), the length of the field adjacent to the surface water as measured in Farm-PREP is assumed to be the length of the buffer. This is different than how the Farm-PREP model calculated the length of a buffer if there is not currently one in use. Farm-PREP calculates proposed buffer lengths as: buffer length = long side of field = sqrt(2*fieldarea) (Barbara Patterson, personal correspondence). We also found a glitch where buffers entered under current practices were not showing up in the Current practices scenarios. We relayed this information to Stone Environmental and they worked on a solution.	The glitch causing buffers to not show up under Current practices has been resolved by Stone Environmental.

Table 5. *Farm-specific assumptions and limitations.*

Farm	Description
Farm 6	We excluded fields 63, 69, 70, 72, 74 and 75 because those fields were grayed out in the supplemental data available for Farm-PREP modeling, although the initial nutrient application data we received indicates that field 63 received 46 lbs/acre commercial N fertilizer and 1 cut of hay was harvested, field 69, 70, 72 had two cuts of hay harvested, fields 74 and 75 received 46 lbs/acre commercial N and had two cuts of hay harvested.
Farm 8	We excluded fields 82 and 94 because there is no "pasture" option in Farm-PREP, though 13 lbs/acre P_2O_5 were added to field 82. There is no option for "0 cuts" in Farm-PREP so there was no way to model this field.
Farm 11	We excluded fields 194, 197 and 201 because there is no "pasture" option in Farm-PREP currently. There was no soil test P value for field 200 included in the dataset available, the default value was used for that field only.

2.3. Results

One challenge with the interpretation of Farm-PREP results at the farm-level is the large amount of data resulting from model runs. We have included four appendices (in .xslx format) with this report that provide full results from 30, 40, 50 and 60% P reduction assessments for Farm 6 and 11, and 50% and 60% P reduction assessments for Farm 8. The 30% and 40% reduction targets were not applicable to Farm 8 since the Current practices already achieve 49% P reduction from Baseline.

As can be seen in each appendix file, results are shown for baseline, current, and target reduction scenarios by field ("Field" tabs) and for the farm as a whole ("Farm" tabs). For the target reduction scenarios, 10 alternatives (labeled 0 – 9) are provided. While providing so many alternative routes to meeting the target P reduction could potentially enhance the freedom of the farmer to select the route that they find most attractive, this creates a very large amount of data output at the farm-level to assess. We found it difficult to determine the best way to summarize such large model outputs. Therefore, we anticipate that others will also find interpretation of the full farm output by field challenging. **Table 6** below provides some high-level results from each run.

Table 6. *Summary of model outputs for the assessments run in Farm-PREP for this study.*

Farm	Assessment (target reduction relative to Baseline)	Summary of Output
6	Target = 30% P reduction	Current practices already result in a 27% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 6-7% total P load reduction relative to Current practices (32% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.0, 0.7, and 0.7 lbs/acre, respectively.
6	Target = 40% P reduction	Current practices already result in a 27% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 18% total P load reduction relative to Current practices (40% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.0, 0.7, and 0.6 lbs/acre, respectively.
6	Target = 50% P reduction	Current practices already result in a 27% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 31% total P load reduction relative to Current practices (50% reduction

		compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.0, 0.7, and 0.5 lbs/acre, respectively.
6	Target = 60% P reduction	Current practices already result in a 27% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 45% total P load reduction relative to Current practices (60% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.0, 0.7, and 0.4 lbs/acre, respectively.
8	Target = 30% P reduction	Current practices already result in a 49% total P load reduction at the farm level relative to the Baseline. Therefore, this target reduction level is not applicable to this farm.
8	Target = 40% P reduction	Current practices already result in a 49% total P load reduction at the farm level relative to the Baseline. Therefore, this target reduction level is not applicable to this farm.
8	Target = 50% P reduction	Current practices already result in a 49% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 3% total P load reduction relative to Current practices (50% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.2, 0.6, and 0.6 lbs/acre, respectively.
8	Target = 60% P reduction	Current practices already result in a 49% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 22% total P load reduction relative to Current practices (60% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 1.2, 0.6, and 0.5 lbs/acre, respectively.
11	Target = 30% P reduction	Current practices already result in a 2% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 29% total P load reduction relative to Current practices (30% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 0.5, 0.5, and 0.3 lbs/acre, respectively.
11	Target = 40% P reduction	Model run completed – however, alternative scenarios yield 52% reduction from baseline.
11	Target = 50% P reduction	Current practices already result in a 2% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 51% total P load reduction relative to Current practices (51% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 0.5, 0.5, and 0.2 lbs/acre, respectively.
11	Target = 60% P reduction	Current practices already result in a 2% total P load reduction at the farm level relative to the Baseline. Ten alternative scenarios all resulted in a 66% total P load reduction relative to Current practices (66% reduction compared to the Baseline). Baseline, Current, and Alternatives total P loading rates were 0.5, 0.5, and 0.2 lbs/acre, respectively.

Results for P load reductions in Farm-PREP output are also separated into soluble P, sediment P and tile P. **Figures 6, 7, and 8** below illustrate the proportions of total P accounted for by soluble and sediment forms for the Baseline, Current, and two applicable target reduction Assessment model runs for Farm 6, 8 and 11, respectively.

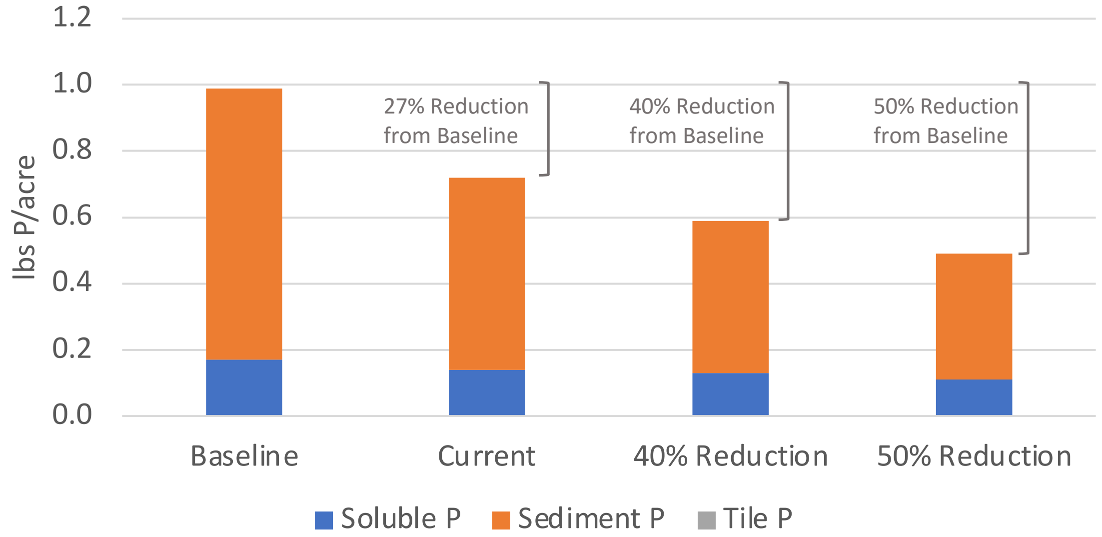

Figure 6. *Modeled whole-farm P reduction on Farm 6 under baseline, current, 40% and 50% P reduction scenarios.*

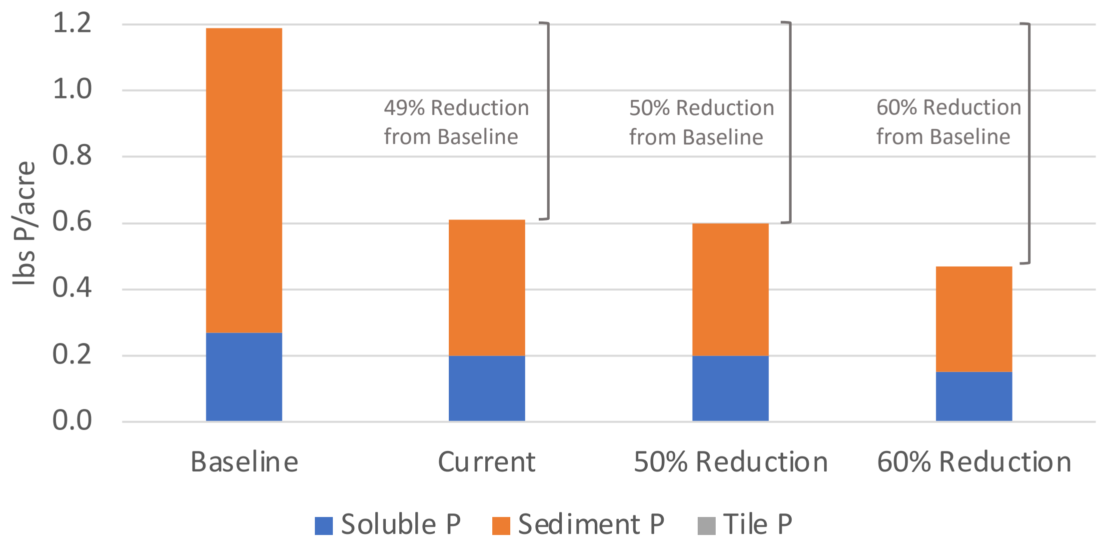

Figure 7. *Modeled whole-farm P reduction on Farm 8 under baseline, current and 50% and 60% P reduction scenarios.*

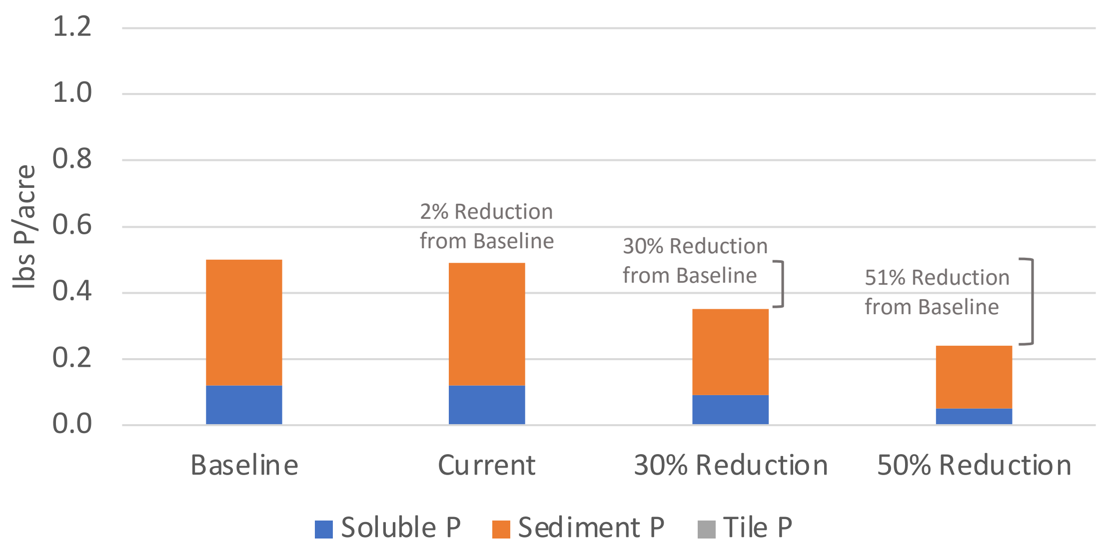

Figure 8. *Modeled whole-farm P reduction on Farm 11 under baseline, current, 30% and 50% P reduction scenarios.*

2.4. Conclusions

2.4.1. Challenges working with Farm-PREP

Running Farm-PREP at the farm scale is a time-consuming process that requires substantial data collection and data entry. The glitches that we encountered when testing the model were resolved by the Stone Environmental team during a recent update. Their team has been very helpful and responsive.

2.4.2. Modeled P loads

The Farm-PREP model shows that Current practices have already resulted in substantial P load reductions (27 – 49%) relative to the Baseline for two of the three farms modelled in this study (6 & 8). The third farm (Farm 11) already had a low Baseline P loss due to most of the fields being in continuous hay, therefore the model showed only a modest reduction in P loss from Baseline under Current practices (2%). For each of the three farms, our simulations illustrate 10 alternative pathways to further reducing P loads to 30, 40, 50 or 60% relative to the Baseline depending on the reduction already achieved by Current practices. The current P load range modeled by Farm-PREP (0.5 to 0.7 lbs P loss per acre) is similar to the P mass balance we estimated for the Lake Carmi watershed in Part 1 of this report (+1.0 lbs P/acre, **Table 2**), but less than county-level P mass balance estimates for the same years (+10.8 to +13.4 lbs P/acre, **Table 2**). We have no field data to compare the modeled P loads to, therefore we cannot assess the accuracy of these predictions for Current practices. We also cannot assess the accuracy of the partitioning of soluble and sediment P. Field verification of Farm-PREP results in the Lake Carmi watershed is needed to increase confidence in these estimates. See additional notes on FarmPREP in Section 3 below.

2.5. References

None

3. Assessment of Wetland Restoration Opportunities in the Lake Carmi Watershed

3.1. Background

Dr. Roy's team (including Kate Porterfield and Adrian Wiegman), with the assistance of NWCS staff, assessed three pieces of land in the Lake Carmi watershed for restoration and/or conservation potential, and the associated water quality benefits. These parcels are located on three different farms. Purchase of these parcels has been the focus of past discussions with the State of Vermont or conservation organizations, and farmers remain interested in that option if the offers meet their expectations.

Each of the parcels contain, or are adjacent to, channels showing evidence of past straightening to promote drainage. This channel straightening can cause:

(1) Depletion of organic matter in soil through oxidation.
(2) Bank and channel bed erosion/incision, which can increase the export of particulate phosphorus (P).

We analyzed areal imagery and elevation data to identify soil sampling locations on actively farmed fields as well as reference ecosystems of similar elevation and flooding potential at each site. Next, we conducted in-person site assessments and collected soil samples (0 – 10 cm) for measurement of modified Morgan P (MMP), inorganic P (IP), organic P (OP), total P (TP), organic matter (% loss on ignition, LOI), water-extractable P (WEP), and P saturation ratio (PSR). These soil metrics can be used to predict risk of P loss to overlying water upon inundation with floodwater. We then used Farm-PREP to estimate the potential P load reduction of largely ceasing farming on these sites (i.e., passive restoration where P inputs are eliminated and fields are harvested for hay). Finally, we provide recommendations for potential restoration activities to improve water quality.

3.2. Site Assessments

We analyzed areal imagery and elevation data in order to identify several soil sampling locations with associated reference points at three sites in the Lake Carmi watershed. Below we indicate the sampling locations and reference ecosystems and provide some additional comments on each site.

3.2.1. Site 1

Site 1 hosts 40 acres of wetland and pasture on the north end of Lake Carmi. This parcel drains immediately into the lake and there is a straightened channel running east towards Alder Run. Restoration on this site would involve reconnecting the straightened channel with the nearby fields. Based on areal imagery, there are several fields with different land use history in this parcel.

Figure 9. *Candidate parcel for wetland restoration (Site 1).*

Figure 10. *Soil sampling locations at Site 1.*

3.2.2 Site 2

Site 2 has high value resource area around the head waters of the Marsh Brook (**Figure 11**). While a biological assessment was not part of our scope, we noted the scenic nature of the pond and surrounding wetlands. The headwaters of Marsh Brook drain through a channel surrounded by fields. This site demonstrates evidence of channel straightening. There is a forested section of channel just west of the field which serves as a reference point for the eastern field (**Figure 12**). There is a field just downstream of the pond outlet which could be converted back to wetland.

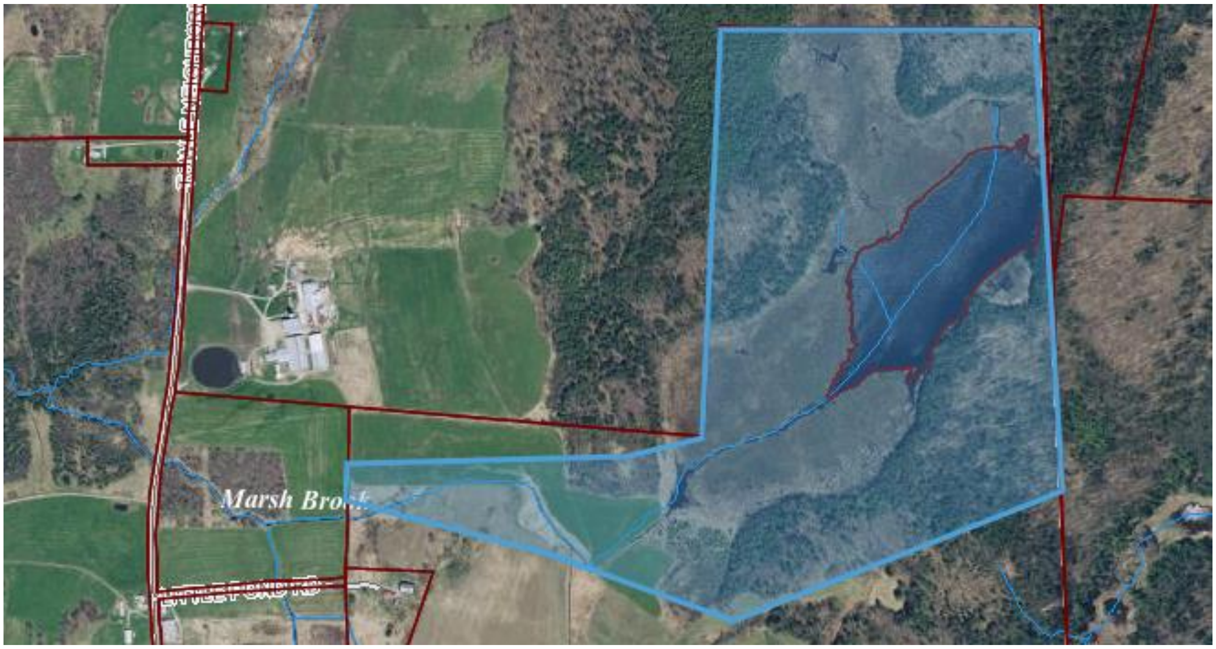

__Figure 11.__ Candidate parcel for wetland restoration (Site 2).

__Figure 12.__ Soil sampling locations on the Site 2 parcel.

3.2.3 Site 3

Site 3 has 50 acres of wooded land that bounds the State Park Land on the south end of the Lake Carmi (**Figure 13**). This parcel is mostly woodland swamp with a steep gradient dropping from west to east. This parcel would be a good conservation candidate, especially if there is risk of development to the western portion. There is little evidence of legacy hydrologic modifications on this parcel. However, the farm fields west and south show evidence of channel modification to a stream. The stream runs east along the southern boundary of the Site 3 parcel then runs southeast under swamp road. According to the National Hydrography dataset this stream may flow seasonally into the Missisquoi River. Any restorative activity on this site that involved the stream would affect the adjacent farm fields, so more parcels would need to be included in any buyouts for restoration in this zone.

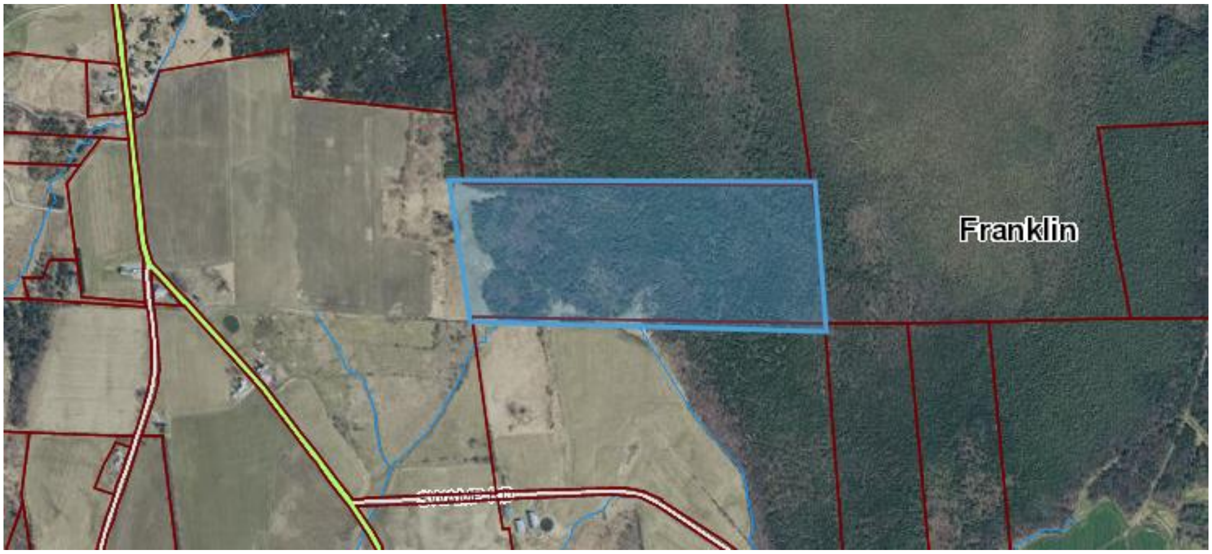

Figure 13. *Candidate parcel for wetland restoration (Site 3).*

Figure 14. *Soil sampling locations on Site 3.*

3.3. Soil Analysis

We measured surface soil properties (0-10 cm) on actively farmed fields for comparison to nearby natural reference points (**Table 7** and **Table 8**). These soil analyses will help us estimate the potential improvement that restoration actions could have on P loss from these sites and help inform the recommendations for restoration activity. Soil test P, inorganic P (IP), organic P (OP), total P (TP), organic matter (% loss on ignition, LOI), water-extractable P (WEP), and P saturation ratio (PSR) were measured. Soil P storage capacity (SPSC) was determined based on PSR and WEP results. Modified Morgan P was also determined by colorimetric (MM-P-Color) and by ICP-OES (MM-P-ICP) at the University of Maine Analytical Laboratory.

Table 7. *Sites sampled in the Lake Carmi watershed, including farm fields being considered for wetland restoration or conservation and nearby reference ecosystems. Soils were sampled from 10 locations along a transect and composited before soil analysis.*

ID	site	plot	lon	lat	field
01FE	01	FE	-72.87203	44.99183	field east
01FW	01	FW	-72.87346	44.99194	field west
01R	01	R	-72.87268	44.99257	reference
02FE	02	FE	-72.83421	44.95267	field east
02FW	02	FW	-72.83518	44.95223	field west
02RN	02	RN	-72.83359	44.95324	reference north
02RS	02	RS	-72.83237	44.95279	reference south
03F	03	F	-72.89168	44.94555	field
03R	03	R	-72.89164	44.94712	reference

Table 8. *Soil properties (0 – 10 cm) of locations sampled in the Lake Carmi watershed (see **Table 7** for site IDs).*

ID	BD (g/cm3)	LOI (%)	MC (%)	WEPw (mg/kg)	IP (mg/kg)	TP (mg/kg)	OP (mg/kg)	Ox.P (mg/kg)	Ox.Al (g/kg)	Ox.Fe (g/kg)	Ox.PSR %	Ox.SPSC (mg/kg)	MM-P-Color (mg/kg)	MM-P-ICP (mg/kg)
01FE	0.55	19	50	0.16	167	901	733	384	1.49	2.81	0.12	334	3	8.5
01FW	0.76	18	38	1.40	196	996	800	431	1.26	2.00	0.17	130	5.7	12.4
01R	0.45	16	47	0.19	203	631	428	427	1.90	4.30	0.09	577	1.9	6.3
02FE	0.93	9	26	0.10	300	514	214	195	0.86	2.26	0.09	297	1.6	3.9
02FW	0.98	10	27	4.21	1007	964	0	636	1.19	1.27	0.31	-179	25.9	29.3
02RN	0.31	22	56	0.35	144	703	559	318	1.33	1.73	0.13	229	2.2	5.1
02RS	0.08	76	82	0.26	24	503	479	67	0.49	0.79	0.07	153	11	34
03F	0.83	12	28	0.40	476	1123	646	512	1.69	4.17	0.12	422	1.5	5.4
03R	0.14	62	79	0.51	269	2625	2356	1319	4.61	7.25	0.14	728	4.2	12.6

Abbreviations in Table 8:

BD – Bulk Density
LOI = Loss on Ignition (proxy for organic matter)
MC = Moisture Content
WEPw = Water Extractable P
IP = Inorganic P
TP = Total P
OP = Organic P
Ox.P = Oxalate Extractable P
Ox.Al = Oxalate Extractable Al
Ox.Fe = Oxalate Extractable Fe
Ox.PSR = P Saturation Ratio based on Oxalate Extractions
Ox.SPSC = Soil P Storage Capacity based on Oxalate Extractions
MM-P-Color* = Modified Morgan P (aka Soil Test P in Vermont) with P measured by colorimetric method
MM-P-ICP* = Modified Morgan P (aka Soil Test P in Vermont) with P measured by ICP (tends to be higher than MM-P-ICP)

*Note that agronomic assessments typically measure soil test P in the 0-15 cm layer (i.e., top 6 inches). Here we used the 0-10 cm layer because that is the most important layer in flooded soils. Evaluations of soil test P relative to RAPs should utilize results from UVM Extension, not those shown in the table above.

We used three key metrics to gauge the risk of P loss to overlying water upon inundation with floodwater. The first is water extractable P (performed here on wet soils) (WEPw) – sometimes referred to as water soluble P (WSP), which has been shown to correlate with soluble reactive P concentrations in runoff (Pote et al., 1996). The second is the P saturation ratio based on oxalate extractable P, Al, and Fe (Ox.PSR), which is calculated as:

$$Ox.PSR = (Ox.P / 31) / ((Ox.Al / 27) + (Ox.Fe / 56))$$

where Ox.P, Ox.Al, and Ox.Fe are oxalate extractable P, Al, and Fe (mg/kg), respectively (Nair et al. 2015).

The Roy lab has measured WEPw and Ox.PSR on a large number of riparian wetland and farmland sites in VT, enabling the determination of a VT-specific breakpoint in the relationship between Ox.PSR and WEPw at Ox.PSR ≈ 0.22. That is, above Ox.PSR = 0.22, soils become more likely to release dissolved P into solution. Below Ox.PSR = 0.22, dissolved P release is less likely during inundation events.

WEPw and Ox.PSR can also be used to estimate a soil P storage capacity (Ox.SPSC):

$$Ox.SPSC = 31 \times (0.22 - Ox.PSR) \times ((Ox.Al/27) + (Ox.Fe/56))$$

where Ox.P, Ox.Al, and Ox.Fe are oxalate extractable P, Al, and Fe (mg/kg), respectively (Nair et al. 2015; VanZomeren et al. 2020). **Figure 15** summarizes the entire process leading to the interpretation of Ox.SPSC.

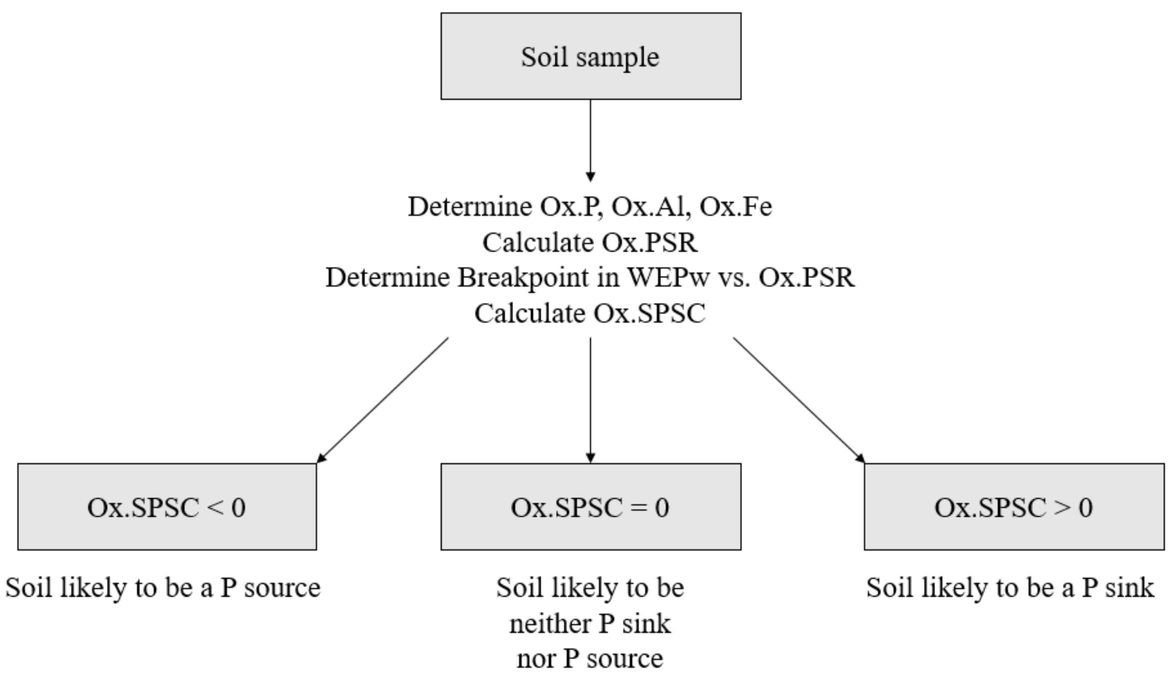

Figure 15. *Process for determination and interpretation of the soil P storage capacity (SPSC) metric used here.*

In the left panel of **Figure 16** below, sites with Ox.PSR greater than the dotted threshold line are more likely to release P to floodwater upon inundation. In the right panel of **Figure 16** below, soils with Ox.SPSC < 0 are more likely to be sources of P upon floodwater inundation.

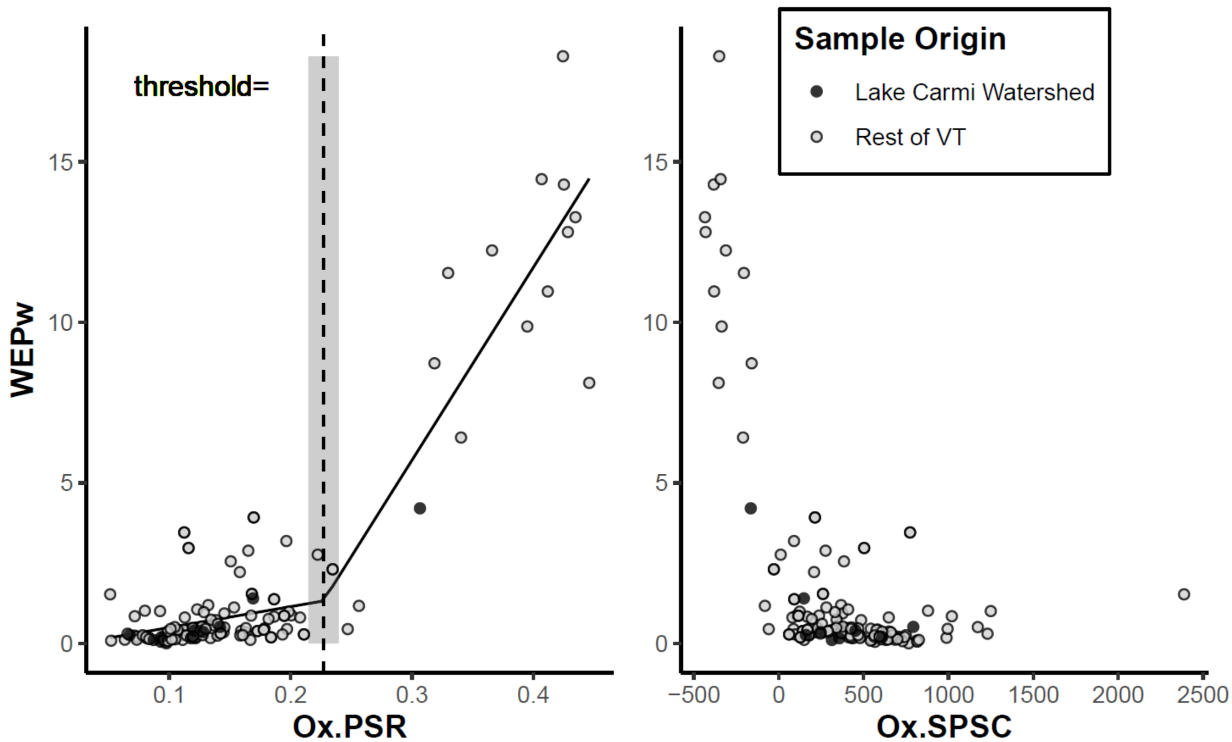

Figure 16. *Soil water extractable P (WEPw) versus the soil P saturation ratio (Ox.PSR, left panel) and the soil P storage capacity (Ox.SPSC, right panel). Black dots are soil samples collected in the Lake Carmi watershed from farm fields that are potential riparian wetland restoration sites and existing wetlands. Grey dots are other riparian farm fields and wetlands around VT assessed by the Roy lab in recent years (Wiegman et al. unpublished data). All data are for surface soils (0-10 cm).*

As can be seen in **Figure 16**, only one Lake Carmi site (black dot) where soils were collected in this study appears to be a potential P source upon inundation based on Ox.PSR and Ox.SPSC. This site is Site 2 "field west" (02FW), which was under corn in 2019 and had the highest MMP, WEP and IP concentrations of all soils sampled (**Table 8**). 02FW was also characterized by the greatest bulk density, relatively low organic matter, and high soil test P, indicating impacts of intensive farming. For comparison, Site 2 "field east" and Site 2 reference ecosystem sites (02FE, 02RS, 02RN) have low/negligible WEP and relatively low IP concentrations, as do the other sites we sampled at Sites 1 and 3 (**Table 8**).

3.4. Farm-PREP Modeling

We used Farm-PREP to help gauge the potential change in total P loss if the three actively farmed fields (01FW, 02FW and 02FE, **Figure 17**) were taken out of production.

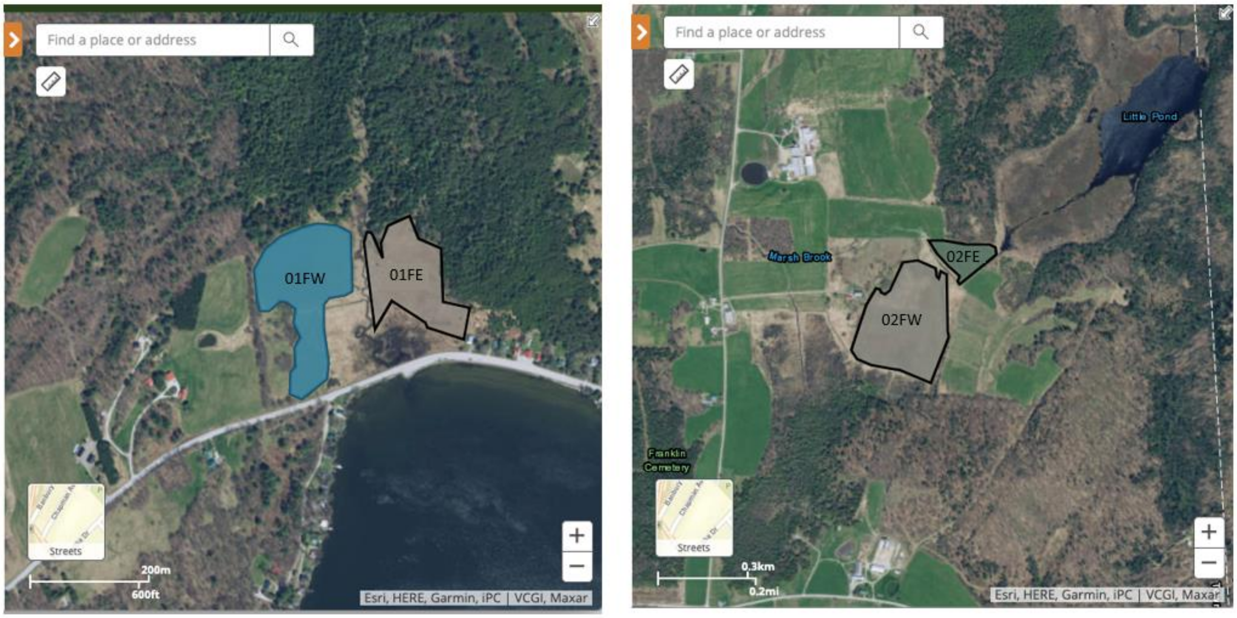

Figure 17. *Actively farmed fields under consideration for restoration (MLFW, MSFW and MSFE).*

In **Table 9** below, the "Current Total P" column represents P loss under current practices and the "Managed P Drawdown Total P" represents P loss if each field were converted to continuous grass hay with the minimum number of cuts removed (2), no nutrient inputs from manure or fertilizers, no tillage and no cover cropping. It was not possible to model more realistic restoration scenarios in Farm-PREP – the model is not designed to assess fields with fallow vegetation, hay fields with 0 hay cuts, revegetation, or changes in flood inundation frequency and duration. We recommend that future versions of Farm-PREP enable modeling fallow conditions.

The 02FW field is currently in corn grain and receives fertilizer application and the 01FW and 02FE fields are currently in continuous grass hay and receive manure applications. The model that simulates a 2 cut managed P drawdown yields a 79% reduction in total P loss from 02FW and a 34% and 35% reduction in total P loss from 02FE and 01FW where P losses are already relatively low.

Table 9. *Predicated total P loss from 3 fields under current practices & P drawdown scenario.*

Field	**Current Total P (lbs/acre)**	**2 Cut Managed P Drawdown Total P (lbs/acre)**
02FW	2.38	0.49
02FE	0.44	0.29
01FW	0.60	0.39

3.5. Recommendations

We used a combination of areal imagery and elevation data, in-person site assessment, soil property analysis and Farm-PREP modeling to assess three pieces of land in the Lake Carmi watershed for restoration and/or conservation potential. In our opinion, all sites have good restoration and/or conservation potential.

Phosphorus (P) mitigation actions on straightened channels would involve cessation of farming on adjacent floodplains, revegetation of the banks and floodplain, and additional measures to encourage reconnection of the channels and their floodplains (Beechie et al., 2010). Revegetation could be active plantings or passive ecological succession. Channel reconnection to adjacent floodplains could be catalyzed by placement of large woody debris in the channels and realigning some sections to promote flow into low areas in adjacent fields. These measures would result in more frequent and prolonged flooding. Over time this will improve water retention, helping to reduce peak flow, erosive force, and particulate P loss downstream, while capturing particulate P during flood events via the settling of particles on the floodplain. However, increased water contact with former farm fields may also promote loss of dissolved P from the soils, so it is best if these fields have low soil test P levels before restoration actions that encourage more frequent and prolonged flooding are taken.

Our soil analysis indicates that Site 2 "field west" (02FW) is the only field assessed with notable potential for dissolved P release if inundated with floodwater. In order to reduce this risk, we recommend that 02FW be fallowed and/or phytoremediated for a period of time before actions are taken to promote hydrologic reconnection with the nearby stream. Doing this will draw down levels of inorganic P and water-extractable P and thereby reduce the risk of dissolved P loss due to hydrologic restoration. More research is needed to determine the timeline of P drawdown required, and to determine how the magnitude of potential increased dissolved P loss during flood inundation compares to the substantial reduction in P loss possible through cessation of farming as suggested by the Farm-PREP modeling (**Table 9**) and the deposition of particulate P during flood events.

Other than 02FW, all other fields sampled appear to be characterized by low risk for P release upon inundation with floodwaters following restoration, making them good candidates for wetland restoration from a P perspective immediately. Farm-PREP modeling was less helpful for 02FE and 01FW as they already host relatively low P loss per acre.

3.6. References

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