Water Quality Effects of Multifunctional Working Buffers for Seasonally Wet Farmland

July 2025

Skagit Conservation District, Snohomish Conservation District, Whidbey Island Conservation District

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Abstract

Seasonal standing water in agricultural fields presents problems for annual crop production and can have negative impacts on nearby water quality, but farmers must maximize production on their available land to remain economically viable. Multifunctional working buffers are a form of riparian agroforestry buffers which incorporate trees and shrubs that provide fruits, nuts, flowers, and materials for making baskets into areas adjacent to streams and drainage ditches. This study evaluated the effects of multifunctional working buffers on water quality and soil health at three farms in three Western Washington counties, Island County, Skagit County, and Snohomish County. Water temperature was recorded, and water and soil chemical analyses were conducted on samples collected upstream and downstream of multifunctional working buffers for approximately one year prior to buffer installation and approximately one year after buffer installation. This dataset is intended to serve as a baseline for future evaluation of the effects of multifunctional working buffers after trees and shrubs in the buffers have reached maturity. Farmer maintenance activities like mowing, mulching, and watering contribute to successful buffer establishment.

Introduction

Changing climate, residential and commercial development, and the need for habitat protection is increasing pressure on US farmland. Climate-related changes in precipitation and drainage challenges are leading to areas of formerly productive agricultural lands becoming increasingly saturated, and regulations restrict the addition of new drainage infrastructure. Meanwhile, the decreasing availability and rising cost of agricultural land is driving new farmers to purchase marginal land that often suffers from hydrologic issues. These factors especially impact socially and economically disadvantaged farmers, limiting their access to well-drained land.

Farming seasonally wet fields presents problems for annual crops and can negatively impact nearby water quality, but farmers must maximize land resources to remain economically viable. This makes it difficult to set aside land for conservation or restoration without sufficient financial incentives, yet existing incentive payments are often not large enough to offset production losses.

Multifunctional "working buffers"—a perennial agroforestry cropping system that can be used on seasonally wet farmland—are a promising approach for farmers to both protect water and soil resources and generate income on marginal areas (Figure 1). This study seeks to understand the effects on water quality and soil health of multifunctional working buffers in the Pacific Northwest.

The scientific efficacy of working buffers is largely unknown due to a lack of scientific research providing soil- and water-quality data. It is the intention of this research to lay the foundation for obtaining the necessary metrics for both policy decision-makers and producers, to find a win-win situation between buffer regulations and production for farmers.

Figure 1. Multifunctional working buffer at Tangled Thicket Farm, Skagit County, May 2025.

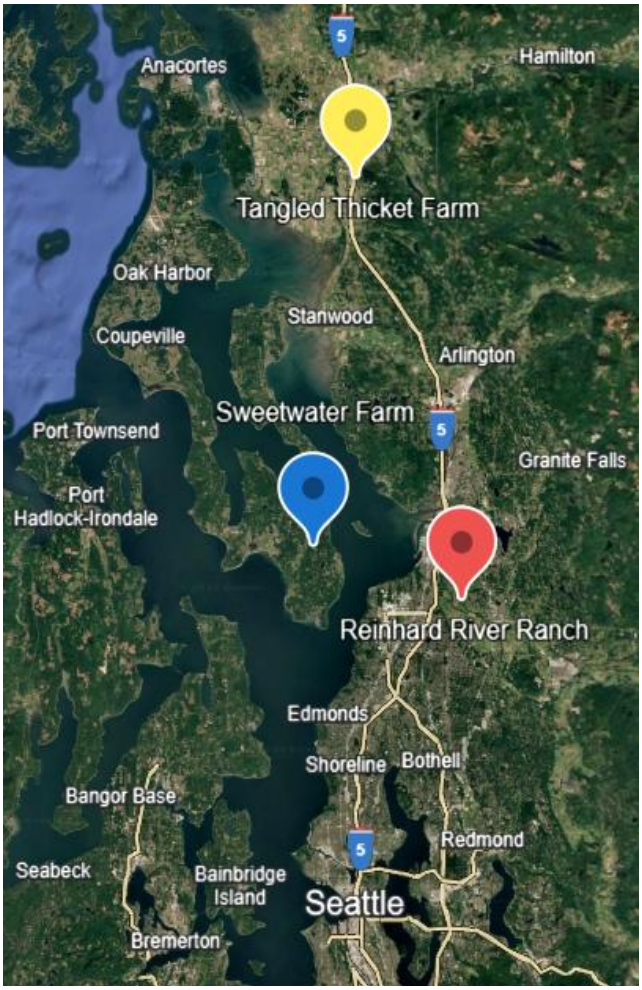

Figure 2. Experimental Farm Site Locations within western Washington (Google Earth).

In this study, Skagit Conservation District (Skagit CD), Snohomish Conservation District (SCD), and Whidbey Island Conservation District (WICD), collaborated with Snohomish County, Washington State University (WSU) Extension staff, and farmers in three western Washington counties to study the water quality effects of multifunctional working buffers. Multifunctional working buffers were established along waterways at three farms: Reinhard Ranch in Snohomish County, Tangled Thicket Farm in Skagit County, and Sweetwater Farm in Island County (Figure 2). These buffer plantings comprised a range of native and non-native woody species and were selected for their capacity to thrive in saturated soils and to provide useful products (e.g., fruits, floral material, etc.). Data collection for this project began in 2022. Continuous water temperature data were collected starting in December 2022, and soil and water laboratory testing began in February 2023. Soil and water data were collected for approximately 15 months before buffers were planted to establish baseline conditions before the treatment was implemented. Multifunctional working buffers were established in March 2024. Additional water and soil samples were collected at regular intervals until May 2025.

Woody perennials (like the trees and shrubs planted in this study) take years to mature (Figure 1). Their effects on water quality and soil health may become more prominent once the plants have established a canopy cover over their neighboring waterways. The soil and water data collected in this study are intended to provide baseline information on the condition of soil health and water quality for future comparison with conditions under the mature buffer plantings.

Methodology

This study took place between 2022 and 2025 and involved working riparian buffers planted at three separate commercial farm sites, one each within the boundaries of the Skagit, Snohomish, and Whidbey Island Conservation Districts. These three fields were selected for this experiment based on the following criteria: 1) landowner willingness; 2) presence of wet areas; 3) geographic distribution for visibility across all conservation districts. Buffer placement location within each site was selected based upon hydrogeography and soil type.

In approximately the first six months of the project, literature reviews were performed to establish optimal buffer locations for each experimental site. Pre-existing soil and/or water quality impairments relative to current regional standards were noted for each site. We hypothesized that multifunctional working buffers will reduce water temperatures and decrease nutrient and sediment pollution in waterways adjacent to the buffers.

Figure 3: Multifunctional working buffer at Reinhard River Ranch, Snohomish County, July 2025.

Field personnel were trained in soil- and water-quality Quality Assurance and Quality Control methodology, equipment operation, basic hydrology, and safety considerations. Field personnel made monthly trips to the sites to collect data and retrieve soil and water samples. Sampling procedures followed United Stated Geographical Survey (USGS) runoff methodology and sampling protocol. Field sampling used a standard protocol to avoid errors caused by disturbance of the substrate and to ensure representative sampling. Water quality sampling was conducted in accordance with USGS National Field Manual for the Collection of Water-Quality Data. Soil sampling was done in accordance with Soiltest Farm Consultants' Routine Soil Sampling Guidelines

and Techniques.[1] Continuous water quality sampling was conducted using HOBO v2 water loggers. Water samples were submitted at the end of each day of collection, and soil samples were mailed within 48 hours of collection.

Prior to any field alterations we installed all research-related equipment, took appropriate samples, and collected a year of baseline data. Immediately following, we installed agroforestry plantings within known seasonally wet buffers on the commercial agricultural pilot sites (Figure 3), collected a year's worth of data downstream of the installed working buffer, and collected baseline data upstream of the treatment area as a control.

Water Quality Sampling

Water temperature data were collected in waterways, drainage pathways, or points of concentrated flow, using two (2) HOBO v2 water temperature data loggers, one upstream and one downstream of the buffer planting location (Figure 4). Water samples were collected using HDPE containers, using a separate container for solids and nutrient samples in accordance with laboratory standards. Water grab samples were collected at the location of the HOBO water temperature data loggers. Water samples were collected from the middle of the water column, but no deeper than two feet from the surface. Water depth was measured using a stadia rod.

Soil Sampling

Soil samples were prepared by collecting subsamples from at least ten (10) locations at each farm. Composite samples were sent to Soiltest Farm Consultants for analysis within 48 hours of collection.

Soil quality sampling locations were both in-field and/or at drainage outlets, depending on the topography. These sampling locations were selected due to their ease of access for year-round sampling. All soil samples were collected within the top six inches of the soil profile. The top six inches of the soil profile are the most important predictor of non-point source pollution runoff. Runoff becomes more important relative to the nutrient load within seasonally wet areas and other critical areas, where nutrient loading may be significant for aquifer recharge, transport via subsurface drainage, and/or downstream discharge into waterways. Subsamples were collected from within the buffer planting areas. Upstream composite samples were prepared by collecting subsamples from the upstream area of the

[1] Soiltest Farm Consultants. "Routine Soil Sampling Guidelines and Techniques." https://soiltestlab.com/wp-content/uploads/2019/02/Sampling-guide-and-tech.pdf. Accessed 28 July, 2025.

planting, while downstream composite samples were prepared by collecting subsamples from the downstream area of the buffer planting.

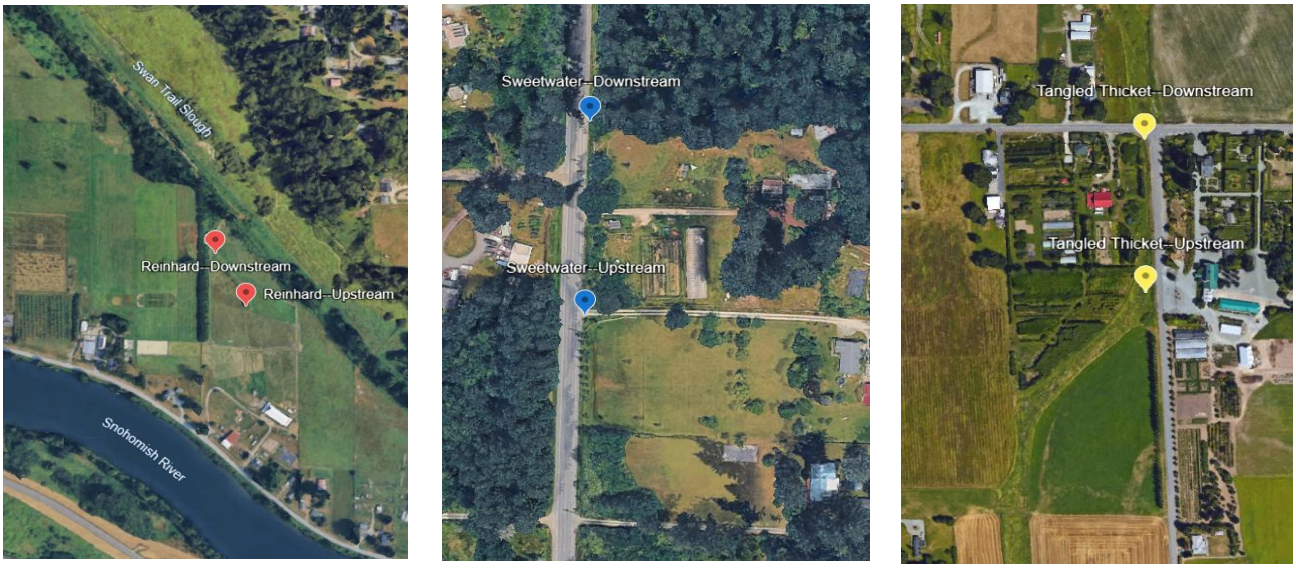

Figure 4: Water sampling locations at each of the three farms (Google Earth).

Soil and Water Sample Analysis

Soil samples were submitted to Soiltest Farm Consultants, Inc., Moses Lake, WA, for chemical analysis. Soil samples were stored in coolers or refrigerators during transport or storage to reduce the risk of degrading samples. Samples were mailed to the laboratory within 48 hours of collection. Soil analyses included available phosphorus (Bray and Olsen), available potassium (ammonium acetate), pH, electrical conductivity (1:1 and saturated paste), ammonium-N, nitrate-N, and organic matter/organic carbon (Walkley-Black).

Water samples were submitted to the City of Everett Environmental Laboratory, Everett, WA, for chemical analysis. Water samples were stored in coolers or refrigerators during transport or storage to reduce the risk of degrading samples. Samples were submitted to the laboratory the day they were collected. Water analyses included alkalinity (SM2320 B), electrical conductivity (SM2510 B), total dissolved solids (TDS, SM2540 C), total solids (TS, SM2540 B), total suspended solids (TSS, SM2540 D), nitrate and nitrite (NO_3-NO_2, EPA 353.2), total Kjeldahl nitrogen (TKN, SM4500-N_{org} D), total nitrogen, and total phosphorus (EPA 365.1).

Data from water temperature loggers were downloaded at each water quality sampling site visit. Retrieving this data required removal of the units from the water to connect and upload data to a laptop. Water temperature was recorded at 15-minute intervals. HOBO v2 temperature data loggers have an accuracy of ±0.38 °F for temperatures between 32 °F and 122 °F.[2] All data were collated and analyzed in Excel.[3]

[2] OnSetComp. "HOBO Water Temperature Pro v2 Data Logger." https://www.onsetcomp.com/products/data-loggers/u22-001?srsltid=AfmBOooqRrphZNJOPU3RJnzGTd0vdts7vEfpwCXgdIGawjw7YQqmsUbg. Accessed 28 July, 2025.

[3] Microsoft Corporation. Microsoft® Excel® for Microsoft 365 MSO (Version 2506 Build 16.0.18925.20076) 64-bit, 2025.

Results

Soil Quality Indicators

Soil quality metrics analyzed for each site included the nutrient levels (such as phosphorus, potassium, and multiple nitrogen ions), pH, electrical conductivity, and organic matter levels.

Soil phosphorus levels ranged from a low of 4 mg/kg at the Sweetwater downstream sampling location to a high of 180 mg/kg at the Tangled Thicket sampling location. The mean upstream soil phosphorus level was 42 mg/kg, and the mean downstream soil phosphorus level was 47 mg/kg. The median upstream soil phosphorus level was 35 mg/kg, and the median downstream soil phosphorus level was 23.5 mg/kg.

Soil potassium levels ranged from a low of 41 mg/kg at the Sweetwater downstream site to a high of 743 mg/kg at the Tangled Thicket downstream site. The mean upstream soil potassium level was 280.9 mg/kg, and the mean downstream soil potassium level was 236.0 mg/kg. The median upstream soil potassium level was 241.5 mg/kg, and the median downstream soil potassium level was 145.5 mg/kg.

Soil pH ranged from a low of 4.7 at the Reinhard downstream site to a high of 6.3 at the Sweetwater upstream site. The mean upstream soil pH was 5.8 and the mean downstream pH was 5.8. The median upstream pH was 5.75 and the median downstream pH was 5.85.

Soil electrical conductivity (EC, 1:1) ranged from a low of 0.04 mmhos/cm at the Sweetwater downstream site to a high of 0.52 mmhos/cm at the Tangled Thicket upstream site. The mean upstream soil EC was 0.15 mmhos/cm, and the mean downstream EC was 0.13 mmhos/cm. The median upstream EC was 0.11 mmhos/cm, and the median downstream EC was 0.08 mmhos/cm.

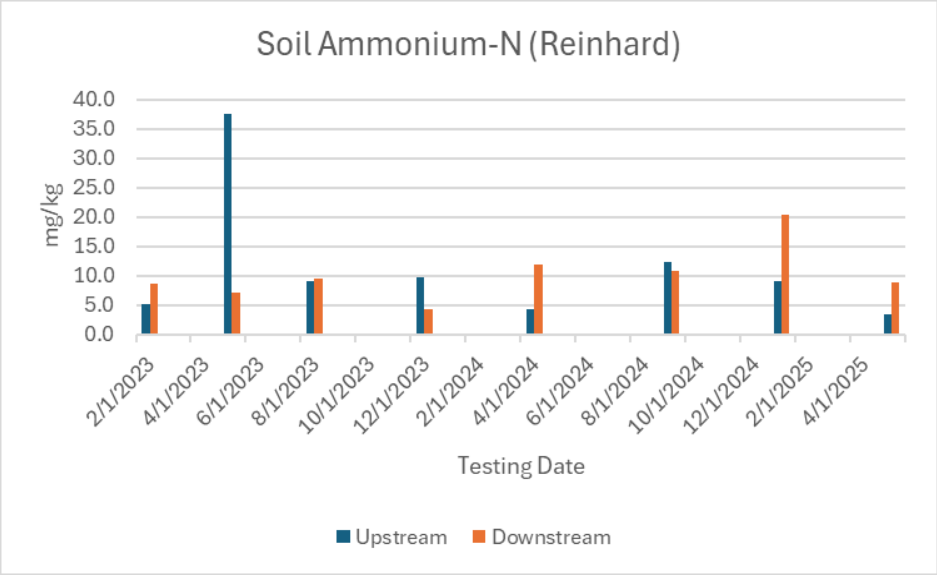

Figure 5: Soil ammonium-N levels between 2023 and 2025 at Reinhard River Ranch.

Soil ammonium-N (NH_4^+) levels ranged from a low of 1.9 mg/kg at the Tangled Thicket downstream site to a high of 37.6 mg/kg at the Reinhard upstream site (Figure 5). The mean upstream soil ammonium level was 8.8 mg/kg, and the mean downstream ammonium level was 7.9 mg/kg. The median upstream soil ammonium level was 6.95 mg/kg, and the median downstream ammonium level was 6.95 mg/kg.

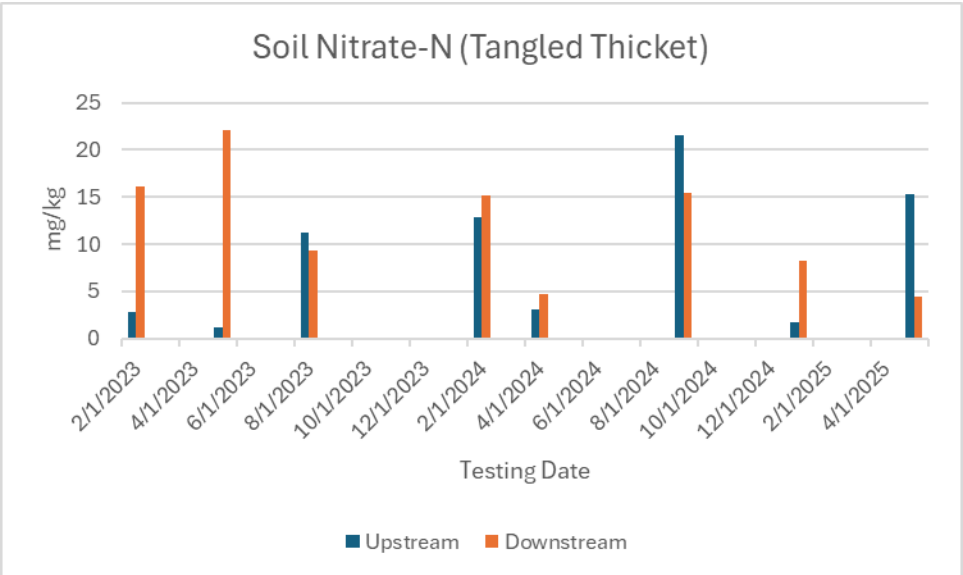

Figure 6: Soil nitrate-N levels at Tangled Thicket Farm between 2023 and 2025.

Soil nitrate-N (NO_3^-) levels ranged from a low of 0.4 mg/kg at the Sweetwater upstream site to a high of 22.1 mg/kg at the Tangled Thicket downstream site (Figure 6). The mean upstream soil nitrate level was 4.9 mg/kg, and the mean downstream nitrate level was 4.9 mg/kg. The median upstream soil nitrate level was 2.4 mg/kg, and the median downstream nitrate level was 1.6 mg/kg.

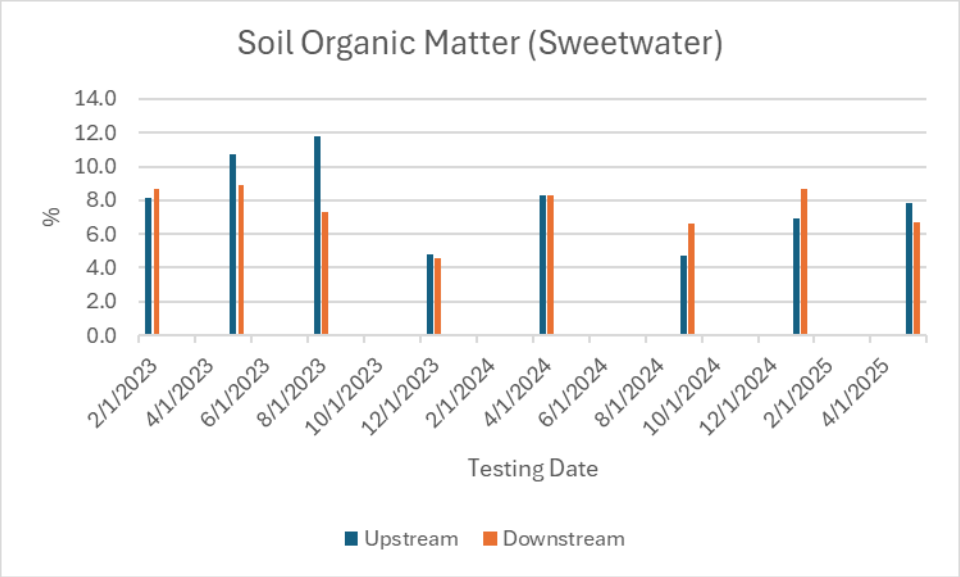

Figure 7: Soil Organic Matter (%, Walkley-Black) levels between 2023 and 2025 at Sweetwater Farm.

Soil organic matter levels (SOM, Walkley-Black) ranged from a low of 3.0% at the Reinhard downstream site to a high of 11.8% at the Sweetwater upstream site (Figure 7). The mean upstream SOM level was 7.3%, and the mean downstream SOM level was 7.3%. The median upstream SOM level was 6.9%, and the median downstream SOM level was 7.0%.

Table 1: P values from Student's t-tests comparing soil quality metrics upstream and downstream (two sample, two-tailed, unequal variance). P values that are significant at the 0.05 level are in bold.

Farm	Phosphorus	Potassium	pH (1:1)	EC (1:1)	Est. Sat. Paste EC	Ammonium-N	Organic Matter	ENR	Nitrate N	Sum of tested N
Reinhard	0.63	**0.03**	0.54	0.55	0.56	0.79	0.80	0.77	**0.04**	0.47
Sweetwater	**0.04**	**0.01**	0.52	0.08	0.07	0.53	0.70	0.62	0.27	0.73
Tangled Thicket	0.17	0.26	**0.02**	0.88	0.88	0.84	0.85	0.35	0.37	0.45

Student's t-tests (two sample, two-tailed, assuming unequal variance) were conducted in Excel to evaluate whether differences between upstream and downstream soil quality indicators were statistically significant. Few statistically significant differences between upstream and downstream soil quality indicators were observed (Table 1). At Reinhard Ranch, potassium levels were found to be lower at the downstream site than at the upstream site ($P = 0.03$) and nitrate-N levels were found to be lower at the downstream site ($P = 0.04$). At Sweetwater Farm, phosphorus levels were found to be lower at the upstream site ($P = 0.04$), while potassium levels were found to be lower at the downstream site ($P = 0.01$). At Tangled Thicket Farm, pH was found to be lower at the downstream site ($P = 0.02$).

Water Quality Chemical Indicators

Water quality metrics analyzed for each site include the nutrient levels (such as phosphorus and multiple nitrogen ions), alkalinity, electrical conductivity, and dissolved and suspended solids levels.

Water alkalinity level ranged from a low of 6.8 mg/L at the Sweetwater upstream site to a high of 141.0 mg/L at the Sweetwater upstream site (Figure 8). The mean upstream alkalinity was 62.6 mg/L and the mean downstream alkalinity was 33.6 mg/L. The median upstream alkalinity was 60.5 mg/L and the median downstream alkalinity was 30.0 mg/L.

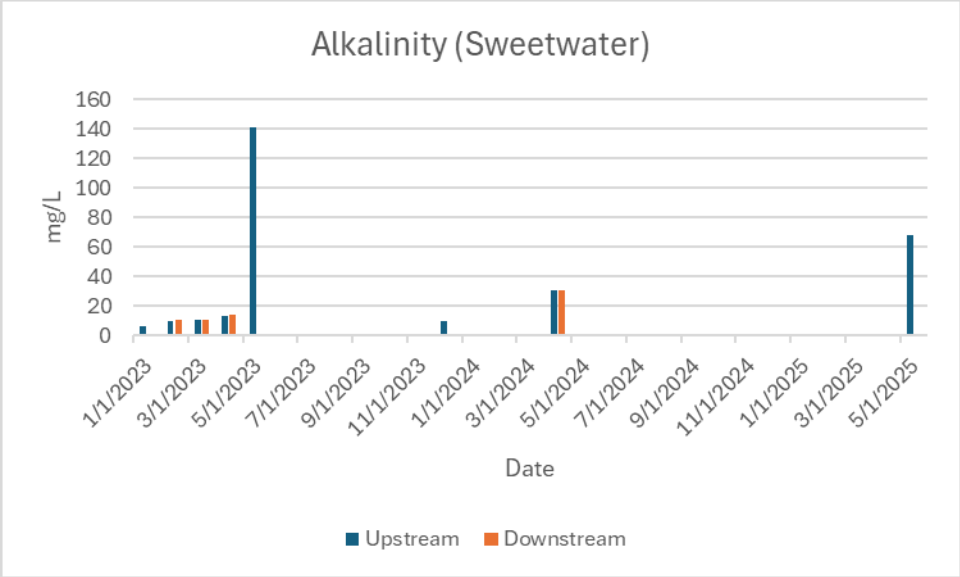

Figure 8: Water alkalinity levels at Sweetwater Farm between 2023 and 2025.

Water total phosphorus levels ranged from a low of 47 µg/L at the Reinhard upstream sampling location to a high of 12,100 µg/L at the Sweetwater upstream sampling location. The mean upstream total phosphorus level was 2,152 µg/L and the mean downstream total phosphorus level was 439.3 µg/L (though these means exclude samples which were below the 100 µg/L testing threshold). The median upstream total phosphorus level was 1,100 µg/L and the median downstream soil phosphorus level was 338 µg/L (though these medians exclude samples which were below the 100 µg/L testing threshold).

Water electrical conductivity (EC) ranged from a low of 40.4 µmhos/cm at the Sweetwater upstream site to a high of 2,820.0 µmhos/cm at the Tangled Thicket downstream site. The mean upstream EC was 206.7 µmhos/cm, and the mean downstream EC was 600.4

µmhos/cm. The median upstream EC was 151.0 µmhos/cm and the median downstream EC was 155.0 µmhos/cm.

Water nitrate and nitrite (NO_3^- and NO_2^-) levels ranged from a low of 0.012 mg/L at the Sweetwater upstream site to a high of 1.45 mg/L at the Reinhard upstream site. The mean upstream nitrate and nitrite level was 0.22 mg/L, and the mean downstream nitrate and nitrite level was 0.17 mg/L (though these medians exclude samples which were below the testing threshold). The median upstream nitrate and nitrite level was 0.02 mg/L, and the median downstream nitrate and nitrite level was 0.03 mg/L (though these medians exclude samples which were below the testing threshold).

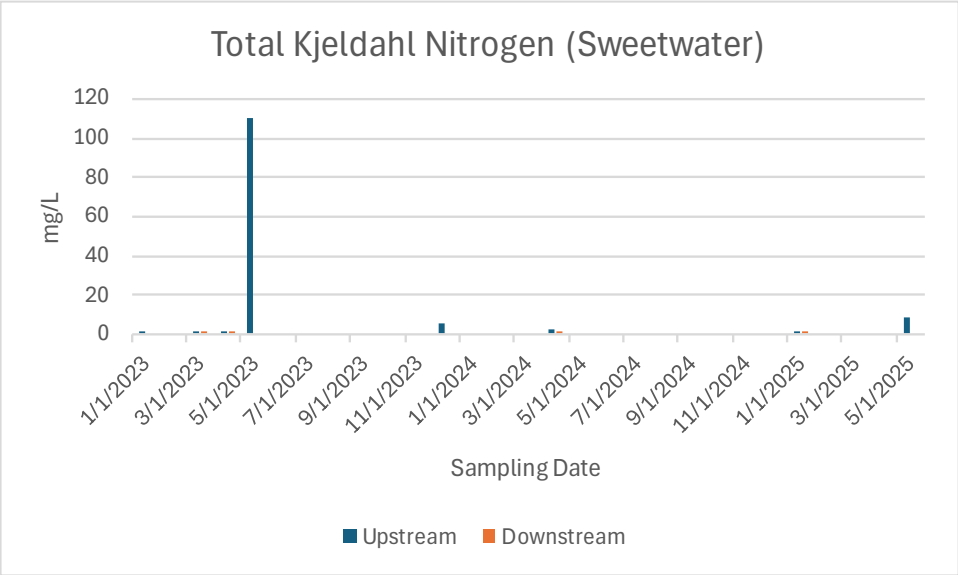

Figure 9: Total Kjeldahl Nitrogen at Sweetwater Farm between 2023 and 2025.

Water total Kjeldahl nitrogen (TKN) levels ranged from a low of 0.36 mg/L at the Sweetwater upstream sites to a high of 110.0 mg/L at the Sweetwater upstream site (Figure 9). For the three sites combined, the mean upstream TKN level was 8.94 mg/L, and the mean downstream TKN level was 1.60 mg/L. The median upstream TKN level was 2.90 mg/L, and the median downstream TKN level was 1.31 mg/L.

Water total nitrogen (TN) levels ranged from a low of 0.39 mg/L at the Sweetwater upstream sites to a high of 110.0 mg/L at the Sweetwater upstream site. The mean upstream TN level was 8.7 mg/L, and the mean downstream TN level was 1.7 mg/L. The median upstream TN level was 2.4 mg/L, and the median downstream TN level was 1.4 mg/L.

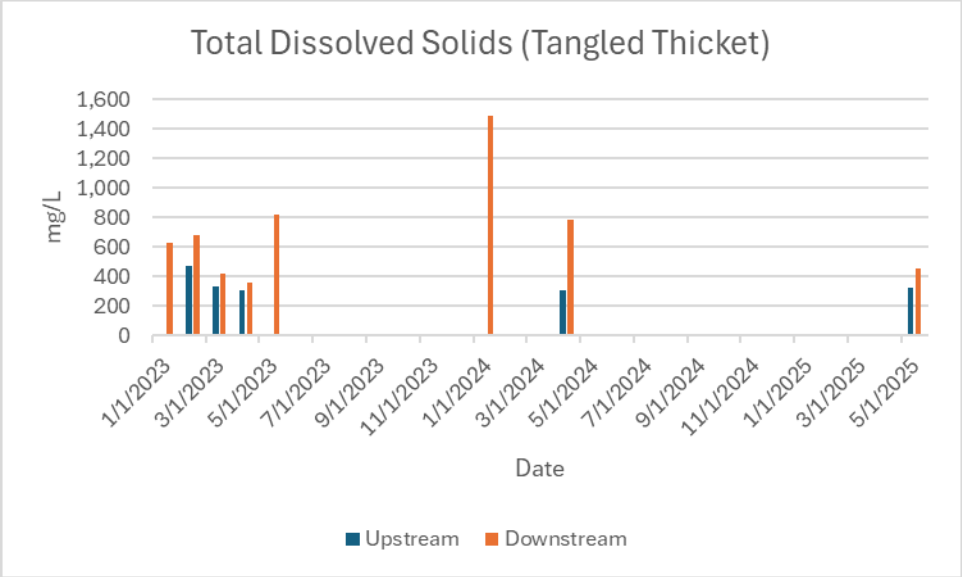

Figure 10: Total Dissolved Solids at Tangled Thicket Farm between 2023 and 2025.

Water total dissolved solids (TDS) levels ranged from a low of 51 mg/L at the Sweetwater upstream site to a high of 1,490 mg/L at the Tangled Thicket downstream site (Figure 10). The mean upstream TDS level was 162.4 mg/L, and the mean downstream TDS level was 338.4 mg/L. The median upstream TDS level was 110.0 mg/L, and the median downstream TDS level was 110.0 mg/L.

Water total solids (TS) levels ranged from a low of 46 mg/L at the Sweetwater upstream site to a high of 18,700 mg/L at the Sweetwater upstream site. The mean upstream TS level was 1,185.3 mg/L, and the mean downstream TS level was 364.4 mg/L. The median upstream TS level was 210.0 mg/L, and the median downstream TS level was 175.0 mg/L.

Water total suspended solids (TSS) levels ranged from a low of <3 mg/L at the Reinhard, Sweetwater, and Tangled Thicket sites to a high of 18,200 mg/L at the Sweetwater upstream site. The mean upstream TSS level was 1,350.3 mg/L, and the mean downstream TSS level was 37.8 mg/L (though these means exclude samples which were below the testing threshold). The median upstream TSS level was 100.0 mg/L, and the median downstream

TSS level was 8.0 mg/L (though these medians exclude samples which were below the testing threshold).

Table 2: P values from Student's t-tests comparing water quality metrics upstream and downstream (two sample, two-tailed, unequal variance). P values that are significant at the 0.05 level are in bold.

Farm	Alkalinity	Conductivity	TDS	TS	TSS	NO_3-NO_2	TKN	Total Nitrogen	Total Phosphorus
Reinhard	0.37	0.19	0.19	0.37	0.73	0.61	0.43	0.38	0.35
Sweetwater	0.28	0.21	0.30	0.25	0.26	0.66	0.29	0.29	0.28
Tangled Thicket	**0.02**	**0.01**	**0.04**	0.06	0.31	0.22	0.20	0.21	0.22

Student's t-tests (two sample, two-tailed, assuming unequal variance) were conducted in Excel to evaluate whether differences between upstream and downstream water quality indicators were statistically significant. Except for alkalinity, conductivity, and total dissolved solids (TDS) at Tangled Thicket Farm, no statistically significant differences between upstream and downstream water quality indicators were observed (Table 2). At Tangled Thicket Farm, alkalinity was found to be lower at the downstream site (P = 0.02), conductivity was found to be lower at the upstream site (P = 0.01), and total dissolved solids were found to be lower at the upstream site (P = 0.04).

Water Temperature

Water temperature at the Reinhard upstream sampling location ranged from a low of 25.7 °F to a high of 138.3 °F (though this high temperature may reflect the water level being below the sensor, leaving the sensor in the air and where it could be warmed by the sun) between the beginning of data recording on December 6, 2022 and the end of data recording on January 2, 2025 (Figure 11, Table 3). The mean upstream water temperature was 54.6 °F and the median upstream water temperature was 50.8 °F over the course of the sampling period.

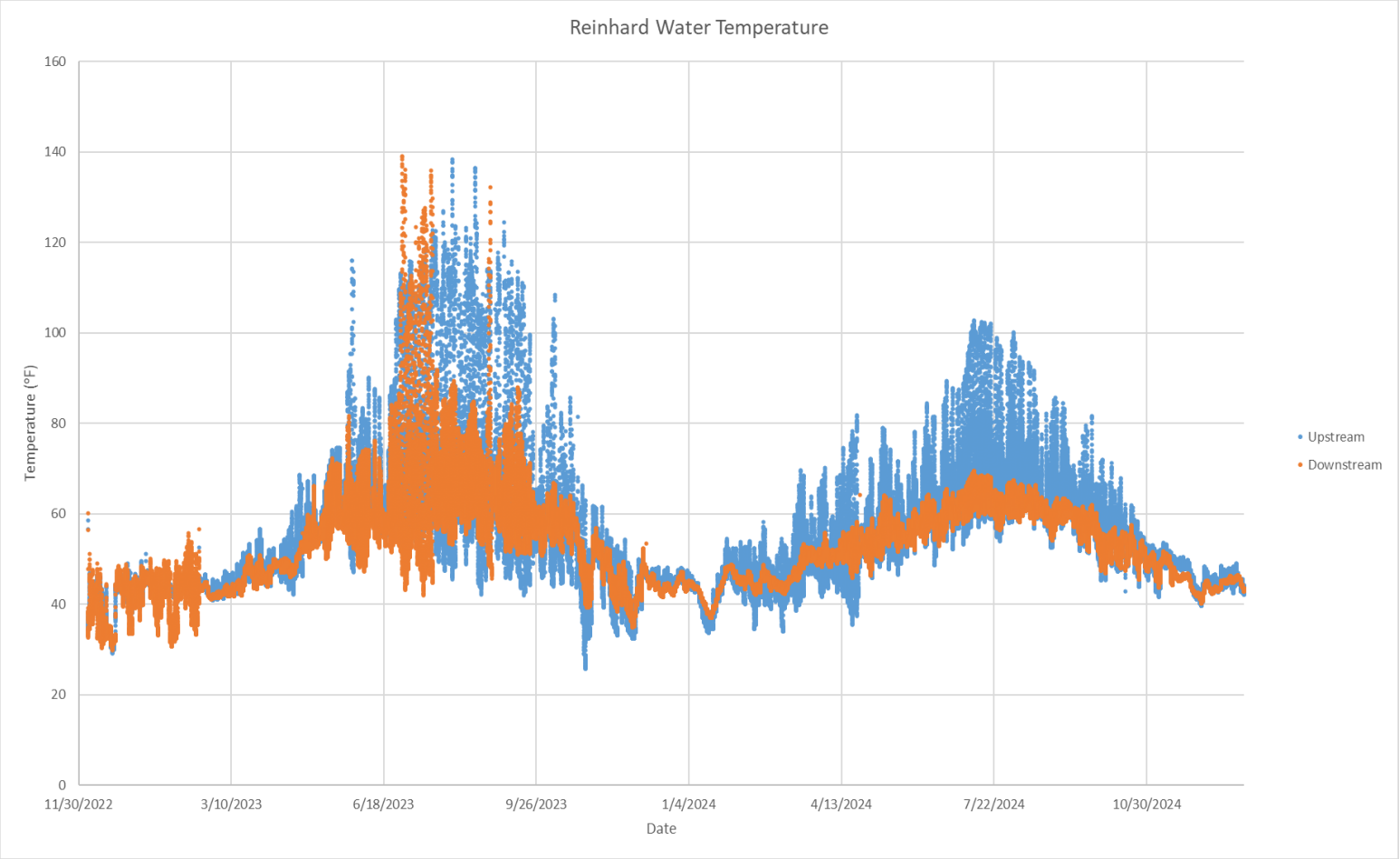

Figure 11: Water temperature data for Reinhard River Ranch. Data were collected every 15 minutes between 12/6/2022 and 1/2/2025.

Water temperature at the Reinhard downstream sampling location ranged from a low of 29.9 °F to a high of 139.1 °F (though this high temperature may reflect the water level being below the sensor, leaving the sensor in the air and where it could be warmed by the sun) between the beginning of data recording on December 6, 2022 and the end of data recording on January 2, 2025. The mean downstream water temperature was 52.4 °F and

the median downstream water temperature was 50.9 °F over the course of the sampling period.

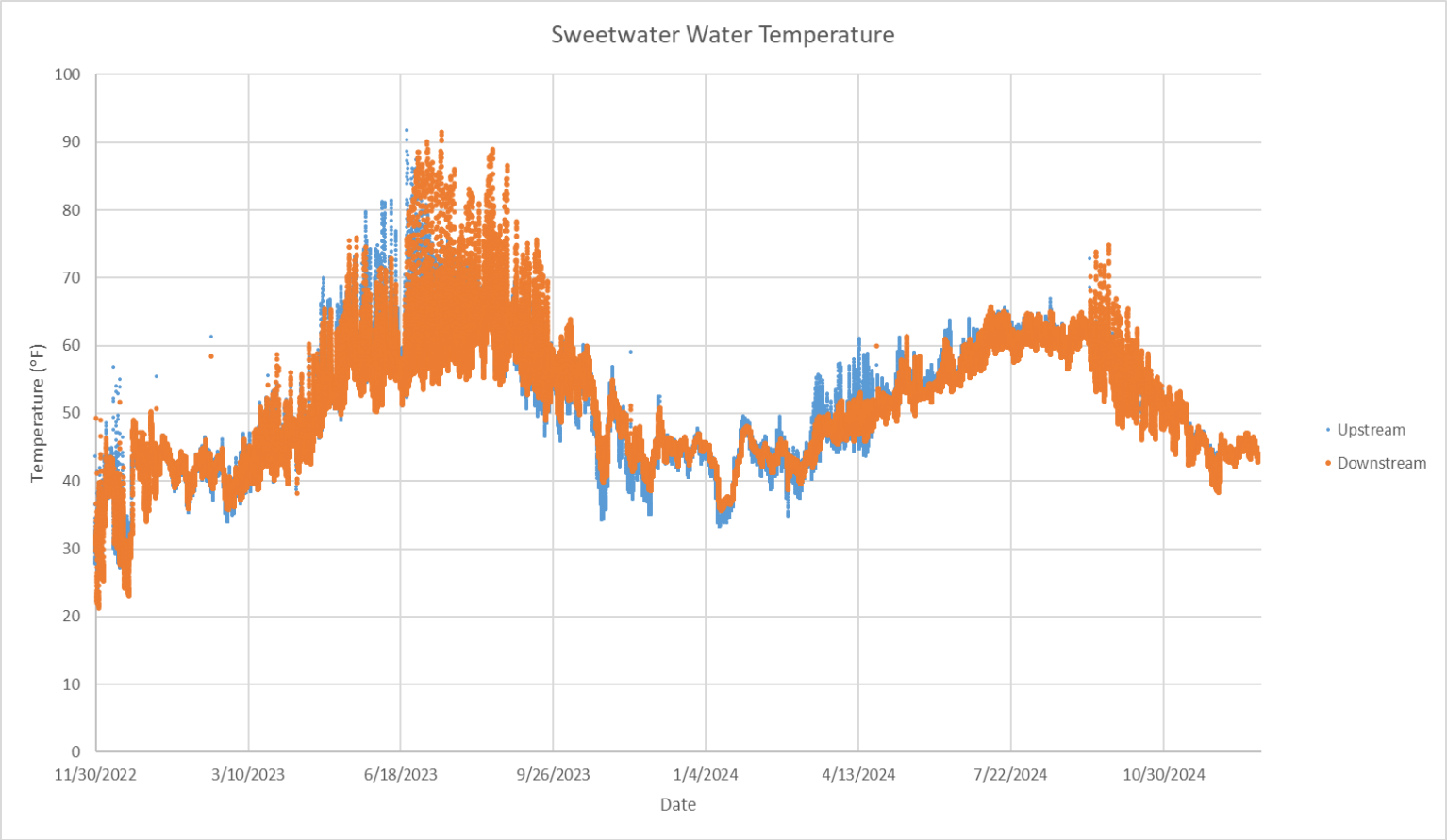

Figure 12: Water temperature data for Sweetwater Farm. Data were collected every 15 minutes between 11/30/2022 and 12/31/2024.

Water temperature at the Sweetwater upstream sampling location ranged from a low of 23.6 °F to a high of 91.8 °F between the beginning of data recording on November 30, 2022, and the end of data recording on December 31, 2024 (Figure 12, Table 3). The mean upstream water temperature was 51.1 °F and the median upstream water temperature was 50.9 °F over the course of the sampling period.

Water temperature at the Sweetwater downstream sampling location ranged from a low of 21.3 °F to a high of 91.5 °F between the beginning of data recording on November 30, 2022, and the end of data recording on December 31, 2024. The mean downstream water temperature was 50.8 °F and the median downstream water temperature was 50.0 °F over the course of the sampling period.

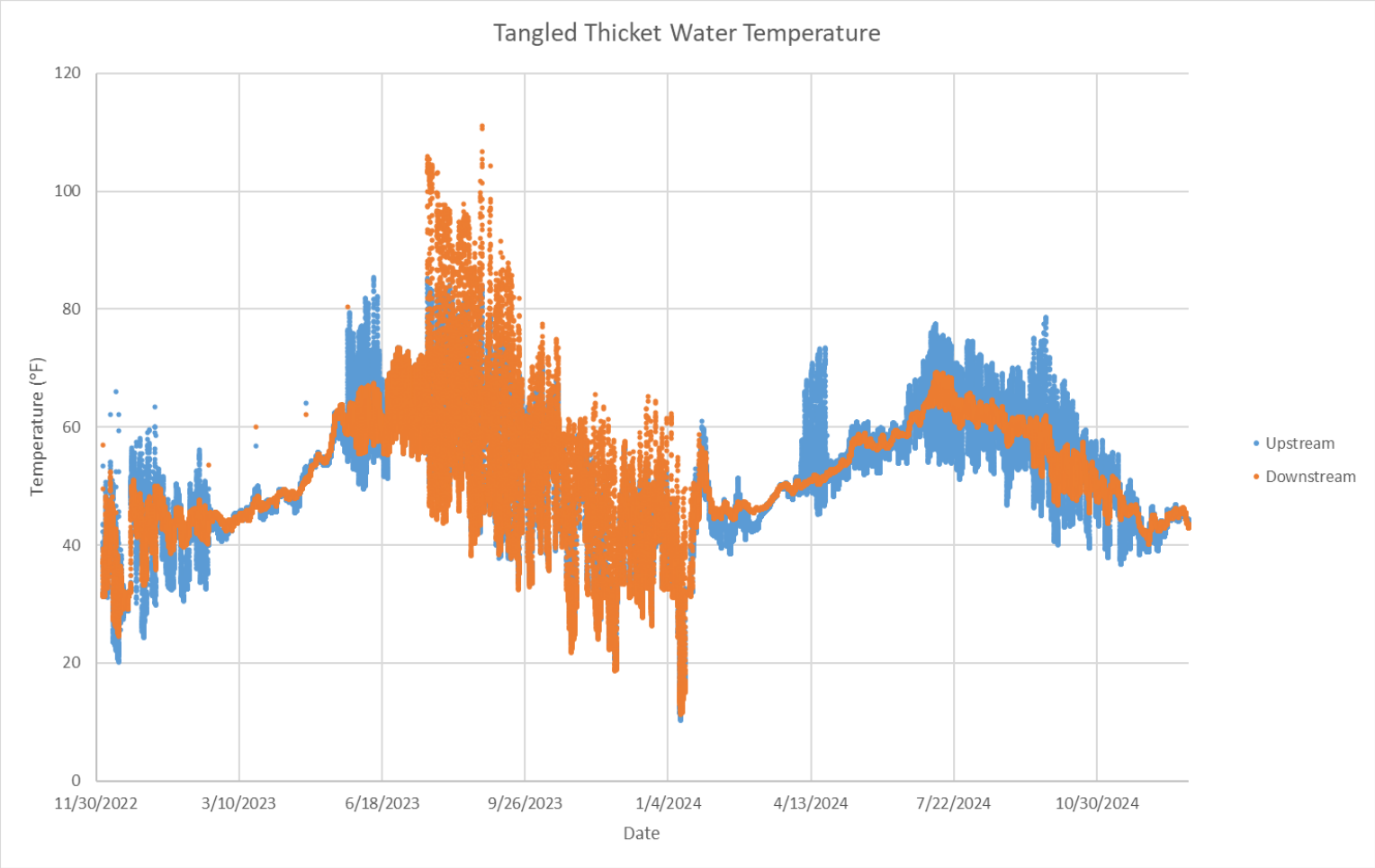

Figure 13: Water temperature data for Tangled Thicket Farm. Data were collected every 15 minutes between 12/5/2022 and 1/2/2025.

Water temperature at the Tangled Thicket upstream sampling location ranged from a low of 10.3 °F to a high of 85.4 °F between the beginning of data recording on December 5, 2022,

Table 3: Minimum, maximum, average (mean and median) temperatures at the three study farms.

		Temperature (°F)			
Location		*Minimum*	*Maximum*	*Mean*	*Median*
Reinhard	Upstream	25.7	138.3	54.6	50.8
	Downstream	29.9	139.1	52.4	50.9
Sweetwater	Upstream	23.6	91.8	51.1	50.9
	Downstream	21.3	91.5	50.8	50.0
Tangled Thicket	Upstream	10.3	85.4	50.9	50.2
	Downstream	11.2	111.1	51.5	50.3

and the end of data recording on January 2, 2025 (Figure 13, Table 3). The mean upstream water temperature was 50.9 °F and the median upstream water temperature was 50.2 °F over the course of the sampling period.

Water temperature at the Tangled Thicket downstream sampling location ranged from a low of 11.2 °F to a high of 111.1 °F (though this high temperature may reflect the water level being below the sensor, leaving the sensor in the air and where it could be warmed by the sun) between the beginning of data recording on December 5, 2022 and the end of data recording on January 2, 2025 . The mean downstream water temperature was 51.5 °F and the median downstream water temperature was 50.3 °F over the course of the sampling period.

Farmer Maintenance Activities and Working Buffer Management

Research staff members were in regular communication with the farmers involved in this project, discussing the health of the trees and shrubs planted in the multifunctional working buffers and any necessary maintenance. Through the course of these conversations, researchers identified that pressure from weeds (including invasive species like *Phalaris arundinacea* and *Rubus armeniacus*) and pasture grasses threatened the health and survival of trees and shrubs in the buffers. Buffer plantings at one site needed to be fenced for protection from deer and livestock. Farmers and researchers controlled these herbaceous plants using mowing, weed whacking, and mulching. Irregular spacing of trees sometimes interfered with the use of equipment like mowers and brush hogs, making maintenance activities more time-consuming for farmers (and less likely to happen with adequate frequency).

Summers in the study area are typically warm and dry. The lack of precipitation during the summer months means that newly planted trees and shrubs in working buffers may suffer from heat and water stress as they establish themselves. Mulching and watering contribute to the successful tree and shrub establishment. One of the farmers in the current study did not need to water their trees and shrubs during establishment, this may be due to the soil and water conditions at that site.

Conclusions and Recommendations for Future Research

The soil and water data collected in this study are intended to provide baseline information on the condition of soil health and water quality for future comparison with conditions under the mature buffer plantings. By collecting thorough data over the course of several calendar years (and thus several cycles of rainy and dry seasons) we have established a robust dataset describing baseline soil and water conditions in the study areas. While some differences may be observed between upstream and downstream water quality conditions, we cannot conclude that the implementation of the multifunctional working buffer was responsible for these differences.

For many water quality metrics, conditions in downstream samples may have been more favorable than those upstream. Average (both mean and median) total phosphorus and total nitrogen levels were lower in downstream samples than in upstream samples at all three farms. Average total dissolved solids (TDS) were lower in downstream samples than upstream samples at Reinhard River Ranch and Sweetwater Farm. It is important to note that these differences were not statistically significant.

For some metrics, water quality conditions downstream of the planting may have been more impaired than those upstream. For example, for both post-planting sampling dates at Tangled Thicket Farm, total dissolved solids (TDS) were higher in the downstream sample than in the upstream sample. Average conductivity was higher in downstream samples from Tangled Thicket Farm than in upstream samples. These differences at Tangled Thicket Farm were statistically significant ($P < 0.05$).

For the Sweetwater and Tangled Thicket sites, water quality samples were collected only twice after the buffers were planted; at the Reinhard site, one post-planting water sampling occurred but a sample was only collected from the upstream site which precludes any comparison between upstream and downstream conditions. Some difficulties were encountered in achieving the desired frequency of water testing. For example, the waterways occasionally ran dry, making it impossible to collect water samples and creating anomalies in the water temperature data. We recommend selecting sites for future research based on the year-round presence of water. We also recommend selecting sites which occupy similar positions within their respective watersheds (e.g., upland or lowland). These sites should be as isolated as possible from contamination sources outside of the farm. Since weather conditions can vary substantially across microclimates, we recommend installing weather monitoring stations at each study site to facilitate the analysis of the impacts of multifunctional working buffers on water quality metrics such as water temperature.

Additional research will be needed to evaluate the impacts of mature multifunctional working buffers on soil health and water quality. This research should be conducted at regular intervals (perhaps every 5 years) as the trees and shrubs planted in these buffers mature, allowing for conclusions to be drawn about the impact of mature buffer plantings before and after canopy closure.

List of Figures and Tables

Appendices

Appendix 1: Water Chemical Testing Data, Upstream, 2022-2025

		Upstream								
		Alkalinity	Conductivity	TDS	TS	TSS	NO_3-NO_2	TKN	Total Nitrogen	Total Phosphorus
		mg/L	*µmhos/cm*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*µ g/L*
Farm	**Date Received**									
Reinhard	12/8/2022	113.0	281.0	290	320	47	0.044	10.300	10.400	1,960
	1/13/2023	43.2	155.0	100	100	<3	1.450	0.666	2.110	<100
	2/17/2023	60.5	147.0	90	82	<3	0.010	0.519	0.529	<100
	3/24/2023	71.6	151.0	110	100	<3	0.004	0.403	0.407	<100
	4/26/2023	81.9	169.0	120	110	<3	0.024	0.450	0.474	<100
	12/7/2023	37.5	147.0	110	120	<3	1.050	0.876	1.930	109
	4/25/2024	67.6	151.0	160	530	362	<0.05	7.770	7.780	1,350
	1/2/2025	57.0	161.0	110	120	13	0.693	0.800	1.493	47
Sweetwater	1/9/2023	6.8	46.4	53	46	NA	0.071	0.356	0.428	NA
	2/14/2023	9.5	43.8	51	160	104	NA	NA	0.393	NA
	3/24/2023	10.7	40.4	53	59	4	0.022	0.668	0.691	NA
	4/26/2023	13.2	41.9	60	55	7	0.012	0.719	0.731	NA
	5/25/2023	141.0	217.0	120	18,700	18,200	0.014	110.000	110.000	12,100
	12/7/2023	9.6	57.3	66	350	163	0.166	5.780	5.940	942
	4/25/2024	30.7	68.2	62	210	170	NA	2.440	2.440	262
	1/2/2025	10.8	43.1	57	180	108	0.023	0.900	0.923	88
	5/22/2025	67.9	148.0	74	3,530	3,350	NA	8.600	8.610	1,390
Tangled Thicket	1/12/2023	NA	NA	NA	NA	NA	NA	NA	NA	NA
	2/17/2023	9.0	683.0	470	480	12	0.008	3.510	3.520	488
	3/22/2023	97.2	397.0	330	350	3	0.021	3.630	3.650	1,100
	4/26/2023	133.0	384.0	310	460	278	0.026	3.350	3.380	1,530
	5/25/2023	NA	NA	NA	NA	NA	NA	NA	NA	NA
	1/31/2024	NA	NA	NA	NA	NA	NA	NA	NA	NA
	4/25/2024	140.0	400.0	310	350	30	<0.050	4.000	4.000	974
	1/2/2025	90.5	379.0	310	330	4	0.022	4.600	4.622	1,500
	5/22/2025	138.0	442.0	320	520	100	<0.0160	26.400	26.500	8,440

Appendix 2: Water Chemical Testing Data, Downstream, 2022-2025

		Downstream								
		Alkalinity	Conductivity	TDS	TS	TSS	NO_3-NO_2	TKN	Total Nitrogen	Total Phosphorus
		mg/L	*µmhos/cm*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*mg/L*	*µ g/L*
Farm	**Date Received**									
Reinhard	12/8/2022	NA	NA	NA	NA	NA	NA	NA	NA	NA
	1/13/2023	41.9	132.0	93	89	<3	0.706	0.80	1.50	<100
	2/17/2023	60.4	149.0	94	86	<3	0.004	0.56	0.56	<100
	3/24/2023	71.9	152.0	110	110	3	0.002	0.76	0.76	<100
	4/26/2023	74.3	157.0	110	240	242	0.024	3.42	3.44	518
	12/7/2023	35.0	137.0	110	120	<3	0.699	1.03	1.72	133
	4/25/2024	NA	NA	NA	NA	NA	NA	NA	NA	NA
	1/2/2025	56.0	153.0	100	120	28	0.519	2.40	2.92	377
Sweetwater	1/9/2023	NA	NA	NA	NA	NA	NA	NA	NA	NA
	2/14/2023	10.6	46.4	56	48	6			0.42	102
	3/24/2023	11.1	42.3	55	61	5	0.020	0.41	0.43	NA
	4/26/2023	14.0	44.2	59	55	7	0.019	0.68	0.70	NA
	5/25/2023	NA	NA	NA	NA	NA	NA	NA	NA	NA
	12/7/2023	NA	NA	NA	NA	NA	NA	NA	NA	NA
	4/25/2024	30.6	67.9	62	110	60		1.39	1.40	108
	1/2/2025	11.0	47.3	59	68	<3	0.073	0.70	0.77	43
	5/22/2025	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tangled Thicket	1/12/2023	20.4	1,190.0	630	630	<3	0.105	1.31	1.41	338
	2/17/2023	22.5	1,300.0	680	670	<3	0.026	1.36	1.38	242
	3/22/2023	37.2	777.0	420	420	4	0.017	1.29	1.30	288
	4/26/2023	44.1	613.0	360	360	7	0.045	1.50	1.55	475
	5/25/2023	39.0	1,460.0	820	850	9	<0.050	4.64	4.69	1,470
	1/31/2024	10.5	2,820.0	1,490	1,520	<3	0.447	1.43	1.88	256
	4/25/2024	29.3	1,470.0	780	810	28	<0.050	1.76	1.80	651
	1/2/2025	27.2	409.0	230	230	<3	0.029	1.10	1.13	349
	5/22/2025	24.7	840.0	450	690	55	0.026	3.79	3.82	1,240

Appendix 3: Water Chemical Testing Data Summary Statistics, 2022-2025

		Alkalinity (mg/L)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	37.5	113.0	66.5	64.1
	Downstream	35.0	74.3	56.6	58.2
Sweetwater	Upstream	6.8	141.0	33.4	10.8
	Downstream	10.6	30.6	15.5	11.1
Tangled Thicket	Upstream	9.0	140.0	101.3	115.1
	Downstream	10.5	44.1	28.3	27.2

		Conductivity (µmhos/cm)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	147.0	281.0	170.3	153.0
	Downstream	132.0	157.0	146.7	150.5
Sweetwater	Upstream	40.4	217.0	78.5	46.4
	Downstream	42.3	67.9	49.6	46.4
Tangled Thicket	Upstream	379.0	683.0	447.5	398.5
	Downstream	409.0	2820.0	1208.8	1190.0

		TDS (mg/L)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	90.0	290.0	136.3	110.0
	Downstream	93.0	110.0	102.8	105.0
Sweetwater	Upstream	51.0	120.0	66.2	60.0
	Downstream	55.0	62.0	58.2	59.0
Tangled Thicket	Upstream	310.0	470.0	341.7	315.0
	Downstream	230.0	1490.0	651.1	630.0

		TS (mg/L)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	82.0	530.0	185.3	115.0
	Downstream	86.0	240.0	127.5	115.0
Sweetwater	Upstream	46.0	18,700.0	2,587.8	180.0
	Downstream	48.0	110.0	68.4	61.0
Tangled Thicket	Upstream	330.0	520.0	415.0	405.0
	Downstream	230.0	1,520.0	686.7	670.0

		TSS (mg/L)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	13.0	362.0	140.7	47.0
	Downstream	3.0	242.0	91.0	28.0
Sweetwater	Upstream	4.0	18,200.0	2,763.3	135.5
	Downstream	5.0	60.0	19.5	6.5
Tangled Thicket	Upstream	3.0	278.0	71.2	21.0
	Downstream	4.0	55.0	20.6	9.0

		NO_3-NO_2 (mg/L)			
Location		Minimum	Maximum	Mean	Median
Reinhard	Upstream	0.004	1.450	0.468	0.044
	Downstream	0.002	0.706	0.326	0.272
Sweetwater	Upstream	0.012	0.166	0.051	0.023
	Downstream	0.019	0.073	0.037	0.020
Tangled Thicket	Upstream	0.008	0.026	0.019	0.022
	Downstream	0.017	0.447	0.099	0.029

Location		TKN (mg/L)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	0.40	10.30	2.72	0.73
	Downstream	0.56	3.42	1.49	0.91
Sweetwater	Upstream	0.36	110.00	16.18	1.67
	Downstream	0.41	1.39	0.79	0.69
Tangled Thicket	Upstream	3.35	26.40	7.58	3.82
	Downstream	1.10	4.64	2.02	1.43

Location		Total Nitrogen (mg/L)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	0.41	10.40	3.14	1.71
	Downstream	0.56	3.44	1.82	1.61
Sweetwater	Upstream	0.39	110.00	14.46	0.92
	Downstream	0.42	1.40	0.74	0.70
Tangled Thicket	Upstream	3.38	26.50	7.61	3.83
	Downstream	1.13	4.69	2.11	1.55

Location		Total Phosphorus (µg/L)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	47.0	1,960.0	866.5	729.5
	Downstream	133.0	518.0	342.7	377.0
Sweetwater	Upstream	88.0	12,100.0	2,956.4	942.0
	Downstream	43.0	108.0	84.3	102.0
Tangled Thicket	Upstream	488.0	8,440.0	2,338.7	1,300.0
	Downstream	242.0	1,470.0	589.9	349.0

Appendix 4: Soil Testing Data, Upstream, 2023-2025

		Upstream											
		Phosphorus	Potassium	pH (1:1)	EC (1:1)	Est Sat Paste EC	Ammonium-N	Ammonium-N	Organic Matter WB	ENR	Nitrate-N	Nitrate-N	Sum of tested N
		mg/kg	*mg/kg*		*m.mhos/cm*	*m.mhos/cm*	*mg/kg*	*lbs/acre*	*%*	*lbs/acre*	*mg/kg*	*lbs/acre*	*lbs/acre*
Farm	**Date**												
Reinhard	2/22/2023	40	275	6.0	0.09	0.23	5.1	16	6.9	120	2.3	7	143
	5/30/2023	28	329	5.7	0.13	0.34	37.6	120	6.0	119	10.6	34	273
	8/28/2023	16	208	5.3	0.14	0.36	9.0	29	6.5	120	5.1	16	165
	12/11/2023	18	583	5.7	0.11	0.29	9.6	31	3.5	69	5.9	19	119
	4/29/2024	18	195	5.4	NA	NA	4.2	13	5.5	109	2.5	8	130
	9/17/2024	14	214	5.8	0.06	0.16	12.4	40	6.6	120	1.9	6	166
	1/9/2025	15	449	6.0	0.15	0.39	9.0	29	7.0	120	3.6	12	161
	5/27/2025	9	123	6.1	0.10	0.26	3.5	11	6.6	120	2.1	7	138
Sweetwater	2/16/2023	28	101	5.8	0.06	0.16	4.7	15	8.1	120	0.4	1	136
	5/30/2023	41	124	6.0	0.09	0.23	15.0	48	10.7	120	4.8	15	183
	8/28/2023	23	89	5.3	0.05	0.13	5.4	17	11.8	120	1.5	5	142
	12/11/2023	8	80	5.7	0.06	0.16	4.8	15	4.8	96	1.1	4	115
	4/29/2024	48	146	5.8	NA	NA	12.5	40	8.3	120	1.6	5	165
	9/17/2024	10	76	5.9	0.06	0.16	13.5	43	4.7	94	0.7	2	139
	1/9/2025	43	192	5.9	0.07	0.18	8.0	26	6.9	120	1.4	4	150
	5/27/2025	30	197	6.3	0.12	0.31	7.1	23	7.8	120	1.8	6	149
Tangled Thicket	2/22/2023	112	269	5.9	0.16	0.42	4.3	14	9.0	120	2.8	9	143
	5/30/2023	56	435	6.1	0.15	0.39	5.0	16	5.9	119	1.2	4	139
	8/28/2023	66	388	5.7	0.36	0.94	8.7	28	8.7	120	11.3	36	184
	2/2/2024	77	462	5.7	0.37	0.96	8.6	28	9.7	120	12.8	41	189
	4/29/2024	81	345	5.7	0.07	0.18	6.0	19	6.8	120	3.1	10	149
	9/17/2024	63	441	5.6	0.23	0.60	6.6	21	8.8	120	21.5	69	210
	1/9/2025	56	464	5.5	0.08	0.21	6.8	22	6.8	120	1.8	6	148
	5/27/2025	107	556	5.7	0.52	1.35	4.2	13	8.5	120	15.3	49	182

Appendix 5: Soil Testing Data, Downstream, 2023-2025

		Downstream											
		Phosphorus	Potassium	pH (1:1)	EC (1:1)	Est Sat Paste EC	Ammonium-N	Ammonium-N	Organic Matter WB	ENR	Nitrate-N	Nitrate-N	Sum of tested N
		mg/kg	*mg/kg*		*m.mhos/cm*	*m.mhos/cm*	*mg/kg*	*lbs/acre*	*%*	*lbs/acre*	*mg/kg*	*lbs/acre*	*lbs/acre*
Farm	**Date**												
Reinhard	2/22/2023	28	228	5.9	0.08	0.21	8.6	28	6.7	120	1.9	6	154
	5/30/2023	22	150	5.8	0.07	0.18	7.1	23	6.0	120	1.5	5	148
	8/28/2023	15	159	4.7	0.17	0.44	9.4	30	6.0	120	3.2	10	160
	12/11/2023	18	126	5.8	0.07	0.18	4.2	13	3.0	60	0.9	3	76
	4/29/2024	25	124	5.5	NA	NA	11.8	38	4.7	95	1.6	5	138
	9/17/2024	23	141	5.5	0.06	0.16	10.7	34	10.0	120	1.3	4	158
	1/9/2025	24	196	5.9	0.16	0.42	20.4	65	8.1	120	0.8	3	188
	5/27/2025	18	122	6.0	0.08	0.21	8.8	28	5.9	118	1.1	4	150
Sweetwater	2/16/2023	22	94	5.8	0.05	0.13	4.3	14	8.7	120	1.4	4	138
	5/30/2023	22	75	5.9	0.07	0.18	12.8	41	8.9	120	1.7	5	166
	8/28/2023	6	43	5.0	0.05	0.13	4.5	14	7.3	120	0.9	3	137
	12/11/2023	5	47	5.8	0.05	0.13	5.7	18	4.6	92	1.0	3	113
	4/29/2024	26	88	5.7	NA	NA	6.2	20	8.3	120	1.3	4	144
	9/17/2024	4	47	5.7	0.06	0.16	13.3	43	6.6	120	1.0	3	166
	1/9/2025	20	84	6.0	0.05	0.13	7.6	24	8.7	120	0.7	2	146
	5/27/2025	12	41	6.0	0.04	0.10	6.6	21	6.7	120	0.6	2	143
Tangled Thicket	2/22/2023	180	743	6.2	0.23	0.60	5.0	16	10.9	120	16.1	52	188
	5/30/2023	132	540	6.0	0.25	0.65	6.8	22	7.7	120	22.1	71	213
	8/28/2023	25	312	5.8	0.35	0.91	7.5	24	10.2	120	9.4	30	174
	2/2/2024	119	540	5.8	0.38	0.99	5.2	17	10.0	120	15.2	49	186
	4/29/2024	83	432	6.0	0.11	0.29	6.6	21	7.0	120	4.7	15	156
	9/17/2024	67	469	5.9	0.13	0.34	9.2	29	6.8	120	15.4	49	198
	1/9/2025	136	530	5.9	0.24	0.62	6.4	20	6.9	120	8.2	26	166
	5/27/2025	97	332	6.2	0.17	0.44	1.9	6	6.0	120	4.5	14	140

Appendix 6: Soil Testing Summary Statistics, 2023-2025

Location		Phosphorus (mg/kg)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	9.0	40.0	19.8	17.0
	Downstream	15.0	28.0	21.6	22.5
Sweetwater	Upstream	8.0	48.0	28.9	29.0
	Downstream	4.0	26.0	14.6	16.0
Tangled Thicket	Upstream	56.0	112.0	77.3	71.5
	Downstream	25.0	180.0	104.9	108.0

Location		Potassium (mg/kg)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	123.0	583.0	297.0	244.5
	Downstream	122.0	228.0	155.8	145.5
Sweetwater	Upstream	76.0	197.0	125.6	112.5
	Downstream	41.0	94.0	64.9	61.0
Tangled Thicket	Upstream	269.0	556.0	420.0	438.0
	Downstream	312.0	743.0	487.3	499.5

Location		pH (1:1)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	5.3	6.1	5.8	5.8
	Downstream	4.7	6.0	5.6	5.8
Sweetwater	Upstream	5.3	6.3	5.8	5.9
	Downstream	5.0	6.0	5.7	5.8
Tangled Thicket	Upstream	5.5	6.1	5.7	5.7
	Downstream	5.8	6.2	6.0	6.0

Location		EC (1:1, mmhos/cm)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	0.06	0.15	0.11	0.11
	Downstream	0.06	0.17	0.10	0.08
Sweetwater	Upstream	0.05	0.12	0.07	0.06
	Downstream	0.04	0.07	0.05	0.05
Tangled Thicket	Upstream	0.07	0.52	0.24	0.20
	Downstream	0.11	0.38	0.23	0.24

Location		Est. Sat. Paste EC (mmhos/cm)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	0.16	0.39	0.29	0.29
	Downstream	0.16	0.44	0.26	0.21
Sweetwater	Upstream	0.13	0.31	0.19	0.16
	Downstream	0.10	0.18	0.14	0.13
Tangled Thicket	Upstream	0.18	1.35	0.63	0.51
	Downstream	0.29	0.99	0.61	0.61

Location		Ammonium-N (mg/kg)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	3.5	37.6	11.3	9.0
	Downstream	4.2	20.4	10.1	9.1
Sweetwater	Upstream	4.7	15.0	8.9	7.6
	Downstream	4.3	13.3	7.6	6.4
Tangled Thicket	Upstream	4.2	8.7	6.3	6.3
	Downstream	1.9	9.2	6.1	6.5

Location		Organic Matter (%, Walkley-Black)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	3.5	7.0	6.1	6.6
	Downstream	3.0	10.0	6.3	6.0
Sweetwater	Upstream	4.7	11.8	7.9	8.0
	Downstream	4.6	8.9	7.5	7.8
Tangled Thicket	Upstream	5.9	9.7	8.0	8.6
	Downstream	6.0	10.9	8.2	7.4

Location		Nitrate-N (mg/kg)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	1.9	10.6	4.3	3.1
	Downstream	0.8	3.2	1.5	1.4
Sweetwater	Upstream	0.4	4.8	1.7	1.5
	Downstream	0.6	1.7	1.1	1.0
Tangled Thicket	Upstream	1.2	21.5	8.7	7.2
	Downstream	4.5	22.1	12.0	12.3

Location		Sum of Tested Nitrogen (lbs/acre)			
		Minimum	Maximum	Mean	Median
Reinhard	Upstream	119	273	162	152
	Downstream	76	188	147	152
Sweetwater	Upstream	115	183	147	146
	Downstream	113	166	144	144
Tangled Thicket	Upstream	139	210	168	166
	Downstream	140	213	178	180