Assessing the Effects of Cattle Grazing on Riparian Vegetation, Groundwater, and Soils and Implications for Carbon Storage Potential

Final Technical Report for Boulder County Parks and Open Space

PO BC16917

November 18, 2022

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Abstract

Wetland and riparian habitats are significant carbon sinks due to their high productivity and ability to efficiently sequester carbon in soils. Livestock grazing of riparian areas can affect the riparian environment by impacting vegetation biomass and composition and altering the stream characteristics and functions. In this study, we investigated the benefits of livestock exclosures on riparian condition and carbon sequestration potential. We hypothesized that riparian habitats on Boulder Parks and Open Space lands that have been isolated from livestock grazing will demonstrate increased carbon sequestration potential in both soil and vegetation biomass as compared to grazed locations, in addition to comparatively higher functioning ecological condition.

Study Objectives:

1. Characterize depth of saturation or groundwater as a measure of wetland hydrology at various temporal scales across the riparian zone;
2. Evaluate soil characteristics, including indicators of hydric soils and soil carbon content, at various temporal scales across the riparian zone;
3. Assess vegetation community composition, including dominant species by strata and total cover, and estimate carbon sequestration potential;
4. Correlate active wetland indicators (hydrology, soils, vegetation) with above and below ground carbon storage estimates; and
5. Compare data collected at stream locations within and outside of cattle grazing exclosures.

We documented marked impacts of grazing pressure on vegetation community composition and quality, above ground biomass, wetland extents, and influences on groundwater levels and stream morphology. However, for this study we did not document clear differences in belowground carbon storage between exclosure sites and grazed sites. Our work suggests that grazing exclosures contribute significant habitat improvement benefits, but more extensive soil investigations are needed to understand the potential influence on below ground carbon sequestration potential.

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1 Introduction

The negative effects of livestock grazing on stream health and riparian habitats are well documented (Belsky et al. 1999); however, with proper management practices, land stewards can facilitate both preservation of agricultural uses and healthy ecosystems. Boulder County Parks and Open Space (POS) manages over 100,000 acres of lands for mixed uses including agriculture and recreation, with an overarching commitment to conservation of natural, cultural, and agricultural resources for environmental and public benefit. As part of this legacy, an intergovernmental agreement in the 1970's led to creation of an agricultural land leasing program on POS lands which allowed purchase of open space lands as a mechanism to protect agricultural lands from urban development. Land conservation for the primary purpose of protecting working land assets can provide multiple benefits for agricultural uses, wildlife, and natural resources. Well-functioning riparian habitats can be the most productive assets on working and natural lands – by providing an important water source, shade/shelter, forage, soil and stream bank stabilization, critical habitat, sediment and nutrient capture, flood protection, and groundwater recharge. Riparian and wetland habitats have also become a focus for conservation and restoration efforts because of their ability to sequester atmospheric carbon in soils and in aboveground biomass.

Though wetlands are a known source of methane (CH_4) emissions, various studies demonstrate that most undisturbed wetlands become net carbon and radiative sinks (Mitsch et al., 2013). The role of wetlands, and more specifically emergent freshwater mineral-soil wetlands in North America on the global carbon budget is less well understood and difficult to quantify (Bridgham et al., 2006) as carbon dynamics are influenced by different climate and environmental conditions (Limpert et al., 2020; Valach et al., 2021). For example, sedimentation inputs into freshwater wetlands may be potentially substantial carbon sink that are not accurately accounted for in carbon budgets (Bridgham et al., 2006). Further, site specific factors including small and large-scale disturbances, land-use practices, and water management can influence wetland stability and their ability to effectively sequester carbon (Valach et al., 2021).

At the forefront of developing sustainable land management practices to protect ecosystem services and socioeconomic factors are implications of anthropogenic climate change. In the past 60 years, atmospheric carbon dioxide has increased over 100 times faster than previous natural increases, magnifying the Earth's natural greenhouse effect (NOAA 2022). The combined impacts of land use practices and climate charge are projected to further enhance impacts on natural resources (Copeland et al. 2017). Continuous grazing practices on agricultural lands supporting riparian and wetland habitats often lead to preferential use of aquatic areas and degradation of vegetation primary productivity, soil health, and stream geomorphology (George et al. 2011). Management practices including rotational grazing or fencing out livestock from streams and riparian areas can help to protect sensitive aquatic systems and associated ecosystem functions. Riparian habitats are generally characterized as the interface between the terrestrial and aquatic environment; the composition and extent of the riparian zone are shaped by geomorphic and hydrologic gradients. Critical to the gradient dynamic is the relationship between streamflow and groundwater. The influence of soil type and groundwater depth on riparian vegetation community composition can be pronounced. For example, a reduction of water table levels by one meter can induce water stress in hydric pioneer trees and shrubs resulting in a shift in community composition (Sawyer & Service, n.d., Stromberg et al. 2009).

In this study, we compare the condition of freshwater floodplain wetlands and their ability to sequester carbon under two different management regimes by estimating soil carbon and herbaceous vegetation biomass. We worked with POS staff to identify an open space property located west of Hygiene, CO (Figures 1 and 2, "Gage Property") that is currently leased for grazing and supports existing riparian habitat grazing exclosures. The Gage Property was purchased by the County in the late 1990's and has been under continuous agricultural use since its acquisition. The U.S. Fish and Wildlife Service identified this area as a Mouse Management Area for the federally listed species Preble's meadow jumping mouse (PMJM, *Zapus hudsonius preblei)* and the property supports BCPOS-designated Significant Wetlands. POS received a Natural Resources Conservation Service (NRCS) – Wildlife Habitat Incentive Program (WHIP) grant in 2006 for habitat enhancement associated with the South Branch of St. Vrain Creek on the Gage Property, which was focused on improving habitat for PMJM and enhancing general riparian condition. POS subsequently installed the grazing exclosures in 2006 for the purpose of improving habitat conditions for PMJM. Flows within the South Branch of St. Vrain Creek are perennial and controlled by multiple diversion structures, including the upstream branch from the mainstem of St. Vrain Creek downstream at the confluence with James Ditch, and again at the confluence with Peck Ditch. Flows are generally maintained from April 1 through mid- to late-October at 25 to 40 cubic feet per second (cfs). The South Branch of St. Vrain Creek is thought to be a relic floodplain overflow channel of the St. Vrain but has been co-opted for the delivery of irrigation water and is no longer naturally connected to the main branch. The geomorphic and physical characteristics of the South Branch still mimic natural stream channel conditions, but flows are highly regulated. It does not experience regular high flow events and perennial winter flows are primarily groundwater fed (BPOS pers. comm.).

We hypothesized that riparian habitats on POS lands that have been isolated from livestock grazing will demonstrate increased carbon sequestration potential in both soil and vegetation biomass as compared to grazed locations, in addition to comparatively higher ecological condition. The outcomes of this study can assist POS in adopting strategic and adaptive land management practices to support high functioning riparian and wetland systems and promote carbon storage and sequestration on open space lands.

1.1. Study Objectives:

1. Characterize depth of saturation or groundwater as a measure of wetland hydrology at various temporal scales across the riparian zone;
2. Evaluate soil characteristics, including indicators of hydric soils and soil carbon content, at various temporal scales across the riparian zone;
3. Assess vegetation community composition, including dominant species by strata and total cover, and estimate carbon sequestration potential;
4. Correlate active wetland indicators (hydrology, soils, vegetation) with above and below ground carbon storage estimates; and
5. Compare data collected at stream locations within and outside of cattle grazing exclosures.

2 Methods

2.1 Site Selection

The study focused on stream segments associated with a tributary channel of Saint Vrain Creek located on POS lands that are leased for year-round grazing. Stream segment one (Outside Exclosure #1 or O1) and segment two (Outside Exclosure #2 or O2) have open access to grazing livestock. Stream segment three (Exclosure #4 or E4) and stream segment four (Exclosure #5 or E5) are located within livestock exclosures that were erected by POS in 2006. The study sites described were suggested by POS and possess ideal characteristics for the proposed study which include a stream system located on rangeland with similar soil classifications, stream order, and flow regime. Further, study sites three (E4) and four (E5) support extant occurrences of PMJM and more broadly the St. Vrain Creek Watershed provides important recreation opportunities, wildlife habitat values, and affords numerous economic and cultural features. At each study site, a representative "evaluation area" was selected for installation of shallow groundwater wells, vegetation monitoring, and soil and plant material collection.

Figure 1. Selected study sites on the Gage Property. Sites E4 and E5 are located within grazing exclosures. Sites O1 and O2 are open for grazing. Site O1 is influenced by flood irrigation from the adjacent pasture.

Figure 2. Overview of the study site locations.

2.2 Determination of Growing Season

The U.S. Army Corps of Engineers defines *wetlands* as "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." Further, the Natural Resources Conservation Service (NRCS) describe the development of hydric soils as being dependent upon "conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (NRCS 2022). Various methods can be used to determine growing season, including evaluation of estimated timeframes included in WETS tables (Wetlands Climate Tables) or observable indicators of biologic activity such as: emergence of herbaceous plants, appearance of new growth of vegetative crowns, buds on woody plants, and emergence or growth of leaves on woody plants. We relied on information from POS on typical periods of early growing season conditions and visual observations of the field sites in early spring.

2.3 Hydrologic Monitoring

Depth to groundwater was measured at the study sites through placement of simple groundwater wells which were installed on April 11 and April 29, 2022 and removed on September 2, 2022. This timeframe was selected to capture the variability of water table depths during the primary growth period for most perennial plant species.

Installation of shallow monitoring wells is a commonly used practice to understand the hydrology of wetland systems and to support wetland determinations for regulatory purposes. The U.S. Army Corps of Engineers (USACE) developed technical standards for monitoring hydrology at wetland sites (Figure 3; USACE 2005). Three groundwater wells were installed at each site within the stream floodplain at standardized intervals (2 meters [“a” wells], 5 meters [“b” wells], and 8 meters [“c” wells]) from the bankfull edge of the stream channel to encompass a gradient across the active floodplain. Monitoring wells were installed up to a maximum depth of 24 inches, which encompasses the primary root zone of most perennial plant species and captures the minimum depth to observe shallow groundwater for the purpose of documenting wetland hydrology (*Wetlands*, 1995). Groundwater wells were installed by augering a hole at the desired sampling location and placing a well consisting of a well stock (PV pipe), well screen, riser, well cap, sand filter pack, and native clay sealant.

Water levels were measured using a steel tape measure marked with chalk or other water-soluble material. Groundwater levels were taken weekly starting with the installation of the wells in April to target the estimated growing season (March or April) and ending in early September. Water level data were graphed over time to show relative weekly water table depth. Additionally, stream discharge data were obtained from the closest monitoring gages gauges to compare water table fluctuations with stream flow/discharge increases.

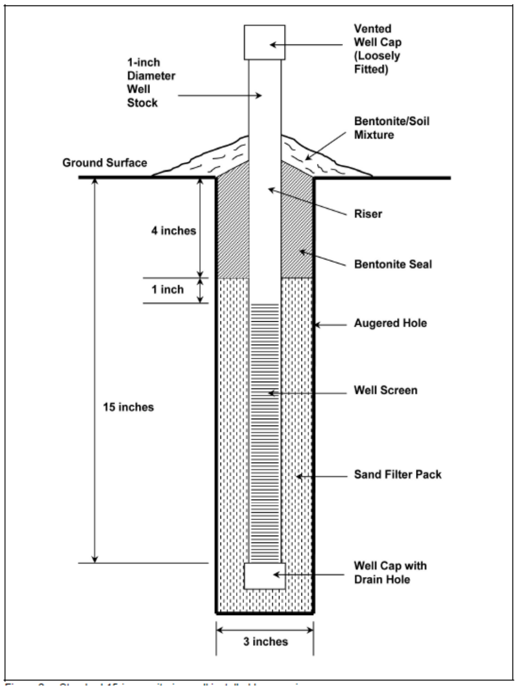

Figure 3. Diagram of shallow groundwater monitoring well.

2.4 Stream Channel Morphology

We evaluated stream channel morphology by characterizing a channel cross-sectional profile associated with each study site evaluation area. The objectives of this were to establish the natural dimensions of the channel and describe bank and channel stability, which can be correlated with fluvial processes and interacting factors (i.e., stream flows, sediments, vegetation condition, and cross section geometry). Using a stadia rod and auto-level, we recorded the relative elevation of the streambed (to bank height) to characterize the cross-section area along a transect line extending across the bankfull channel width.

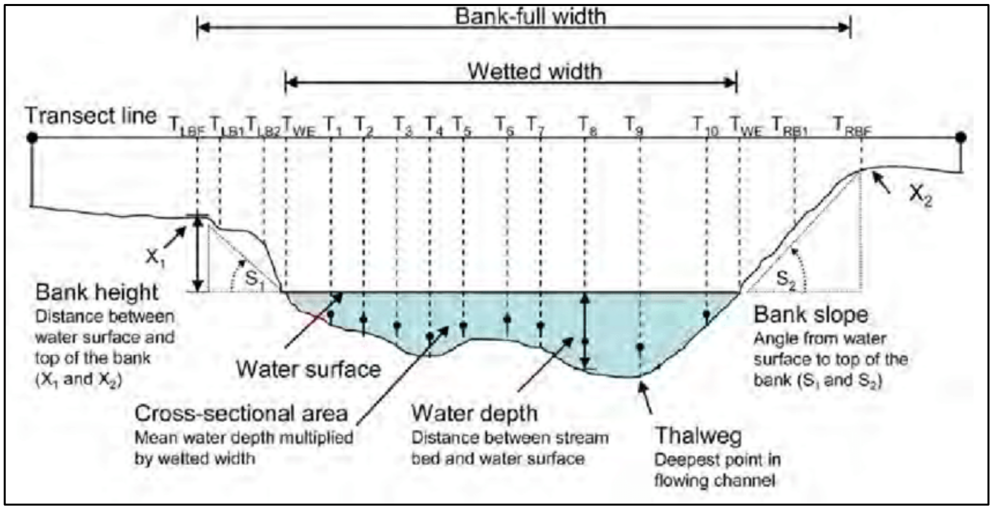

Figure 4. Diagram of a typical channel cross-section. Source: Harding, 2009.

Using information collected along each channel cross-section we evaluated channel geometry characteristics including mean depth, channel cross-sectional area, width to depth ratio, and hydraulic radius (RH = A/P, where A is the cross-sectional area and P is the wetted perimeter).

2.5 Soil Characterization and Carbon Storage

Soil sampling was performed at locations directly adjacent to installed groundwater wells. At each soil sampling location, a soil pit was excavated using an auger or spade shovel to evaluate soils from the upper 30 cm (roughly 12 inches). Soil samples, including root materials, were collected from each soil horizon (if multiple were observed within 30cm) for estimation of percentage of soil organic carbon (SOC) and bulk density; however, due to cost constraints, only samples collected from the upper soil horizons were submitted for carbon analysis.

Soil samples for estimate of soil organic matter (SOM) were submitted to Weld Laboratories for a Loss on Ignition (LOI) study. We selected a LOI study to estimate SOM in soils collected from the upper soil horizon (within 20 cm to 30 cm depending on upper soil horizon depth) as this method offers a simple, and inexpensive alternative to a carbon-nitrogen- sulfur (CNS) analyzer for measurement of soil carbon. SOM generally comprises the living organisms, fresh plant material entering the soil as litter or roots, organic compounds exuded from roots, and other forms of organic material that were broken down during decomposition processes in the soil. LOI involves measuring the weight of dry soil before burning away the organic material in the soil in a high temperature oven. Dried soil samples were heated in a muffle furnace at 550°C for 4 hours. The resulting SOM values were converted to SOC using the conventional conversion factor known as the “van Bemmelen factor” of 1.724, which assumes that most soils are comprised of 58 percent carbon, 40 percent oxygen, and 2 percent hydrogen (SOC = 58% of SOM).

Bulk density samples were collected from the upper 10, 20, or 30 cm of the soil profile depending on soil horizon depth using a 3-inch diameter by 4-inch depth open ended soil core. A total of 14 soil cores were collected on July 29 and August 17, 2022. The core samples were dried and weighed, and bulk density was then calculated as the dry weight of soil divided by its volume. Bulk density was then used to estimate total carbon per area following the equations described in Bernal and Mitsch and Goslee et al. (Bernal & Mitsch, 2012; Goslee et al., n.d.):

$$TC(g) = W(g) \times TC(\%) \times 10^{-2}$$

TC is total carbon and W is the dry weight of soil

$$Cstock = [(BDsoil]) \times \text{Depth of soil} \times C)] \times 100$$

Cstock is carbon per unit area (t/ha), BD is bulk density of soil (g/cm3), Depth of sampled soil (cm), and C is carbon concentration.

In addition to soil sample collection, we characterized soil texture, soil color (using the Munsell soil color chart), indicators of hydric soils (following NRCS field indicators), and representative composition of rocks/cobbles/gravels. Observations of hydric soil conditions were used to assist with determining the wetted extent of the active floodplain.

2.6 Vegetation Characterization and Biomass Estimation

Vegetation at the study sites was characterized to correlate plant species composition with hydrologic regimes and grazing pressure and to estimate above ground biomass. At each study site location, vegetation was evaluated within a 10-meter by 10-meter (100-m^2) nested plots located following the vegetation survey method developed by the Environmental Protection Agency (EPA) for the National Wetland Condition Assessment (Figure 5). This technique was developed by EPA to describe species composition, abundance/cover, and vegetation structure in order to characterize ecological integrity or stress (U.S. Environmental Protection Agency, 2016). Further, this method facilitates classification of vegetation cover and height which served as the basis for estimating representative above ground biomass at each study site.

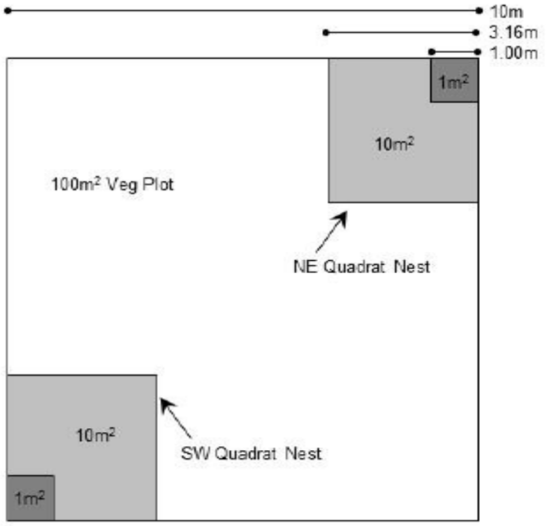

Figure 5. Vegetation Plot Configuration adopted from the EPA's National Wetland Condition Assessment.

Vegetation community composition within each plot was characterized by recording species presence in nested 1- m^2 and 10- m^2 quadrants in each corner, followed by overall cover and height class by species within the 100-m^2 plot. Any tree species located within the plot was characterized by height class. Collectively, these data were analyzed to assess biological condition as measured by a national Vegetation Multimetric Index (VMMI) developed by the EPA to assess the condition of wetlands across the lower United States (Magee et al., 2019). EPA developed a set of four vegetation metrics to include in the VMMI which included taxa composition (richness, frequency, cover, and importance for vascular plant species), floristic quality (mean coefficient of conservatism, floristic quality index), tolerance/sensitivity to disturbance, and life history (richness/abundance by growth habitat type, vascular plant category). Using data collected as part of the national study in 2011, EPA developed

VMMI metric scores based on floor and ceiling values based on a range of values collected during the calibration phase of the study (U.S. Environmental Protection Agency, 2016). We applied the scoring formulas for each of the four VMMI metrics to generate an overall VMMI score for each site plot (Magee et al., 2019; U.S. Environmental Protection Agency, 2016).

Plant community composition and cover data were used to calculate species richness, native species richness and percent cover, non-native species richness and percent cover, and percent wetland plant cover. The wetland indicator status of plant species was obtained from the USACE 2018 National Wetland Plant List (USACE 2020). Coefficients of conservatism (*C values*, scaled from 0 to 10) are assigned to species to describe their responsiveness to disturbance, with zero being applied to non-native species, lower values being applied to species with greater tolerance, and higher values representing greater sensitivity to disturbance (Magee et al., 2019). The Floristic Quality Index (FQI) describes the overall vegetative quality of an area, which is evaluated by:

$$\text{Floristic Quality Index (FQI)} = (\sum C/N_a)\sqrt{Na}$$

Where, FQI is represented by the mean C of all plants multiplied by the square-root of the number of native plants (N_a).

Estimation of above ground vegetation biomass or net primary production (NPP) relied on allometric estimates using vegetation characteristics including plant cover and relative plant height and were focused on herbaceous cover only. In the literature, there are numerous allometric equations and estimates for biomass and plant carbon for tree and shrub species but limited data on herbaceous plant species. We decided to target herbaceous plant biomass specifically for this study due in part to the lack of woody cover within the grazed study site reaches and to highlight the significance of herbaceous plant material for aboveground carbon storage.

Allometric models for estimating biomass generally require limited destructive sampling of plant material to correlate morphological characteristics (e.g., basal diameter, height, canopy diameter, or canopy volume) with biomass (Youkhana et al., 2017). This approach is commonly used to develop proxy-biomass relationships to calibration Normalized Difference Vegetation Index (NDVI) measured by field spectroscopy to estimate vegetation biomass over large areas (Ónodi et al., 2017). For this study, we used destructive sampling of a limited area to develop a biomass proxy to estimate above ground biomass (AGB) within the $100m^2$ study plot. In late July (peak growing season and physiological maturity for the majority of species) we harvested all above ground herbaceous plant material, including plant litter, within a 1 x 1 meter plot placed within a representative area of the larger $100m^2$ vegetation monitoring plot at each sampling location. Plant material was separated by height class (height class 1 <0.5m, height class 2 .0.5 to 2m), dried, and weighed to estimate total biomass as grams per square meter by height class.

To estimate total plant carbon per square meter, an approximated value of the average plant carbon content for herbaceous plant leaf and stem material as report by Ma et al. (2018) of 43% was multiplied by total biomass per square meter. This value was subsequently multiplied by $100m^2$ to obtain total carbon per 100 square meter assessment area and then adjusted by average plant cover by plant height.

$$\text{Estimated total grams of carbon per } 100m^2 = g/\ m^2 \text{ x } 100 \text{ x average percent cover}$$

$$\text{Estimated total grams per hectare} = g/m^2 \text{ x } 10{,}000$$

Lastly, we evaluated the plant community constituents to map the lateral extents of wetland/riparian habitat within the vicinity of the study plot, which was used to estimate the average wetland width. Mapping of the wetland edge also relied on field indicators of hydric soils (from soil investigations) and observations of shallow groundwater (within 12-inches of the ground surface) in groundwater wells.

3 Results

3.1 *Wetland Hydroperiod and Stream Morphology*

Only the groundwater wells located within the exclosures (study sites E4 and E5) demonstrated wetland hydrology during the growing season as defined by the National Research Council as approximately 14 consecutive days during the growing season in most years (*Wetlands*, 1995) (Figure 6). All but one of the wells (E5b – 5 meters from the stream edge) within the exclosures exhibited shallow groundwater for two or more consecutive weeks. These findings suggest that wetland hydrology was supported within and potentially beyond 8 meters from the bankfull edge of the stream within the exclosure study sites.

Several factors influenced the hydroperiod of the study sites selected for this investigation. Study site O1 (outside exclosure 1) is situated on a low terrace that received periodic runoff from flood irrigation from the adjacent pasture. We observed shallow groundwater response and recharge association with surface inundation from irrigation throughout the growing season. Study site E5, which encompasses a low floodplain terrace, became flooded following peak discharges in the creek starting in early May. The floodplain terrace remained saturated and/or flooded for the duration of the groundwater monitoring period and influenced groundwater readings associated with well E5b and E5c (Figure 7).

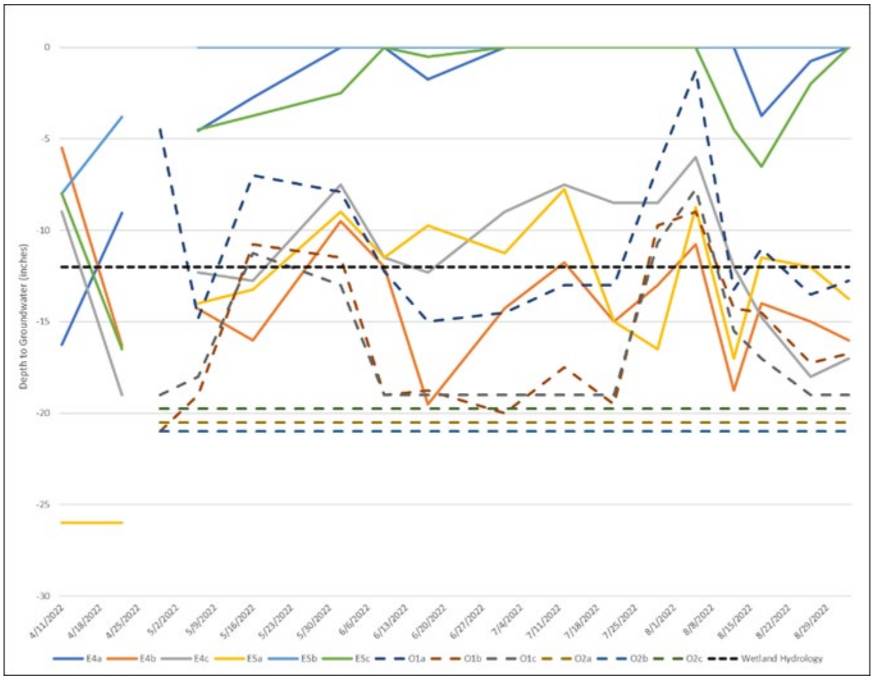

Figure 6. Depth to Groundwater as reported by shallow groundwater wells from April 11 through September 2, 2022. Wetland hydrology is indicated by two consecutive weeks of shallow groundwater within 12 inches of the ground surface during the growing season. Stage zero (0) represents ground surface, groundwater values at zero represent surface inundation.

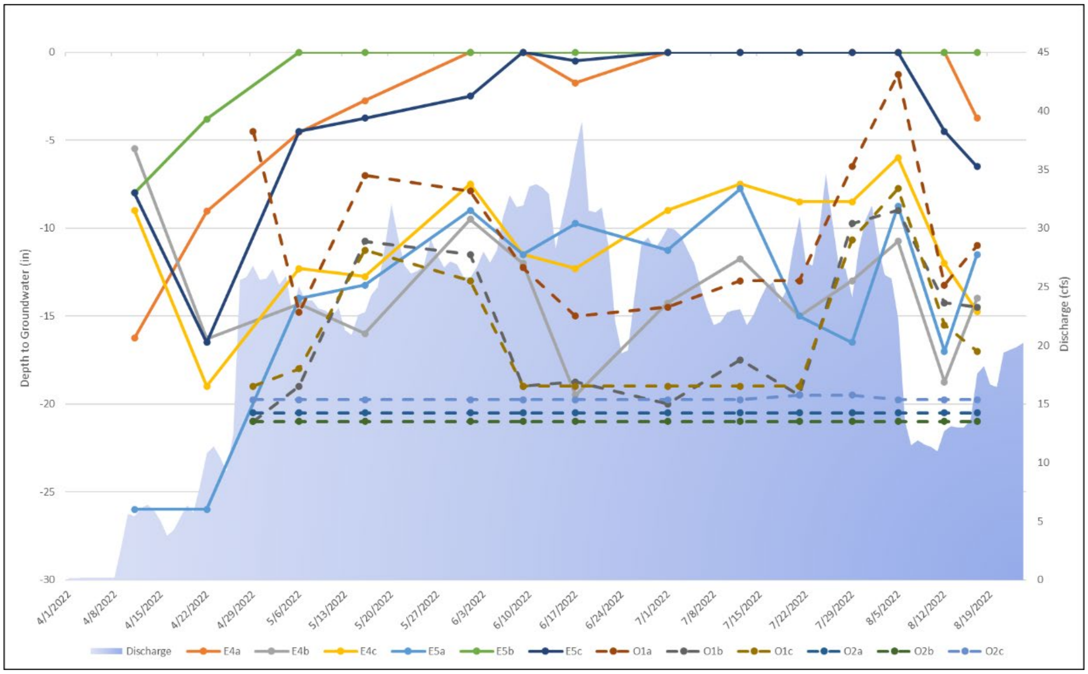

Figure 7. Depth to groundwater relative to stream discharge in the South Branch of St. Vrain Creek downstream of the Davis and Downing Ditch diversion.

Stream channel cross section investigations demonstrated differences within the bankfull channel geometry, with channel profiles exhibiting signs of confinement within grazed reaches and indications of aggradation within the exclosure reaches (Figure 8). Average channel depths were higher within the grazed reaches, as were hydraulic radius (HR) – which describes channel flow efficiency and its ability to move water and sediment and approximates mean depth of a channel (Table 1). A higher HR generally correlates with higher velocity in the stream because less of the water is in contact with the frictional bed of the stream (Seaton, n.d.). Average channel depths and channel morphology of grazed reaches exhibit signs of channel incised leading to reduced access of the stream to the adjacent floodplains, which leads to lowering of the water table near the stream (Burt et al., 2002). The associated influence on water table elevations is evident in the associated wetland extents associated with the stream margin; the average wetland width within the exclosure study reaches are approximately 10 times that of the grazed areas, which were primarily confined to degraded channel banks (Table 1).

Table 1. Stream channel morphology and hydrologic wetland presence.

Plot	Wetted Width (m)	Average Depth (m)	Area (m^2)	Width to Depth Ratio	Hydraulic Radius	Average Wetland Width (m)
O1	8	0.496	3.825	16.12	0.546	2.46
O2	9	0.459	3.815	19.61	0.423	2.07
E4	11	0.403	4.375	27.31	0.398	19.67
E5	11	0.366	3.595	24.59	0.327	12.97

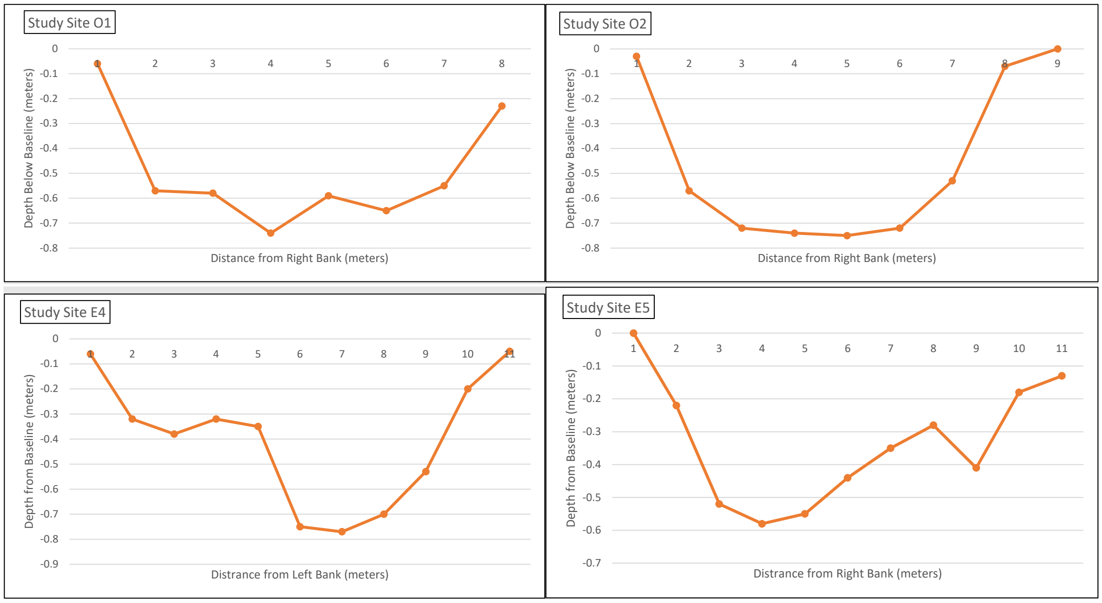

Figure 8. Stream cross section geometry.

3.2 *Wetland Vegetation Condition Wetland Vegetation Condition*

Streamside vegetation community structure and condition were directly affected by grazing pressure. Vegetation community composition within the grazed plots consisted primarily of pasture grasses and ruderal herbs, with low wetland plant cover. The mean C value for both grazed plots ranged between 1 and 2 (Table 2) indicating dominance by species associated with disturbance, and due primarily to high cover by exotic species. Species richness was generally consistent across all sites; however, the grazed study sites were largely dominated by quackgrass (*Elymus repens*), Kentucky bluegrass (*Poa pratensis*), and white clover (*Trifolium repens*), which are rated as facultative upland (FACU) species on the national wetland plant list (USACE 2018). The exclosure study sites were largely dominated by wetland herbs including woolly sedge (*Carex pellita*) and common spikerush (*Eleocharis palustris*), and Canada thistle (*Cirsium arvense*).

Table 2. Vegetation community characteristics for each sample plot.

Sample Plot	**Species Richness**	**Percent Native**	**Total Cover**[a]	**Total Native Cover**	**Total Wetland Plant Cover**[b]	**Percent Wetland Cover**
O1	25	48	99.5	16	17	17.33
O2	22	45	84.5	5	6	7.1
E4	21	76	117.75	106	107	90.87
E5	21	67	91.25	88	89	97.53

a. Absolute cover includes rooted tree canopy cover.
b. Wetland plants include all species defined as facultative (FAC), facultative wetland (FACW), or obligate (OBL) by the 2018 wetland indicator list (USACE 2018)

Vegetation quality and condition indices demonstrate a clear distinction between grazed sites and exclosure sites, which is reflected by prevalence of vegetation associated with disturbed environments.

When all species observed within a site plot were evaluated the mean C, cover weighted C values, and associated FQI values for the ungrazed, exclosure sites were notably higher (Table 3); however, generally scores fell within the “low quality” FQI range of 1-19 (CNHP 2022). In addition to evaluating vegetation quality, we assessed ecological condition used a multimetric index (VMMI) developed by EPA from data collected during the 2011 National Wetland Condition Assessment (U.S. Environmental Protection Agency, 2016). Using data collected from a variety of wetland habitats throughout the lower 48 states, EPA developed a national-scale VMMI and thresholds for condition (good, fair, and poor) for 10 ecoregions by wetland type. We compared VMMI scores calculated for the four study plots to thresholds for palustrine, riverine, and lacustrine herbaceous wetlands in the west (W-PRLH) (poor condition ≤ 30 and good condition ≥ 57.4) and found that the exclosure sites scored just below “good condition” while the grazed sites scored as “poor condition.”

Table 3. Vegetation Quality and Condition Indices

Sample Plot	Mean C[a]	Native Mean C[a]	Cover Weighted Mean C	FQI[b]	FQI native	Mean C	FQI[b]	AdjCWFQI[c]	VMMI[c]
O1	1.84	4.10	0.16	8.74	12.97	1.84	8.74	21.81	11.75
O2	1.68	3.75	0.16	6.55	10.61	1.68	6.55	18.17	2.17
Average	*1.76*	*3.93*	*0.16*	*7.65*	*11.79*	*1.76*	*7.65*	*19.99*	*6.96*
E4	3.33	4.62	4.62	14.14	14.14	3.33	14.14	43.42	55.97
E5	2.90	4.27	3.42	11.08	11.08	2.90	11.08	31.37	56.51
Average	*3.12*	*4.45*	*4.02*	*12.61*	*12.61*	*3.12*	*12.61*	*37.4*	*56.24*

a. Average coefficient of conservatism values and FQI estimated using the Colorado Natural Heritage Program (CNHP) Floristic Quality Assessment Calculator for Colorado (https://cnhp.colorado.edu/cwic/tools/calculator)

b. Floristic Quality Index = mean C x √plant richness

c. Adjusted cover-weighted FQI = cover weighted mean C for native plants divided by 10 multiplied by the square-root of native plants divided by the square root of number of all plants multiplied by 100

3.3 Carbon Sequestration

The total carbon content of soils based on a loss-on-ignition study did not demonstrate a significant difference in below ground carbon storage between the exclosure and grazed sites (Table 4). This finding contradicted our original hypothesis in which we speculated that upland soils within grazed areas would contain lower carbon concentrations than wetland/exclosure soils. Further, estimates of total carbon pools were generally lower than reported by other studies using LOI to estimate soil carbon in wetlands (Braun et al., 2020; Wright et al., 2008).

Table 4. Soil carbon pools for each sample plot.

Sample Plot	Distance (m)[a]	Depth (cm)	Texture	BD (g/cm^3)	SOM (%)	SOC (%)[b]	TClayer (gC kg^{-1})	Cstock (t/ha)
O1a	2	30	Silty clay loam	1.02	10.4	3.38	15.89	102.96
O1b	5	20	Clay loam	1.33	6.9	2.26	13.91	90.14
O1c	8	10	Silty clay loam	1.21	15.6	5.08	28.45	49.16
O2a	2	20	Silty clay loam	1.07	18.79	3.54	17.57	75.90
O2b	5	30	Loam	1.11	11.3	3.67	18.91	122.51
O2c	8	20	Silty clay loam	1.14	12.2	3.98	21.09	91.09
Average (Outside)				*1.15*	*12.2*	*3.98*	*21.09*	*91.09*
E4a	2	30	Mucky clay	0.58	10.9	3.54	9.57	62.00
E4b	5	30	Clay loam	0.68	9	2.94	9.24	59.90

E4c	8	30	Clay loam	0.95	10.3	3.34	14.70	95.26
E5a	2	20	Silty loam	0.78	12.4	4.03	14.49	62.60
E5b	5	20	Clay loam	0.99	14.8	4.80	22.09	95.43
E5c	8	20	Mucky clay	0.59	16.6	5.42	13.29	57.39
Average (Exclosure)				*0.76*	*12.33*	*4.01*	*13.9*	*72.1*

a. Distance from estimated bankfull channel edge.
b. Soil organic carbon estimated using the van Bemmelen conversation factor of 1.724, which assumes that 58% of most soils are comprised of organize carbon.

Aboveground biomass was substantially higher within the exclosure sites (E4 [290 g/m^2] and E5 [184 g/m^2]) compared to the grazed sites (O1 [120 g/m^2] and O2 [60 g/m^2]) (Table 5), which was also related to average overall cover within the 100m^2 evaluation plot (Table 2). It should be noted that cattle breached the exclosure at site E5 in early June, which contributed to reduced aboveground vegetation biomass as compared to site E4. For this study we used values reported by Ma et al. (2018) for average carbon content (%) in leaf and stem material for herbaceous plants (45% in leaf material and 43% in stems ~ 44% combined) to estimate total plant carbon from dried vegetation biomass.

Table 5. Vegetation Biomass and Estimated Vegetation Carbon for each sample plot.

Plot	**Height Class**	**Dry Weight (g/m^2)**	**Carbon (g/m^2)**	**Carbon per plot (g/100m^2)**	**Carbon per hectare (g/ha)**	**Carbon per hectare (t/ha)**
O1	HC1	120	54	4,563	540,000	0.54
O2	HC1	60	27	2,282	270,000	0.27
Average	-	*90*	*40.5*	*3,422.5*	*405,000*	*0.81*
E4	HC1&HC2	290	130.5	13,050	130,500,000	130.5
E5	HC1	184	82.8	8,280	82,800,000	82.8
Average	-	*237*	*106.7*	*10,665*	*106,650,000*	*106.7*

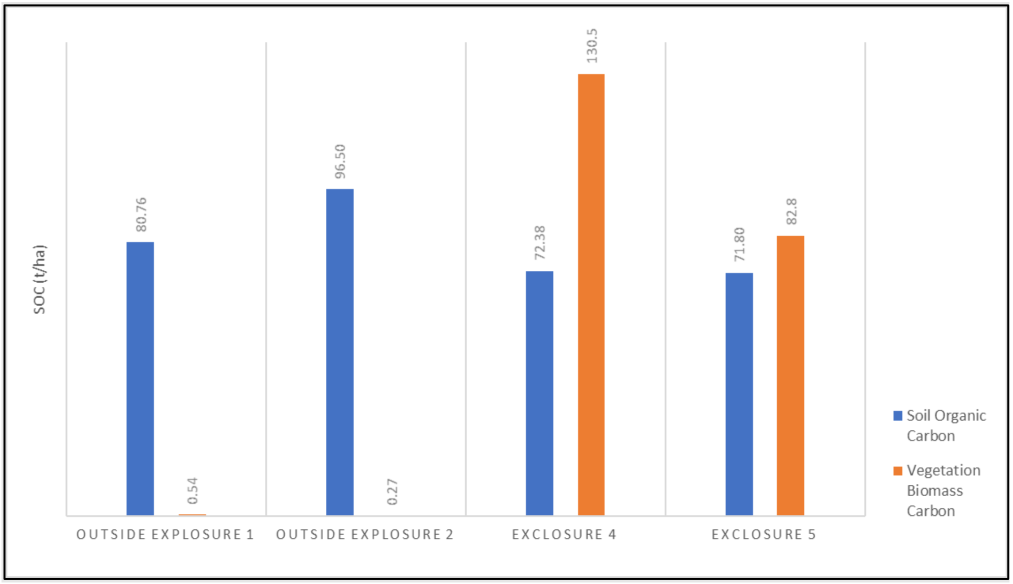

Figure 9. Total soil organic carbon content in soils and above ground biomass per area.

4 Discussion

Our study provides several important insights into the influence of grazing pressure and grazing exclosures on the riparian zone and potential implications for carbon sequestration potential. In our study, we did not document evidence of higher below ground carbon storage associated with grazing exclosures but did demonstrate substantially higher aboveground vegetation biomass. Our findings relating to soil organic carbon storage generally conflict with our initial hypothesis – grazing exclosures support the development and/or persistence of high functioning freshwater wetland systems and contribute to higher belowground carbon density than grazed uplands. This hypothesis is supported by prior studies that demonstrate that wetlands have net retention of organic matter and plant detritus in wetland sediments (Mitsch and Gosselink 2007); organic matter generally contains between 45% and 50% carbon, thereby wetlands serve as important carbon sinks (Kayranli et al., 2010). Estimates of global wetland carbon sequestration potential are roughly 830 Tg/year of carbon with an average of 118 gCm^{-2} year^{-1} (Mitsch et al., 2013) and more specially riparian ecosystems are estimated to accumulate 0.16-0.22 kg Cm^{-2} year^{-1} (McCarty and Richie 2022), values substantially higher than we document in our findings.

Several factors may have complicated our estimates of soil carbon, including our methods for collecting soil samples, the lack of replicates and the low number of samples analyzed, delays between collection time and laboratory analysis, and LOI parameters. Soils are naturally very heterogeneous contributing to significant variability in both SOC and BD; therefore, our low number of samples collected is potentially biased by not adequately representing within variability (Walter et al., 2016). Additionally, soils with high organic matter that are exposed to air can break down due to rapid oxidation by common bacteria (Donovan, n.d.). Further, various studies suggest that ignition conditions – including the location of the soil sample in the furnace, as well as structural water loss or liberation of carbonates, can lead to incorrect estimates of ignition (Whitaker, n.d., Hoogsteen et al. 2015). Lastly, it should be noted that LOI provides an estimation of total organic carbon (TOC) in soils and does not account for inorganic carbon.

Our estimates were, however, generally consistent with findings reported by Bernal (2012) and Bernal and Mitsch (2012), which found that carbon content in riverine soils were significantly lower than depressional isolated wetlands. Bernal (2012) suggested that the constant fluvial process of flow through wetland sites (riverine) contributing to increased soil erosion could influence accumulation of organic matter and persistence of recalcitrant material. Similarly, Matzek et al. found that soil carbon stocks varied among landforms; they documented higher carbon stocks on the upper banks (12-24 meters from the stream edge) compared to the channel floodplain (3-12 meters from the channel edge). We focused soil sample collection within the active channel floodplain, which may support comparatively lower soil carbon values (2020). Matzek et al. compared soil carbon and above and below ground carbon stocks in restored and unrestored riparian corridors and observed that carbon stores associated with stream channels (0-3 meters from stream edge) and floodplains were primarily associated with above and belowground vegetation biomass (trees and shrubs), while soil carbon stocks were the primary source of carbon storage on high banks (2020).

Many studies evaluating carbon storage potential of riparian systems include estimates of aboveground/standing woody biomass, large wood, and belowground vegetation biomass (roots), which can be substantial. Total organic storage associated with riparian biomass ranges from 100 to 300 Mg (t) C per hectare (Sutfin et al. 2015). Our study does not include estimates of woody biomass (above and belowground), which is anticipated to be significantly higher in exclosure areas due to higher cover by woody riparian species. We conjecture that carbon values attributed to riparian biomass values within exclosures would be significantly higher than what we present in this study. Future studies should incorporate direct or allometric estimates of woody biomass to provide more accurate estimates of carbon storage values associated with exclosures.

Though we did not substantiate evidence of increased below ground carbon sequestration potential associated with grazing exclosures, our findings demonstrate the significant contribution of grazing exclosures on improving ecosystem conditions, including aboveground biomass, vegetation quality, groundwater dynamics, and stream morphology. For our study design, we incorporated methods implemented as part of the National Wetland Condition Assessment (NWCA) to evaluate wetland condition. Based on national thresholds defined by a multimetric index VMMI, the wetlands associated with grazing exclosures were rated as fair to good condition, indicating low disturbance. Furthermore, we found that exclosures were strongly correlated with dominance of wetland vegetation species and correspondingly with wetland hydrology as indicated by water table levels.

We theorize that multiple factors influence the development and persistence of wetland characteristics (vegetation, soils, and hydrology) within grazing exclosure areas including stream-floodplain interactions, soil compaction, and channel morphology. Cattle grazing is known to contribute to increased soil compaction and decreased vegetation cover, which can negatively affect rainwater or surface water infiltration into soils and lead to more overland flows into streams. Additionally, less stable streambanks – due to decreased vegetation cover and trampling impacts, can result in channel downcutting or incision. As the channel bed lowers, water drains away from the adjacent floodplain causing lowering of the water table (Belsky and Uselman 1999).

Lastly, we should note that studies have demonstrated positive benefits of well managed grazing regimes on soil carbon. Multiple studies have found that grazing of shortgrass steppe and mixed-grass prairie increased soil organic carbon in the upper 30 cm of the soil compared to un-grazed exclosures (Derner et al. 1997, Reeder and Schuman 2002, Schuman et al. 1999). Further, Harvey et al. 2019 found that livestock grazing on saltmarsh wetland habitats found no detectable relationship between grazing intensity and soil organic carbon, but clear differences in aboveground vegetation composition, structure, and biomass.

4.1 Management Implications

The contribution of grazing exclosures on soil carbon sequestration may be less clearly shown in our data; however, we provide clear evidence of other ecosystem benefits associated with habitat condition and stream morphology. The effects of grazing and exclosures on stream channel morphology have been well documented in other studies (Nagle & Clifton, 2003). We documented differences in groundwater levels within the exclosures, which were supported by vegetation characteristics and average wetland width. Through simple channel profile characterization, we documented channel morphology attributes which demonstrate decreased surface water to floodplain connection within the grazed reaches. These factors all contribute to improved riparian habitat conditions, which are imperative to the threatened Preble's meadow jumping mouse and other riparian associated species. In addition, improved riparian system conditions provide other important ecosystem services including contribution of organic matter, water quantity and quality improvement, and stream stabilization (George et al., 2011).

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Appendix A

Plant Species List

Table 6. Plant species present within each sample plot.

Species	Plot E4	Plot E5	Plot O1	Plot O2
Agrostis gigantea	-	X	X	X
Ambrosia psilostachya	-	-	X	X
Asclepias incarnata	X	-	-	-
Asclepias speciosa	X	-	-	-
Bouteloua gracilis	-	-	X	-
Callitriche palustris	-	X	-	-
Carex duriuscula	-	-	X	X
Carex pellita	X	X	-	-
Carex scoparia	X	-	-	X
Carex utriculata	X	-	-	-
Chenopodium sp.	-	-	X	-
Cirsium arvense	X	X	-	-
Cornus sericea	X	-	-	-
Cyperus acuminatus	-	-	X	-
Distichlis stricata	-	-	X	-
Echinochloa crus galli	-	-	X	-
Eleocharis palustris	X	X	X	X
Elymus repens	-	-	X	X
Epilobium ciliatum	X	X	-	-
Equisetum arvense	-	-	X	X
Glyceria striata	-	X	-	-
Grindelia squarrosa	-	-	-	X
Hordeum jubatum	-	X	X	X
Juncus arcticus	X	X	X	X
Lactuca serriola	-	X	-	-
Lycopus americanus	-	X	-	-
Medicago lupulina	-	-	X	X
Medicago sativa	-	-	-	X
Melilotus albus	-	-	-	X
Mentha arvense	X	-	-	X
Mentha arvensis	-	X	-	-
Myosotis scorpioides	X	-	-	X
Opuntia polyacantha	-	-	X	-
Persicaria hydropiper	X	X	-	X
Persicaria pensylvanica	-	X	-	-
Phalaris arundinacea	-	X	-	-
Plantago lanceolata	-	-	-	X
Plantago lanecolata	-	-	X	-
Plantago major	-	-	X	X

Species	**Plot E4**	**Plot E5**	**Plot O1**	**Plot O2**
Poa pratensis	X	-	X	X
Polygonum aviculare	-	-	X	-
Populus deltoides	X	-	-	-
Portulaca oleracea	-	-	X	-
Potentilla recta	-	X	-	-
Sagittaria cuneata	-	X	-	-
Salix exigua	X	-	-	-
Schoenoplectus pungens	-	-	X	-
Sisyrinchium montanum	-	-	X	-
Solidago canadensis	X	-	-	-
Sonchus arvensis	X	X	-	-
Spartina pectinata	X	X	-	-
Taraxacum officinale	-	-	-	X
Taraxicum offinale	-	-	X	-
Trifolium pratense	-	-	X	X
Trifolium repens	-	-	X	X
Typha sp.	-	X	-	-
Verbena hastata	-	X	-	-