COLORADO
Department of Transportation

CDOT Applied Research and Innovation Branch

# Wetland Plant Species Composition Influences Site Water Use

Anna Wright, Jeremy Sueltenfuss, and Troy Ocheltree

October 2023

Report No. 2023-15

**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No.<br>CDOT-2023-15 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>Wetland Plant Species Composition Influences Site Water Use | | 5. Report Date<br>October 2023<br>6. Performing Organization Code |
| 7. Author(s)<br>Anna Wright, Jeremy Sueltenfuss, Troy Ocheltree | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Colorado State University<br>Fort Collins, CO<br>80523 | | 10. Work Unit No. (TRAIS)<br>11. Contract or Grant No.<br>121.01 |
| 12. Sponsoring Agency Name and Address<br>Colorado Department of Transportation - Research<br>2829 W. Howard Pl.<br>Denver CO, 80204 | | 13. Type of Report and Period Covered<br>Final<br>14. Sponsoring Agency Code |
| 15. Supplementary Notes<br>Prepared in cooperation with the US Department of Transportation, Federal Highway Administration | | |

16. Abstract

The Colorado Department of Transportation (CDOT) is one of the leading organizations in wetland mitigation within the state of Colorado. In an effort to optimize and prioritize their mitigation activities, and to ensure they do not infringe on Colorado Water Law nor downstream water rights, CDOT was interested in understanding the water use of restored wetlands. This study investigated whether wetland species composition affects wetland water consumption. Water-use measurements were taken throughout the summer of 2022 at 2 restored wetland sites in Colorado's Front Range; one in St. Vrain State Park near Longmont, Colorado and the other at McMurry Natural Area in Fort Collins, Colorado. Water-use measurements were taken on five focal species representing dominant wetland species; *Salix exigua* (Coyote Willow), *Populus deltoides* (Plains Cottonwood), *Typha latifolia.* (Cattail), *Phalaris arundinacea* (Reed Canarygrass), and *Carex emoryi* (Emory Sedge). In this study, the focal species transpired different amounts of water, and species lost similar amounts of water at both sites despite differences in soil type and groundwater flow.

Communities with an even balance of species lose less water to transpiration than wetlands with communities solely comprised of plants with high water-use rates. Species transpire similar amounts of water regardless of site or location. Thus, transpiration between impacted and restored sites will be similar so long as the species composition is also similar.

Implementation (Optional)

| | |
|---|---|
| 17. Keywords<br>Wetland mitigation; Evapotranspiration; Water Use; Restoration | 18. Distribution Statement<br>This document is available on CDOT's website<br>https://www.codot.gov/programs/research |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | | |

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

## WETLAND PLANT SPECIES COMPOSITION INFLUENCES SITE WATER-USE

### Contents



### Acknowledgement


I would like to express my gratitude to everyone who supported and guided this research. This includes the study panel, especially Bryan Roeder and Becky Pierce. A special thanks goes to my advisors, Troy Ocheltree and Jeremy Sueltenfuess. Lastly, a big thank you goes to Scott Bradfield, Zoe Lipscomb, and Seton Bachle for assisting me with field work and training me on research methods.


### Abstract


The Colorado Department of Transportation (CDOT) is one of the leading organizations in wetland mitigation within the state of Colorado. In an effort to optimize and prioritize their mitigation activities, and to ensure they do not infringe on Colorado Water Law nor downstream water rights, CDOT was interested in understanding the water use of restored wetlands. This study investigated whether wetland species composition affects wetland water consumption. Water-use measurements were taken throughout the summer of 2022 at 2 restored wetland sites in Colorado's Front Range; one in St. Vrain State Park near Longmont, Colorado and the other at McMurry Natural Area in Fort Collins, Colorado. Water-use measurements were taken on five focal species representing dominant wetland species; *Salix exigua* (Coyote Willow), *Populus deltoides* (Plains Cottonwood), *Typha latifolia.* (Cattail), *Phalaris arundinacea* (Reed Canarygrass), and *Carex emoryi* (Emory Sedge). In this study, the focal species transpired different amounts of water, and species lost similar amounts of water at both sites despite differences in soil type and groundwater flow.

Communities with an even balance of species lose less water to transpiration than wetlands with communities solely comprised of plants with high water-use rates. Species transpire similar amounts of water regardless of site or location. Thus, transpiration between impacted and restored sites will be similar so long as the species composition is also similar.

**Executive Summary**

Wetlands occur where water levels are near the ground surface. Because of their importance to water quality and ecosystem health, federal regulation requires wetlands that are impacted and lost through development activities be replaced by restoring wetlands elsewhere. The Colorado Department of Transportation (CDOT) is one of the largest wetland mitigators in the state of Colorado. If CDOT were to expand a road and impact a wetland, it would then have to restore or create a wetland of equal or greater acreage nearby. This process of wetland mitigation can be difficult and costly, and CDOT is therefore interested in ways to make wetland mitigation more efficient and effective. A limiting factor in wetland mitigation projects is often water availability.

Quantifying transpiration of wetland plant communities is the critical step in accurately allocating water rights for restoration projects and enabling wetland restoration projects to minimize water loss. Water-use measurements were taken throughout the summer of 2022 at 2 restored wetland sites in Colorado's Front Range; one in St. Vrain State Park near Longmont, Colorado and the other at McMurry Natural Area in Fort Collins, Colorado. Water-use measurements were taken on five focal species representing dominant wetland species; *Salix exigua* (Coyote Willow), *Populus deltoides* (Plains Cottonwood), *Typha latifolia.* (Cattail), *Phalaris arundinacea* (Reed Canarygrass), and *Carex emoryi* (Emory Sedge). Measurements were taken using a handheld porometer (LI-600; LICOR Environment, Lincoln, USA) which rapidly measures stomatal conductance and transpiration on plants in situ. Results were scaled to the site level using leaf area index values for each species.

In this study, the focal species transpired different amounts of water. *S. exigua* (Coyote Willow) lost the most water through transpiration – 325,000 gallons per acre per month –while *T. latifolia* (Cattail) and *P. deltoides* (Plains Cottonwood) lost the least. Water losses from *P. arundinacea* (Reed Canarygrass) and *C. emoryi* (Emory Sedge) were between these. This study was conducted across two sites, and species lost similar amounts of water at both sites despite differences in soil type and groundwater flow. More biodiverse wetlands lose less water to transpiration than wetlands with communities solely comprised of plants with high water-use rates.

Species transpire similar amounts of water regardless of site or location. Thus, transpiration between impacted and restored sites will be similar so long as the species composition is also similar. When water-use is an important restoration project consideration, we recommend the following to improve budgeting for plant water-use:

Recommendation 1: Balance species composition between impacted and restored sites.

Recommendation 2: When restoring a different wetland type than was impacted, consider the water-use impact of planting species with high water-use rates.

Recommendation 3: Maximize planting biodiversity to lessen the impact of plants transpiring at high rates.

## Introduction

Wetlands and riparian corridors provide outsized benefits in terms of wildlife habitat and flood mitigation (Wohl et al. 2021); restoring impaired wetland landscapes thus increases the benefits they provide. However, in the arid west there is a tension between stream/wetland restoration and water rights, to the point where Colorado legislature passed a bill in 2023 (SB 23-270) declaring that “because of the vast amount of benefits that natural streams provide the state’s communities and environment, the state should facilitate and encourage the commencement of projects that restore the environmental health of natural stream systems.” To that end, SB270 sought to create six types of stream restoration projects that can be implemented without being subject to water rights administration. Due to water stakeholder concerns that some types of stream/wetlands restoration projects could potentially increase water loss due to high riparian and wetland evapotranspiration (ET) rates (Maxwell and Kollet 2008; Maxwell and Condon 2016), the first draft of the bill was amended during the legislative session to narrow the types of restoration that can take place without having to obtain a water right.

Because Colorado is relatively arid, creating sustainable wetlands requires a reliable water source. Wetlands have water levels near the ground surface, and a lot of this water is lost through direct evaporation or through transpiration from plants. As wetland plants grow and reproduce, they take up water through their roots and release most of it through their leaves to the air. The actual amount of water loss from wetlands is not well understood. Although previous research has shown little to no difference in water loss between open water and vegetated wetlands, little is known about the water loss of restored wetlands.

Although mitigation for impacts to wetlands has been required for decades, mitigation for impacts to streams has only recently come into focus. The Army Corps of Engineers recently released a tool for quantifying project impacts to streams, which would also be used to calculate mitigation requirements, and stream mitigation is therefore likely to become standard for development projects. As the largest wetland mitigator in the State of Colorado, CDOT will likely also become the largest stream mitigator as well. It is therefore important for CDOT to have a voice in the stream mitigation conversation, as well as be proactive in planning for stream mitigation.

Measuring ET and understanding how each component of evapotranspiration contributes to total water loss is an ongoing challenge, and current methodologies do not allow for accurate total ET measurements in small wetlands adjacent to open water (Stoy et al. 2019). Thus, partitioning ET into evaporation and transpiration is the best option to understand system water-use. Quantifying transpiration of wetland plant communities is the critical step in accurately allocating water rights for restoration projects. Plant communities can often be designed and managed, enabling measurement and control of wetland transpiration.

The primary objective of this study is to investigate whether wetland species composition affects wetland water consumption. Evaluating which wetland community types use the most water can help identify plant communities to prioritize when water loss must be minimized.

**Study Site Description**

The Front Range is a semi-arid grassland in the South Platte River basin and is characterized by rapid population growth. Wetlands are a rare and critical ecosystem in the Front Range; while only 2% of its land area is wetland, over 80% of wildlife in the area rely on wetlands for habitat, food, and nesting (Culver et al. 2013). Due to the regional aridity, wetlands primarily establish adjacent to bodies of water, including rivers and lakes. The wetland types most common in this region are marshes, existing as either small depressional features or along the banks of lakes and reservoirs, and riparian wetlands.

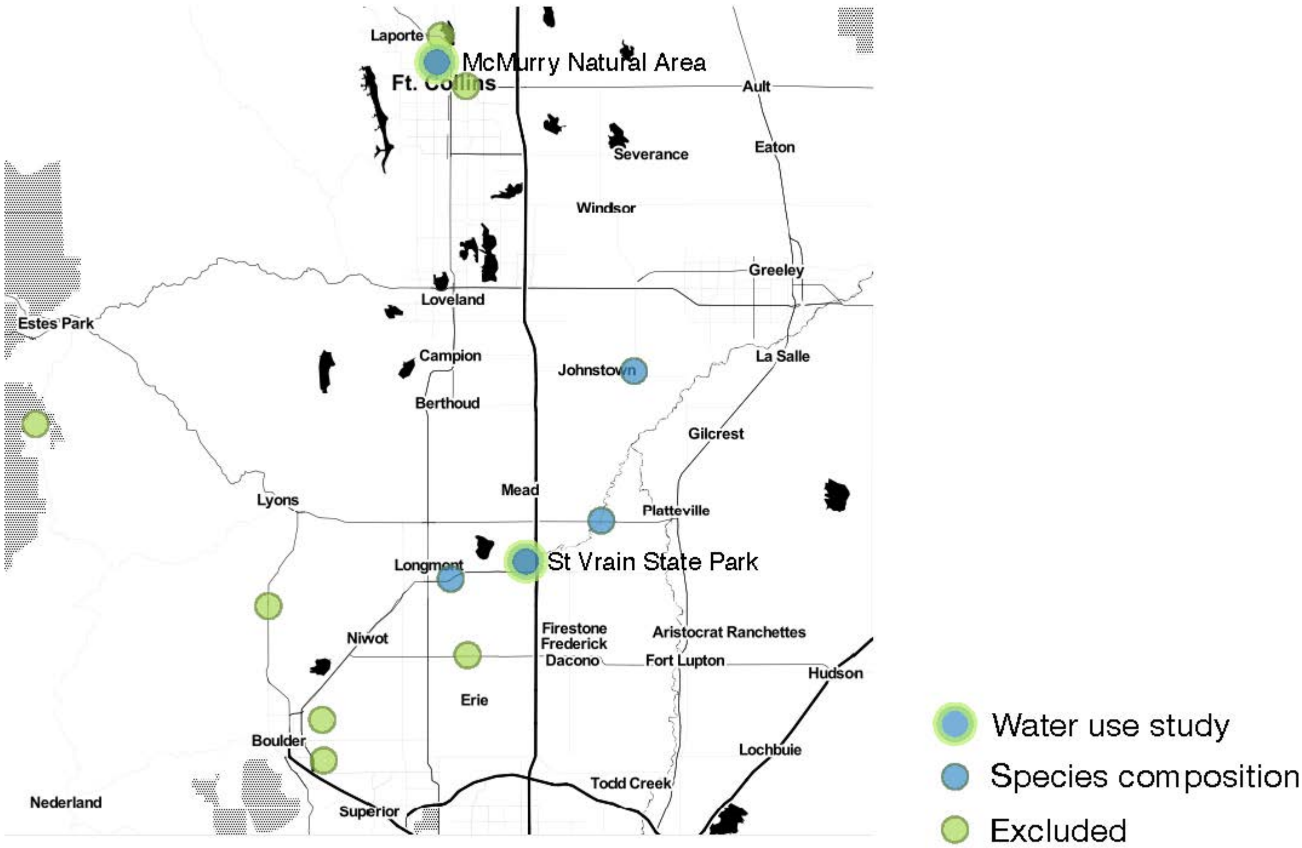


***Figure 1: Map of study sites. Of all the mitigation sites provided by CDOT, five sites were selected for this study. Species composition was recorded from five sites, which were similar in elevation, appeared to have natural hydrology, and were biodiverse enough to contain more than two dominant plant species.***

**Figure 2: a riparian wetland along St. Vrain Creek at state highway 119 is dominated by *S. exigua* and *P. arundinacea.* The wetland restoration area extended on both sides of the overpass.**

We selected 5 mitigation wetland sites to quantify species composition and 2 sites to make detailed water-use measurements. Sites were selected from a list of CDOT wetland restoration projects in the Front Range that received compensatory mitigation credits (Figure 1). These sites were within 2 hours driving of Fort Collins, between 4,500 and 6,000 feet in elevation, a minimum of 1 acre, and were restored between 2007 and 2015. During the growing season of 2021, percent vegetative canopy cover was estimated for each site.

Two of these sites were also selected to test hypotheses about plant water-use strategies: McMurry Natural Area (“McMurry”) and St. Vrain State Park Terrace site (“St. Vrain”). These sites were selected due to similar wetland types, species composition and establishment year. McMurry is in northern Fort Collins, CO along the fringe of ponds created from gravel mining operations in the floodplain of the Cache la Poudre River. Initial mitigation of the 1.5 acres began in 2013 and was re-graded and re-planted in 2014 after destructive floods (Roth 2020). The restored wetlands at McMurry are a pond fringe and a depression along an outflow stream connecting to the Cache la

Poudre River. The wetlands contain willow thickets, young cottonwoods, wet meadow with some willow, and cattail/bulrush marshes. The St. Vrain site is located in Firestone, CO adjacent to St. Vrain Creek. The 6 acre depressional wetland for this mitigation project was created through excavation in 2014 and officially completed in 2016 (Roth 2019). The wetland is separated from St. Vrain Creek by a berm, connected to the creek via groundwater, and contains willow thickets, wet meadows, and cattail marshes.

**Methods**

*Species selection*

Species percent cover data was estimated using Line-Point Intercept (LPI) methods as defined in the BLM draft AIM wetland protocol to obtain percent cover (Reynolds et al. 2021). Three transects were randomly placed within each wetland, with a pin dropped every half meter along the transect (n=50 per transect). At each pin drop, every species that the pin touched was recorded as a “hit.” If the canopy extended above the pin, any hits above the pin were estimated by eye and recorded. Ground cover (soil, rock, moss, water) was also recorded (Figure 3).

**Figure 3: Field data collection.**

Five focal species were selected for evaluating plant-water use strategies, representing the most abundant species in the study system (Table 1), including *Salix exigua* (Coyote Willow), *Populus deltoides* (Plains Cottonwood), *Typha latifolia.* (Cattail), *Phalaris arundinacea* (Reed Canarygrass), and *Carex emoryi* (Emory Sedge). *S. exigua* has one of the largest ranges of any North American willow and is abundant in riparian areas and wetlands across Colorado. *P. deltoides* is a common tree species in riparian areas, mostly occurring in the plains. Both species provide critical habitat for wildlife. *T. latifolia* is a widespread plant that grows in slow-moving or still water and tolerates poor soil and low oxygen conditions. It provides food for many species, from waterfowl to ungulates. *P. arundinacea* is a vigorous grower which will outcompete many other herbaceous species and is broadly considered invasive, as its invasion fundamentally alters community composition and results in negative effects for species from multiple taxa (Lavergne and Molofsky 2004; Annen, Kirsch, and Tyser 2008; Spyreas et al. 2010). *C. emoryi* is a native sedge. It is common in riparian areas and lake or pond fringes and provides nesting cover for waterfowl and rodents.

*Water-use Measurements*

Daily water-use of the five species was measured monthly through the growing season on June 2, June 4, July 8, July 10, and August 8 and 9. The LI-600 porometer (LI-COR Environment, Lincoln, NE, USA) was used to measure transpiration (mmol $m^{-2}$ $s^{-1}$) and stomatal conductance (mol $m^{-2}$ $s^{-1}$). The LI-600 measures transpiration as a function of leaf area, air flow rate ( μmol $s^{-1}$), and the water vapor concentration in the air and in the leaf (mmol $H_2O$ $mol_{air}^{-1}$).


**Figure 4: Measuring stomatal conductance with the LI-600 (LICOR Environment, Lincoln, USA) on a *P. deltoides* leaf. The handheld instrument simultaneously records leaf and air vapor pressure deficit, leaf and air temperature, and solar radiation.**

Stomatal conductance was measured in-situ on fully-grown, healthy leaves randomly selected across the entire site area (Figure 4). Because stomatal conductance changes throughout the day, measurements were taken every 1.5 hours for each focal species (n=5 per species) across a 14-hour period beginning just before dawn. Each measurement took 3 –5 seconds, enabling 5 repetitions per species per time point.

*Estimating Wetland Water Loss*

To estimate community-level transpiration, I combined estimates of daily water-use and leaf area index (LAI) of each species. Daily transpiration of each species was calculated for each species as the area under the diurnal transpiration curve from each day using a trapezoidal integration method (see Kabenge and Irmak 2012). Each daily transpiration estimate (mmol $m^{-2}$ $d^{-1}$) was scaled to ground area by multiplying daily transpiration by the species' LAI.

LAI was calculated using light intensity measurements taken in August at McMurry Natural Area. LAI measurements were taken with a pyranometer and light meter (LI-200R and LI-250A, LI-COR Environment, Lincoln, NE, USA) above and below the canopy of each study species (n=10 per canopy). These measurements were then used in the Beer-Lambert law, solved for L, to calculate LAI:

$$L = \frac{ln\left(\frac{I}{I_o}\right)}{-k}$$

where $I$ is the incident radiation below the canopy of interest, $I_o$ is the incident radiation above the canopy of interest, $k$ is an extinction coefficient pulled from estimates in literature, and L is leaf area index.

K-coefficients were pulled from literature from a search of studies that directly measured LAI (Nagler 2004; Williams et al. 2017). K-coefficients were not available for all species in this study, and so proxy species of similar function and form were used as necessary. Table 1 shows the study species, the proxy species (as necessary), and k-coefficients. LAI estimates for each species were multiplied by daily transpiration to scale to ground area. I then used the August LAI of each species to convert leaf-level transpiration estimates to transpiration per unit ground area using species-specific LAI. LAI values ranged from 1.13 (*T. latifolia*) to 3.15 (*P. arundinacea)*. *P. deltoides* and *S. exigua* k-coefficients were taken from a study with similar species in a semi-arid riparian environment.

| **Study species** | **Species in literature** | **K** | **LAI** |
|---|---|---|---|
| *P. arundinacea* | *P. arundinacea* | 0.75 | 3.15 |
| *S. exigua* | *Salix gooddingii* | 0.6 | 2.68 |
| *P. deltoides* | *Populus fremontii* | 1.25 | 1.71 |
| *C. emoryi* | *Carex atherodes* | 0.8 | 1.54 |
| *T. latifolia* | *T. latifolia* | 0.83 | 1.13 |

**Table 1: k-coefficients and proxy species (as necessary), and LAI values.**

## Results

*Species composition differs across sites*

Across sites, the five most abundant species were *S. exigua*, *P. deltoides*, *T. latifolia*, *P. arundinacea*, and *C. emoryi*. Because fifty-nine unique species were identified, not all are included in Figure 4. A list of all identified species and their abundance at each site can be found in the Appendix (table A1). For the purpose of visualization, species are grouped into the following categories in Figure 5:

- Cattail (*Typha* species);
- Grass (including *P. arundinacea, Polypogon monspeliensis,* and *Poa palustris*);
- Forb (all dicot forbs, including but not limited to *Cirsium arvensis*, *Verbena hastata,* and *Lycopus asper*);
- Rush (including *Juncus balticus, J. gerardii,* and *J. torreyi*);

- Sedge (including *C. emoryi, C. scoparia,* and *Eleocharis palustris*);
- Tree (*Populus deltoides* and *Gleditsia triacanthos*); and
- Willow (*S. exigua, S. fragilis, and S. ligulifolia*).

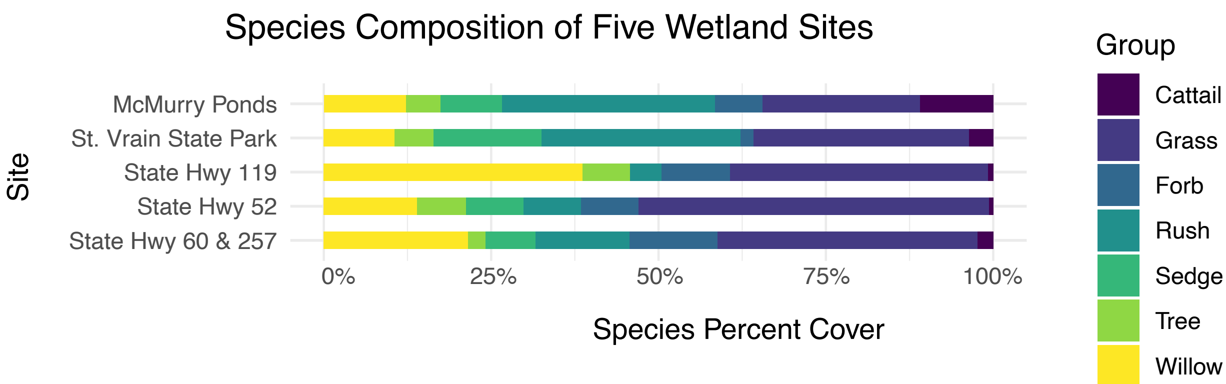


**Figure 5: Species composition of wetland sites by functional group. Most sites are dominated by grass and rush species and have more willow canopy than tree (non-willow woody species) cover. For complete species composition data, see Appendix (table A1).**

Together, grasses, rushes, and sedges comprised over 50% of sites. The site with the most grass species was State Highway 52, a riparian site with little tree and shrub cover. Willows were common at most sites, though their presence ranged from 10% cover at St. Vrain State Park to 33% cover at State Highway 119 (Figure 5).

*P. arundinacea* and *S. exigua* were the most abundant species across all sites. *S. exigua* is a shrubby willow native to the Colorado plains and generally considered beneficial for habitat, food, and bank stabilization. *P. arundinacea* is a perennial grass which dominates wetlands across North America and is broadly considered invasive and has been found to negatively impact plant communities by reducing biodiversity (Werner and Zedler 2002; Foster and Wetzel 2005).

The sites at State Highway 119 and State Highway 60 & 257 were both heavily dominated by *P. arundinacea* and *S. exigua*. Both sites were riparian. The dominance of *P. arundinacea* at these sites is not surprising, as I observed large sediment deposits in spring 2021 and 2022, and *P. arundinacea* commonly outcompetes other plant communities in sediment deposits (Maurer et al. 2003). *S. exigua* also readily establishes in riparian zones, regardless of whether it was intentionally planted. Given the similarity in species composition between the two riparian sites, I would have also expected State Highway 52 to have similar species composition. Instead, it had a diverse wet meadow community on the north side of the site between a berm and an upland. Water level differences may have played a role in species differences.

The sites with a more diverse species list were McMurry Natural Area, St. Vrain State Park, and State Highway 52. These sites do not share many common characteristics in terms of hydrology or construction; McMurry is a pond fringe site with 5 separate wetland areas ranging from 0.02 acres – 0.76 acres in size, and predominantly features wet meadow and willow. Its soils are a mix of sand, clay, and cobble. McMurry received significant sediment deposition after flooding in 2012 and was re-graded and re-planted. The site's topography is mostly homogenous and gently slopes up from the ponds. St. Vrain is a 6-acre depressional wetland that is separated from St. Vrain Creek by a berm, and predominantly features wet meadow, cattail marsh, and willow. Its soils are predominantly clay. Microtopography was a key feature during its construction, with approximately 6-inch troughs installed across the depression to provide niches to different species. The depression features a low-lying cattail marsh, surrounded by slightly dryer wet meadows and willow thickets. Lastly, State Highway 52 is a narrow riparian wetland abutting Boulder Creek totaling 0.51 acres. Boulder Creek floods the wetland seasonally when snow runoff peaks. Its soils are predominantly sand and cobble, with pockets of clay in depressions. The topography of this site varies the most of the three due to its narrow area; it is comprised of low river fringe, wet depressions, and a sloping transition from wetland to upland. Given their differences in restoration type and site history, little can be concluded about why these three sites supported more biodiversity than the others.

*Transpiration differs between species*

In this study, the focal species transpired different amounts of water. *S. exigua* (Coyote Willow) lost the most water through transpiration – 325,000 gallons per acre per month – while *T. latifolia* (Cattail) and *P. deltoides* (Plains Cottonwood) lost the least (Figure 6). Water losses from *P. arundinacea* (Reed Canarygrass) and *C. emoryi* (Emory Sedge) were between these. This study was conducted across two sites, and species lost similar amounts of water at both sites despite differences in soil type and groundwater flow.

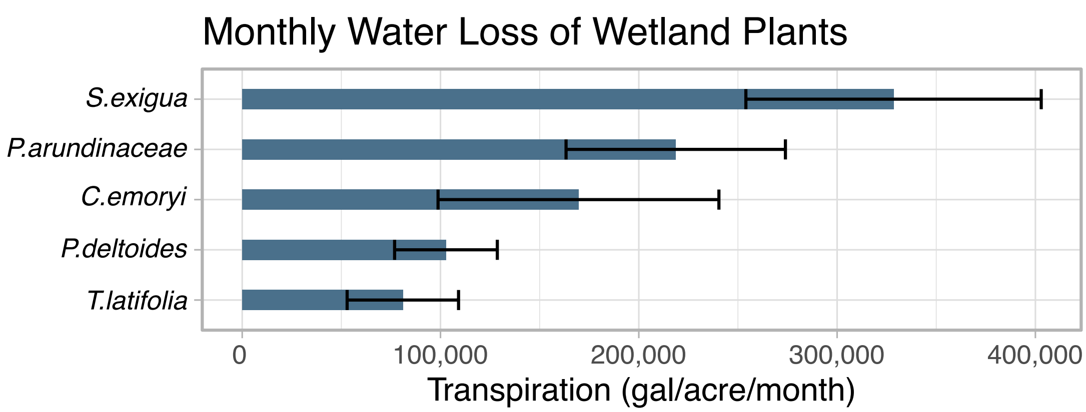


**Figure 6: Transpiration for each species in gallons per acre and scaled to one month using measurements from June through August. Confidence intervals indicate that S. exigua is significantly higher in transpiration than C. emoryi, P. deltoides, and T. latifolia.**

*S. exigua* transpired the most at the leaf level AND at the site level, despite having less total leaf area than *P. arundinacea. P. arundinacea* was the second highest in water loss, which can be attributed to its high total leaf area. *C. emoryi* had mid-level water loss, with higher variability in water loss over time than other species. This is consistent with other *C. emoryi* measurements, which also had significant variability between individuals. *P. deltoides* and *T. latifolia* were very similar in terms of low water loss through transpiration. While old *P. deltoides* has a reputation for high water loss, young *P. deltoides* had a low total leaf area, contributing to its low water loss in this study. *T. latifolia* also had less total leaf area than other species.

These data can be scaled to theoretical water loss for wetlands with different species composition (Figure 7). Sites with more *S. exigua* and *P. arundinacea* lose more water through transpiration than other sites, while marshes of *T. latifolia* lose less water. Figure 7 demonstrates how species with high water-use, like *P. arundinacea* and *S. exigua*, drive overall wetland transpiration. ***Communities with an even balance of species have a median transpiration, meaning that more biodiverse wetlands lose less water to transpiration than wetlands than communities solely comprised of plants with high water-use rates.*** Wet meadows, partly by nature of having less leaf mass, tend to use less water than willow sites or sites with all study species. Considering that it is difficult to establish wet meadows in wetlands dominated by *P. arundinacea* (Green and Galatowitsch 2001; Werner and Zedler 2002), minimizing *P. arundinacea*'s presence is important to minimizing site water use. *P. arundinacea* has much higher water use than native wet meadow species like *C. emoryi*, and once *P. arundinacea* is present, it is difficult to mitigate its spread. Invasion by high water-use plants can significantly increase wetland plant water-use.

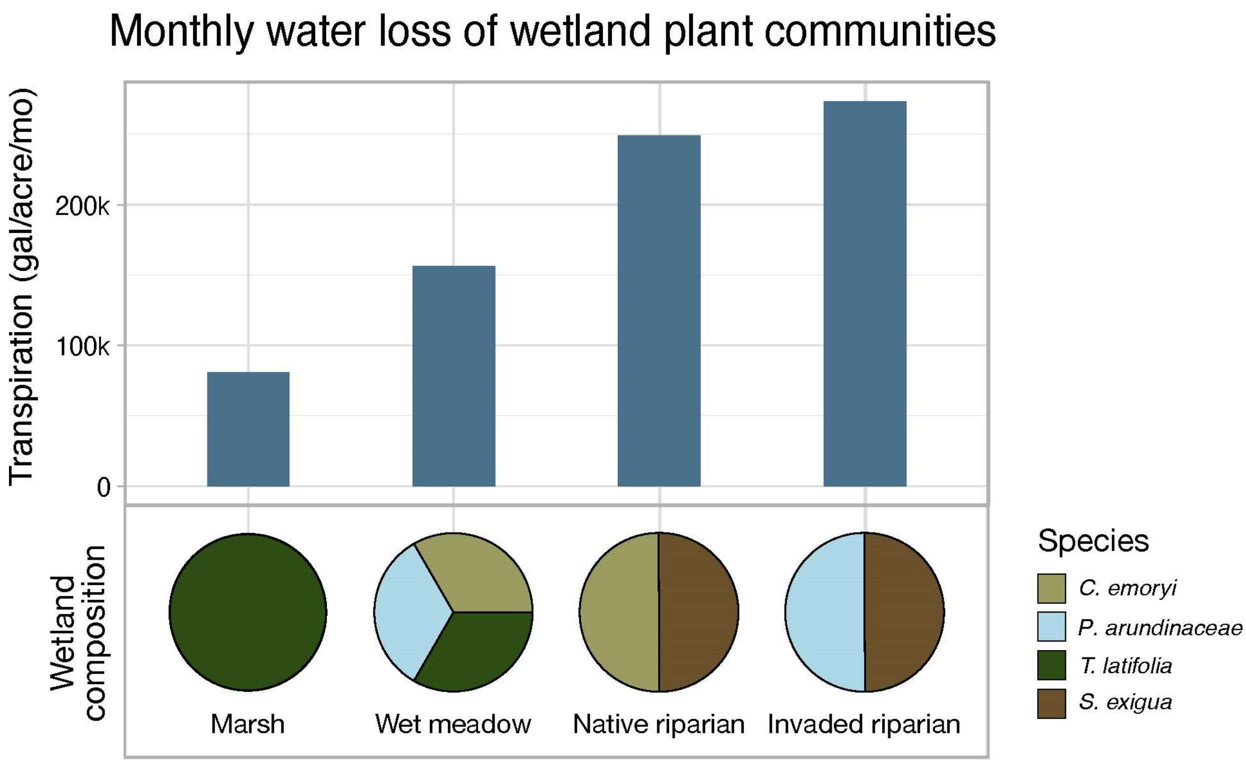


**Figure 7: Transpiration for different wetland communities in gallons per acre (using average values across the summer) and scaled to one month. Wetland plant community composition is shown with the pie charts along the x axis for the following communities: cattail marsh, wet meadow, native riparian, and invaded riparian.**

*Water-use implications for restoring in-kind and with a watershed approach*

"In-kind" restoration was first introduced in federal wetlands restoration policy in the Water Resources Development Act of 2000 for bottomland hardwood forests (Ungaro, BenDor, and Riggsbee 2022). In the context of wetland mitigation, in-kind restoration restores or creates wetlands that are as similar as possible to wetlands that are drained, filled or otherwise affected by development and construction ("impacted wetlands"). In terms of plant water loss, in-kind restoration would enable matching the water loss profiles from impacted site to restored site. ***These results demonstrate that species transpire similar amounts of water regardless of site or location. Thus, transpiration between impacted and restored sites will be similar so long as the species composition is also similar.***

However, watershed approaches to restoration are increasing in popularity as they prioritize enhancing the ecological benefits of restoration projects. The principle behind a watershed approach is to consider watershed needs and characteristics for restoration projects and to restore a wetland of high value for the watershed. In Colorado, a watershed approach has been implemented in the Colorado Water Plan of

2015 and the Colorado Wetland Program for 2020-2024. The Colorado Water Plan (2015) states a purpose to “protect and restore watersheds critical to water infrastructure, environmental or recreational areas” and “work on creating resilient watersheds to protect, restore, and enhance water quality in the face of climate change (Colorado Water Conservation Board 2015). The Colorado Wetland Program for 2020-2024, which was developed across many partner restoration organizations, prioritizes watershed-scale planning and restoration for stream and wetland work (Marshall and Lemly 2020).

If applying a watershed approach to wetland restoration, there is a possibility of increasing overall water loss through transpiration, which should be weighed against the many ecological benefits of a watershed approach. For example, cattails transpired the least of all species in this study. If a cattail marsh is impacted and requires compensatory mitigation, a watershed approach might encourage restoring a wetland with higher ecological value such as a wet meadow or riparian willow shrubland. This approach would provide many ecological benefits but would likely increase watershed water-use. Understanding the water-use profile of different wetland plant communities is therefore an important decision-making tool for restoration managers.

**Conclusion and Recommendations to Managers**

When water-use is an important restoration project consideration, the following recommendations will improve budgeting for plant transpiration and water-use:

*Recommendation 1: To ensure plant community transpiration is not higher at restored wetlands, balance species composition between impacted and restored sites.*

In this study, species had similar water-use rates at two different wetlands, showing that location alone does not affect plant water-use rates. Thus, a simple method to balance plant water-use budgets between sites is to also balance species composition. For example, if the two wetlands have similar percentages of cattails, grasses, willow shrubs, and trees, the plant water-use would likely be similar for both wetlands. If using this approach, it is not necessary to measure the water-use of every species, as these results suggest that water-use rates of wetland species across functional groups do not differ across sites.

*Recommendation 2: When employing a watershed approach to restoration, consider the water-use impact of planting species with high water-use rates.*

Watershed approaches to restoration are intended to improve the health and quality of the entire watershed. High water-use plants may provide significant ecological value but should be carefully considered in watershed restoration plans if water conservation is a project concern. Planting managers could theoretically reduce the water-use impact of restoration by substituting high water-use species with lower water-use species that fill the same functional niche.

*Recommendation 3: Maximize planting biodiversity to lessen the impact of plants transpiring at high rates.*

Mathematically, high biodiversity ensures a wetland plant community with a wide range of water-use. Even among the five species in this study, a site with all five wetland plants had median water-use, which was 125,000 gallons/acre/month less than a site of all *S. exigua* or a mix of *S. exigua* and *P. arundinacea*. Maximizing the biodiversity of a wetland restoration site results in the median theoretical water-use, in effect mitigating for the high water-use of certain species.

The two highest water-use species were *S. exigua* and *P. arundinacea. S. exigua* is a native shrub providing benefits to multiple taxa, including food and habitat for wildlife and pollutant uptake for humans (Franks, Pearce, and Rood 2019). It is also frequently used in restoration for bank stabilization, critical to enabling the establishment of other desired plant communities (Laub, Detlor, and Keller 2020). Its high water-use should not determine its inclusion in restoration plantings, though if overall wetland water loss is of high concern, other functionally similar shrubs could be included to reduce the impact of *S. exigua*. On the other hand, invasions by *P. arundinacea* should be avoided if possible. *P. arundinacea* will increase the water-use of a site due to its rapid growth and ability to outcompete native wet meadow species. When seeking to reduce wetland evapotranspiration, *P. arundinacea* presence should be minimized.

*Recommendation 4: Invest in future water-use studies.*

Considering that this research showed a wide range of water-use among species, it will be important to consider additional species, particularly other dominant wetland species. Future research should test variation across additional sites to determine whether intraspecific variation exists across ranges and elevations. Pairing field-based water-use studies with greenhouse experiments would be useful for determining how transpiration changes under different environmental conditions, such as extreme heat and high vapor pressure deficits.

This study only addressed the “T” of ET and did not address evaporation. More research is needed on how hydrology affects ET, and how constructed hydrology may increase or decrease evaporative wetland water loss. Because current ET methodology cannot reliably and accurately measure small, stream-adjacent wetlands as a whole (Drexler et al. 2004; Kool et al. 2014; Ellsäßer et al. 2020), studying evaporation and transpiration separately is likely the best path forward to quantifying ET in restored wetlands.

Another possibility for measuring ET in these wetlands is to experiment with remote sensing models. There have been many recent advances in calculating ET using remote sensing; one such model is OpenET, which was developed to quantify agricultural ET with satellite imagery. It is limited in its usability with small wetlands, as it cannot reliably estimate ET adjacent to open water and its resolution is approximately 30 ft x 30 ft – meaning any wetland that abuts open water or is less than 60 ft wide will suffer from inaccuracy. However, OpenET could likely be adapted for use in small, restored with drone flights and high-resolution thermal cameras. Developing this method would enable large scale analysis of different types of wetlands in Colorado, setting up the researcher to analyze the effects of elevation, hydrology, soil type, and community composition on ET.

Works Cited


Annen, C. A., E. M. Kirsch, and R. W. Tyser. 2008. “Reed Canarygrass Invasions Alter Succession Patterns and May Reduce Habitat Quality in Wet Meadows.” *Ecological Restoration* 26 (3): 190–93. https://doi.org/10.3368/er.26.3.190

Colorado Water Conservation Board. 2015. “Colorado Water Plan.” https://dnrweblink.state.co.us/CWCB/0/edoc/219188/Colorado_WaterPlan_2023_Digital.pdf.

Culver, Denise R, Joanna M Lemly, United States, Environmental Protection Agency, Region VIII, and Colorado Natural Heritage Program. 2013. *Field Guide to Colorado’s Wetland Plants: Identification, Ecology and Conservation*. Fort Collins, Colo.: Colorado Natural Heritage Program.

Drexler, Judy Z., Richard L. Snyder, Donatella Spano, and Kyaw Tha Paw U. 2004. “A Review of Models and Micrometeorological Methods Used to Estimate Wetland Evapotranspiration.” *Hydrological Processes* 18 (11): 2071–2101. https://doi.org/10.1002/hyp.1462.

Ellsäßer, Florian, Alexander Röll, Christian Stiegler, Hendrayanto, and Dirk Hölscher. 2020. “Introducing QWaterModel, a QGIS Plugin for Predicting Evapotranspiration from Land Surface Temperatures.” *Environmental Modelling & Software* 130 (August): 104739. https://doi.org/10.1016/j.envsoft.2020.104739.

Foster, Richard D., and Paul R. Wetzel. 2005. “Invading Monotypic Stands of Phalaris Arundinacea: A Test of Fire, Herbicide, and Woody and Herbaceous Native Plant Groups.” *Restoration Ecology* 13 (2): 318–24. https://doi.org/10.1111/j.1526-100X.2005.00040.x.

Franks, Carmen G., David W. Pearce, and Stewart B. Rood. 2019. “A Prescription for Drug-Free Rivers: Uptake of Pharmaceuticals by a Widespread Streamside Willow.” *Environmental Management* 63 (1): 136–47. https://doi.org/10.1007/s00267-018-1120-8.

Green, Emily K., and Susan M. Galatowitsch. 2001. “Differences in Wetland Plant Community Establishment with Additions of Nitrate-N and Invasive Species (*Phalaris Arundinacea* and *Typha ×Glauca*).” *Canadian Journal of Botany* 79 (2): 170–78. https://doi.org/10.1139/cjb-79-2-170.

Kabenge, Isa, and Suat Irmak. 2012. “Evaporative Losses from a Common Reed-dominated Peachleaf Willow and Cottonwood Riparian Plant Community.” *Water Resources Research* 48 (9): 2012WR011902. https://doi.org/10.1029/2012WR011902.

Kool, D., N. Agam, N. Lazarovitch, J.L. Heitman, T.J. Sauer, and A. Ben-Gal. 2014. “A Review of Approaches for Evapotranspiration Partitioning.” *Agricultural and Forest Meteorology* 184 (January): 56–70. https://doi.org/10.1016/j.agrformet.2013.09.003.

Laub, Brian G., Jordon Detlor, and Daniel L. Keller. 2020. “Determining Factors of Cottonwood Planting Survival in a Desert River Restoration Project.” *Restoration Ecology* 28 (S1). https://doi.org/10.1111/rec.13086.

Lavergne, Sébastien, and Jane Molofsky. 2004. “Reed Canary Grass ( *Phalaris Arundinacea* ) as a Biological Model in the Study of Plant Invasions.” *Critical Reviews in Plant Sciences* 23 (5): 415–29. https://doi.org/10.1080/07352680490505934.

Marshall, Sarah, and Joanna Lemly. 2020. “Colorado Wetland Program Plan: 2020-2024.” Colorado Natural Heritage Program. https://cnhp.colostate.edu/download/documents/2020/Colorado-Wetland-Program-Plan-2020-2024.pdf.

Maurer, D. A., R. Lindig-Cisneros, K. J. Werner, S. Kercher, R. Miller, and J. B. Zedler. 2003. “The Replacement of Wetland Vegetation by Reed Canarygrass (Phalaris Arundinacea).” *Ecological Restoration* 21 (2): 116–19. https://doi.org/10.3368/er.21.2.116.

Maxwell, Reed M., and Laura E. Condon. 2016. “Connections between Groundwater Flow and Transpiration Partitioning.” *Science* 353 (6297): 377–80. https://doi.org/10.1126/science.aaf7891.

Maxwell, Reed M., and Stefan J. Kollet. 2008. “Interdependence of Groundwater Dynamics and Land-Energy Feedbacks under Climate Change.” *Nature Geoscience* 1 (10): 665–69. https://doi.org/10.1038/ngeo315.

Nagler, P. 2004. “Leaf Area Index and Normalized Difference Vegetation Index as Predictors of Canopy Characteristics and Light Interception by Riparian Species on the Lower Colorado River.” *Agricultural and Forest Meteorology* 125 (1–2): 1–17. https://doi.org/10.1016/j.agrformet.2004.03.008.

Reynolds, Lindsay, Joanna Lemly, Melissa Dickard, Mark Gonzalez, Steve Smit, Sarah Marshall, Mary Manning, et al. 2021. “AIM National Aquatic Monitoring Framework: Field Protocol for Lentic Riparian and Wetland Systems (2021 Review Draft).” Bureau of Land Management. Technical Reference 1735-X. https://aim.landscapetoolbox.org/wp-content/uploads/2021/02/Jan2021DraftLenticAIMProtocol.pdf.

Roth, Jason. 2019. “North I-25 EIS - Corridor Improvement Project: Wetland Mitigation at St. Vrain State Park, Weld County, CO.” Mitigation Monitoring Report. Year 4. St. Vrain State Park, Weld County, CO: Colorado Department of Transportation.

Roth, Jason. 2020. “CDOT Consolidated Wetland Mitigation at McMurry Natural Area.” Mitigation Monitoring Report Year 5. McMurry Natural Area, Fort Collins, CO: Colorado Department of Transportation.

Spyreas, Greg, Brian W. Wilm, Allen E. Plocher, David M. Ketzner, Jeffrey W. Matthews, James L. Ellis, and Edward J. Heske. 2010. “Biological Consequences of Invasion by Reed Canary Grass (Phalaris Arundinacea).” *Biological Invasions* 12 (5): 1253–67. https://doi.org/10.1007/s10530-009-9544-y.

Ungaro, Matthew, Todd K. BenDor, and J. Adam Riggsbee. 2022. “Prioritizing Streams: The Impacts of in-Kind Mitigation Rules on an Ecosystem Offset Market.” *Environmental Science & Policy* 132 (June): 131–41. https://doi.org/10.1016/j.envsci.2022.02.005.

Werner, Katherine J., and Joy B. Zedler. 2002. “How Sedge Meadow Soils, Microtopography, and Vegetation Respond to Sedimentation.” *Wetlands* 22 (3): 451–66. https://doi.org/10.1672/0277-5212(2002)022[0451:HSMSMA]2.0.CO;2.

Williams, Amber S., James R. Kiniry, David Mushet, Loren M. Smith, Scott McMurry, Kelly Attebury, Megan Lang, et al. 2017. “Model Parameters for Representative Wetland Plant Functional Groups.” *Ecosphere* 8 (10): e01958. https://doi.org/10.1002/ecs2.1958.

Wohl, Ellen, Janine Castro, Brian Cluer, Dorothy Merritts, Paul Powers, Brian Staab, and Colin Thorne. 2021. “Rediscovering, Reevaluating, and Restoring Lost River-Wetland Corridors.” *Frontiers in Earth Science* 9 (June): 653623. https://doi.org/10.3389/feart.2021.653623.

APPENDIX A

*Table A1: Species Composition from Five Wetland Sites*

| Site | Name | Percent |
|---|---|---|
| McMurry Ponds | *Astragalus anisus* | 0.2 |
| McMurry Ponds | *Asclepius incarnata* | 0.2 |
| McMurry Ponds | *Carex atherodes* | 0.2 |
| McMurry Ponds | *Carex emoryi* | 5.1 |
| McMurry Ponds | *Carex nebrascensis* | 0.9 |
| McMurry Ponds | *Carex scoparia* | 2.2 |
| McMurry Ponds | *Carex vulpinoidea* | 0.4 |
| McMurry Ponds | *Cirsium arvensis* | 1.1 |
| McMurry Ponds | *Cymopterus acaulis* | 0.7 |
| McMurry Ponds | *Eleocharis palustris* | 0.9 |
| McMurry Ponds | *Unknown perennial graminoid* | 0.2 |
| McMurry Ponds | *Juncus ensifolius* | 0.2 |
| McMurry Ponds | *Juncus balticus* | 13.6 |
| McMurry Ponds | *Juncus gerardii* | 0.7 |
| McMurry Ponds | *Juncus torreyi* | 0.7 |
| McMurry Ponds | *Lycopus asper* | 0.9 |
| McMurry Ponds | *Mentha arvensis* | 0.7 |
| McMurry Ponds | *Muhlenbergia asperifolia* | 1.3 |
| McMurry Ponds | *Pascopyrum smithi* | 0.9 |
| McMurry Ponds | *Panicum virgatum* | 0.7 |
| McMurry Ponds | *Unknown perennial grass* | 0.7 |
| McMurry Ponds | *Unknown perennial grass* | 0.2 |
| McMurry Ponds | *Phalaris arundinacea* | 14.1 |
| McMurry Ponds | *Populus deltoides* | 4.9 |
| McMurry Ponds | *Polygonum lapathifolium* | 0.2 |
| McMurry Ponds | *Poa leptocoma* | 0.2 |
| McMurry Ponds | *Polypogon monspeliensis* | 3.6 |
| McMurry Ponds | *Poa palustris* | 1.3 |
| McMurry Ponds | *Polygonum ramosissium* | 0.4 |
| McMurry Ponds | *Ribes inerme* | 0.2 |
| McMurry Ponds | *Salix amygdaloides* | 0.2 |
| McMurry Ponds | *Salix exigua* | 10.5 |
| McMurry Ponds | *Salix fragilis* | 1.1 |
| McMurry Ponds | *Salix ligulifolia* | 0.4 |
| McMurry Ponds | *Schoenoplectus pungens* | 0.2 |
| McMurry Ponds | *Schoenoplectus tabernamontanii* | 15.7 |
| McMurry Ponds | *Stipa pinetorum* | 0.9 |
| McMurry Ponds | *Thlaspi arvense* | 0.2 |
| McMurry Ponds | *Typha ssp.* | 11.0 |
| McMurry Ponds | *Verbena hastata* | 1.8 |
| St. Vrain State Park | *Carex atherodes* | 11.4 |
| St. Vrain State Park | *Cirsium arvensis* | 0.8 |
| St. Vrain State Park | *Clover* | 0.3 |
| St. Vrain State Park | *Distichlis spicata* | 7.2 |
| St. Vrain State Park | *Eleocharis palustris* | 5.3 |

| | | |
|---|---|---|
| St. Vrain State Park | *Hordeum jubatum* | 0.6 |
| St. Vrain State Park | *Juncus balticus* | 17.8 |
| St. Vrain State Park | *Juncus gerardii* | 3.6 |
| St. Vrain State Park | *Juncus torreyi* | 2.2 |
| St. Vrain State Park | *Muhlenbergia asperifolia* | 3.6 |
| St. Vrain State Park | *Panicum virgatum* | 6.9 |
| St. Vrain State Park | *Unknown dicot forb* | 0.8 |
| St. Vrain State Park | *Phalaris arundinacea* | 0.6 |
| St. Vrain State Park | *Populus deltoides* | 5.8 |
| St. Vrain State Park | *Poa leptocoma* | 0.3 |
| St. Vrain State Park | *Polypogon monspeliensis* | 10.0 |
| St. Vrain State Park | *Poa palustris* | 3.1 |
| St. Vrain State Park | *Salix exigua* | 8.3 |
| St. Vrain State Park | *Salix fragilis* | 2.2 |
| St. Vrain State Park | *Schoenoplectus pungens* | 4.7 |
| St. Vrain State Park | *Schoenoplectus tabernamontanii* | 0.8 |
| St. Vrain State Park | *Typha ssp.* | 3.6 |
| State Hwy 119 | *Agrostis idahoensis* | 1.6 |
| State Hwy 119 | *Carduus nutans* | 0.8 |
| State Hwy 119 | *Cirsium arvensis* | 1.6 |
| State Hwy 119 | *Eleocharis palustris* | 3.9 |
| State Hwy 119 | *Gleditsia triacanthos* | 3.1 |
| State Hwy 119 | *Juncus balticus* | 0.8 |
| State Hwy 119 | *Gleditsia triacanthos* | 0.8 |
| State Hwy 119 | *Unknown perennial grass* | 0.8 |
| State Hwy 119 | *Unknown perennial grass* | 0.8 |
| State Hwy 119 | *Phalaris arundinacea* | 36.2 |
| State Hwy 119 | *Populus deltoides* | 2.4 |
| State Hwy 119 | *Polygonum lapathifolium* | 3.9 |
| State Hwy 119 | *Poa palustris* | 0.8 |
| State Hwy 119 | *Ribes inerme* | 1.6 |
| State Hwy 119 | *Salix exigua* | 37.0 |
| State Hwy 119 | *Salix ligulifolia* | 1.6 |
| State Hwy 119 | *Sagittaria cuneata* | 1.6 |
| State Hwy 119 | *Typha ssp.* | 0.8 |
| State Hwy 52 | *Carex emoryi* | 1.3 |
| State Hwy 52 | *Eleocharis palustris* | 2.6 |
| State Hwy 52 | *Juncus balticus* | 1.3 |
| State Hwy 52 | *Juncus torreyi* | 3.3 |
| State Hwy 52 | *Mentha arvensis* | 4.6 |
| State Hwy 52 | *Muhlenbergia asperifolia* | 5.3 |
| State Hwy 52 | *Panicum virgatum* | 3.3 |
| State Hwy 52 | *Phalaris arundinacea* | 18.5 |
| State Hwy 52 | *Populus deltoides* | 7.3 |
| State Hwy 52 | *Polygonum lapathifolium* | 2.6 |
| State Hwy 52 | *Polypogon monspeliensis* | 23.2 |
| State Hwy 52 | *Poa palustris* | 2.0 |
| State Hwy 52 | *Rumex crispus* | 0.7 |
| State Hwy 52 | *Salix exigua* | 13.2 |

| | | |
|---|---|---|
| State Hwy 52 | *Salix fragilis* | 0.7 |
| State Hwy 52 | *Schoenoplectus pungens* | 7.3 |
| State Hwy 52 | *Schoenoplectus tabernamontanii* | 1.3 |
| State Hwy 52 | *Typha ssp.* | 0.7 |
| State Hwy 52 | *Verbena hastata* | 0.7 |
| State Hwy 60 & 257 | *Astragalus anisus* | 3.0 |
| State Hwy 60 & 257 | *Carex atherodes* | 1.4 |
| State Hwy 60 & 257 | *Carex emoryi* | 3.3 |
| State Hwy 60 & 257 | *Carex nebrascensis* | 1.6 |
| State Hwy 60 & 257 | *Carex scoparia* | 0.2 |
| State Hwy 60 & 257 | *Carex vulpinoidea* | 0.7 |
| State Hwy 60 & 257 | *Cirsium arvensis* | 5.2 |
| State Hwy 60 & 257 | *Cymopterus acaulis* | 0.5 |
| State Hwy 60 & 257 | *Eleocharis elongata* | 0.5 |
| State Hwy 60 & 257 | *Eleocharis palustris* | 4.2 |
| State Hwy 60 & 257 | *Helianthus nuttalli* | 0.7 |
| State Hwy 60 & 257 | *Juncus balticus* | 7.0 |
| State Hwy 60 & 257 | *Juncus torreyi* | 0.2 |
| State Hwy 60 & 257 | *Unknown forb (legume?)* | 0.5 |
| State Hwy 60 & 257 | *Unknown dicot forb* | 0.7 |
| State Hwy 60 & 257 | *Mentha arvensis* | 0.5 |
| State Hwy 60 & 257 | *Mentha officinalis* | 0.2 |
| State Hwy 60 & 257 | *Muhlenbergia asperifolia* | 1.4 |
| State Hwy 60 & 257 | *Pascopyrum smithi* | 1.6 |
| State Hwy 60 & 257 | *Panicum virgatum* | 1.9 |
| State Hwy 60 & 257 | *Phalaris arundinacea* | 29.0 |
| State Hwy 60 & 257 | *Populus deltoides* | 1.9 |
| State Hwy 60 & 257 | *Polypogon monspeliensis* | 3.5 |
| State Hwy 60 & 257 | *Poa palustris* | 1.4 |
| State Hwy 60 & 257 | *Rumex crispus* | 1.6 |
| State Hwy 60 & 257 | *Salix exigua* | 20.8 |
| State Hwy 60 & 257 | *Salix fragilis* | 0.2 |
| State Hwy 60 & 257 | *Salix ligulifolia* | 0.5 |
| State Hwy 60 & 257 | *Schoenoplectus pungens* | 0.2 |
| State Hwy 60 & 257 | *Schoenoplectus tabernamontanii* | 2.1 |
| State Hwy 60 & 257 | *Symphoricarpos albus* | 0.7 |
| State Hwy 60 & 257 | *Typha ssp.* | 2.3 |
| State Hwy 60 & 257 | *Verbena hastata* | 0.2 |