THESIS

DOWNSTREAM EFFECTS OF DIVERSION DAMS ON RIPARIAN VEGETATION COMMUNITIES IN THE ROUTT NATIONAL FOREST, COLORADO

Submitted by

Simeon Tadgerson Caskey

Department of Geosciences

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Master's Committee:

Advisor: Ellen Wohl

Sara Rathburn
Brian Bledsoe
David Merritt

ABSTRACT

DOWNSTREAM EFFECTS OF DIVERSION DAMS ON RIPARIAN VEGETATION COMMUNITIES IN THE ROUTT NATIONAL FOREST, COLORADO

Diversions are ubiquitous throughout the American west, with over 68000 known in Colorado alone. Diversions vary greatly in their structure and ability to extract water, but overall they can alter important components of the flow regime, affecting the magnitude and duration of baseflows and flooding. Riparian plant communities have adapted to unique hydrologic and geomorphic conditions existing in the areas subject to fluvial processes. My study used vegetation and geomorphic data from low-gradient (≤3%) streams, in the Rocky Mountains of north-central Colorado, above 2440 m. Data were collected at 32 reaches, totaling 16 paired upstream and downstream sites, to infer the impact of diversion-induced flow alteration on riparian vegetation communities. Vegetation data were collected using the line-point intercept method along transects oriented perpendicular to the channel, from bankfull to 5-10 meters away, totaling 100 sampling points per reach. Topographic data were associated with each sampling point, to analyze differences in lateral and vertical zonation of communities between upstream and downstream reaches. Vegetation data were analyzed using traditional biological diversity metrics, richness, evenness and diversity, as well as multivariate community analysis using ANOSIM, MRPP, and permanova. Across all data points, field observations indicate evenness increased downstream from diversions, through decreased frequency of hydrophytic, wetland indicator functional species groupings, and increase in frequency of several upland indicator species. Regarding elevation, immediately above the channel no differences were observed between communities, but at 1 m above the channel increase in upland species and decrease in wetland species downstream of diversion became apparent. Logistic regression supports this, indicating probability of occurrence for upland species downstream of diversion increases at a greater rate beginning around 0.5 m above active channel. Related to distance, nearest the channel no compositional differences were observed, but with increasing distance from channel decreased wetland and increased upland species relative frequency were observed downstream of diversion. Fluvial surface analyses, which are related to distinct hydrologic and geomorphic processes, also indicated composition shift as a function of diversion. Floodplains had significantly lower relative frequency of wetland species grouping, whereas low terraces had both increased upland and decreased wetland species relative frequency downstream of diversion. The findings of my study imply that riparian plant communities along low-gradient reaches in montane environments in the Rocky Mountains of Colorado are being impacted by diversion-induced flow alteration, in general having a reduced frequency of hydrophytic, wetland species, and encroachment of non-hydrophytic, upland species.

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1. INTRODUCTION

The link between fluvial process and riparian vegetation in the context of flow diversion is not well understood. Diversions extract water, which affects the flow regime, altering the magnitude, duration and frequency of flows (Poff et al. 1997). The dominant change resulting from diversion is a change in water availability, through reduction in peak flow and base flow, which could negatively impact the riparian vegetation (Hupp and Osterkamp 1996). Bottom land vegetation communities change over space and time, as dictated by environmental factors, and are strongly interrelated with streamflow variability and magnitude, and alluvial landforms (Osterkamp and Hupp 2010). Several studies have attempted to quantify morphological and in-stream sedimentation effects of diversions, and found it difficult to detect changes downstream of diversion points; however, these studies showed greater response in low-gradient reaches (Wesche and Skinner 1988; Ryan 1997; Baker et al. 2011). With the exception of Smith et al. (1991), Bohn and King (2000) and Stromberg and Patten (1990) very little work has been conducted on the impacts of streamflow diversion on riparian vegetation communities, and none in the Rocky Mountains. Therefore, extrapolations regarding the relationships between fluvial processes and vegetation in the context of flow diversions may not be valid or useful for watershed management along small headwater streams of the Inter-mountain West.

This thesis is part of a larger effort to develop an Environmental Flow Strategy for the Routt National Forest (Routt). This strategy will develop a framework using environmental flow protection mechanisms to manage water rights and meet objectives of the Federal Land Policy Management Act of 1976 (FLPMA). The strategy aims to develop standards for minimum environmental flows through understanding how flow alterations influence a range of different fluvial components, including; geomorphic, biologic, riparian and water quality of flows. Systematic investigation into these different aspects of the stream system will provide land managers of basins not yet fully appropriated with the ability to make informed decisions regarding water development proposals, identify sensitive systems or communities and act accordingly. Specifically, this thesis is designed to support the larger effort through assessing the potential effects of flow diversions on low gradient valley segments of headwater streams on the Routt, where headwaters are defined as having a stream order of 3 or less, as well as high snow accumulation in winter and rainstorms in summer.

The following portion of the introduction will provide additional background on the characteristics of headwater streams, water management in the West, geomorphology, riparian vegetation communities, and diversions, and then conclude with a statement of the objectives and hypotheses of my thesis.

2. BACKGROUND

In the mountainous West, water extractions in headwater streams have the potential to alter instream and floodplain processes and biotic communities. This thesis examines physical channel and valley characteristics, hydrology, diversion history and riparian communities in the Routt, with a focus on comparing riparian community characteristics on diverted and undiverted pool-riffle channels and low gradient valleys to examine changes associated with flow diversion. Located in the headwaters of the Colorado and Platte River systems, the Routt spans both sides of the continental divide and lies almost entirely above 2,400 m. The Routt is the only area in Colorado where rivers are not yet fully appropriated, making future water extraction proposals likely. Many small extraction canals siphon water from small, headwater streams in the Routt, but the site-specific or cumulative effects of these diversions on riverine ecosystems have not been investigated. It is possible that the lower gradient riparian communities dominated by willows and other hydric species will show little alteration in response to flow diversions, analogous to a recent study demonstrating minimal effects of flow augmentation in such streams (David et al. 2009). Systematic investigation is necessary, however, to determine whether existing flow diversions have influenced riparian communities and, if so, which communities are most sensitive to diversions. In 1993, a detailed riparian vegetation classification was conducted on the Routt as part of a larger effort to inventory riparian vegetation statewide and inform management decisions (Kettler and McMullen 1996). At present, however, there is no long-term monitoring on the Routt, especially with spatial or temporal relation to water extractions.

2.1 CHARACTERISTICS OF HEADWATER STREAMS

Headwater streams are an important element in the global freshwater system, transporting sediment downstream to floodplains, estuaries and oceans, providing important aquatic and riparian habitat, and maintaining hydrologic connectivity between systems and other important ecosystem services (denitrification, carbon storage, flood control, and habitat and species diversity) (Alexander et al. 2007; Freeman et al. 2007; Meyer et al. 2007). Due to the increasing alteration and fragmentation of river ecosystems worldwide through dams, flow abstractions, and land use change, headwaters are becoming more important for sustaining aquatic and riparian biodiversity. With current freshwater resources being exploited in every system, headwater alteration is occurring and contributing to societal, economic and ecological degradation in downstream systems. Freeman et al. (2007) used examples of downstream eutrophication and coastal hypoxia, lowered secondary productivity of river systems, and reduced viability of freshwater biota to propose that the alteration of headwater ecosystems can change longitudinal exchanges of energy and materials in river segments, eliminating distinctive habitats and potentially decreasing ecological integrity across large spatial scales and, ultimately, causing global losses of biodiversity.

2.1.1 GEOMORPHOLOGY

The morphology of floodplains and channels in mountain drainage basins is controlled by timing, volume and character of sediment supply and capacity, timing and volume of discharge, and governing geomorphology and geology of the basin. In terms of geomorphology, the degree of hillslope coupling, or valley confinement, influences the delivery of sediment to a fluvial system. Geology of the basin also influences sediment input and the hydrologic regime, through erodibility of materials, permeability/porosity/infiltration of bedrock and soils, soil formation and depth to bedrock. Schumm (1977) separated fluvial systems into three major zones; erosion, transport and deposition. This framework provides a broad scale perspective, grouping the upper reaches of a basin with generally steeper channel gradients and higher degrees of hillslope-channel coupling, as the erosional zone. This erosional zone is often associated with the term headwaters, which is defined by a small drainage area near the source of the drainage network.

Headwater, alluvial channels can have a high range of variance in width, lateral confinement, gradient and roughness. These channels can be organized in a process-based framework by steepness, or channel gradient, as a function of sediment transport capacity to supply ratio. Steeper channel reaches, such as cascades or step-pool bedforms, have a high ratio and are less likely to exhibit changes in channel form and process in response to changes in discharge or sediment supply: Montgomery and Buffington (1997) refer to these as transport reaches. Conversely, low-gradient reaches with pool-riffle or plane-bed morphology are more likely to respond to changes in discharge or sediment supply: Montgomery and Buffington (1997) refer to these as response reaches.

2.1.2 DIVERSION-INDUCED FLOW ALTERATION

Anthropogenic disturbances alter river and riparian systems globally, from the headwaters to the ocean. There are major ecological consequences as a result of disturbances that, according to Naiman et al. (2005), can manifest in the form of reduced efficiency of nutrient cycling, increased exotic species dominance, an increase in short-lived opportunistic species, altered productivity and decreased biodiversity (Bunn and Arthington 2002). These human-induced alterations, combined with background natural disturbance regimes, can detrimentally impact river ecosystems. Diversions extract water from the channel, reduce the magnitude, duration and frequency of peak flow, and reduce base flow, potentially increasing terrestrial species in the riparian area. The most pronounced impact of diversions, though, may be the overall reduction in total water discharge throughout the year.

Specific studies have looked at the impacts of diversions on stream characteristics. Kagawa (1992) showed that diversions can alter water chemistry, Englund and Malmqvist (1996) found reduced richness, abundance and diversity of functional feeding groups, and McIntosh et al. (2002) found reduced macroinvertebrate density diversity and individual and total density. McKay and King (2006) experimentally manipulated small, upland, 1st and 2nd order streams in Australia to study the effects of flow diversion on channel morphology, extracting flow during the summer (base flow) months, and found reduced stream wetted area, stream depth and dissolved oxygen concentrations. Investigating impacts to riparian vegetation, Harris et al. (1987) had difficulty detecting difference due to environmental factors, Stromberg and Patten (1990) found reduced growth rates in tree rings and Smith et al. (1991) found reduced stomatal conductance and water potential in response to reduced flows in the eastern Sierra Nevada. This water stress was exacerbated in juveniles, potentially indicating some selective mortality in the downstream populations (Smith et al. 1991).

Rader and Belish (1999) looked at the impacts of diversions on macroinvertebrate communities in headwater, Rocky Mountain streams and found reduced density, diversity and some local extirpation of communities. Ryan (1997) systematically investigated the impacts of flow diversions on Rocky Mountain streams in northern Colorado and saw no change in channel morphology outside of wider, pool-riffle channels (1-3% stream gradient), but observed width reduction of up to 50% in these low-gradient reaches. Bohn and King (2000) found that streams with a gradient less than 1.5% were sensitive to decreased channel capacity, area and depth. Additionally, Baker et al. (2011) showed that fine sediment accumulation and slow-flowing habitats increased downstream of diversions, an effect most prevalent on streams with slope less than 3%. These studies focused solely on physical channel characteristics and, likely because of the location of diversion structures at breaks in gradient and ability to pass high flows, had difficulty detecting significant changes.

2.1.3 RIPARIAN VEGETATION COMMUNITIES

Riparian vegetation communities are an integral component of watersheds and fluvial systems through contributing societal, economic and ecological benefits. Societal and economic benefits include maintenance of water quality in surface and groundwater, aquifer recharge, flood mitigation, recreation, aesthetic value, and sustaining fisheries (Lowrance et al. 1995; NRC 2002). Some ecological benefits include material and energy exchange with the river and upland system through inputs of allochthonous carbon and nutrients, high habitat diversity, habitat for many species, corridors for migrating and dispersing organisms, and filters between terrestrial and aquatic ecosystems (Junk 1997; NRC 2002; McClain et al. 2003; Naiman et al. 2005).

Riparian vegetation communities differ from upland communities because hydrologic and fluvial disturbance regimes are a primary controlling variable. Naiman et al. (2005) stated that riparian zones are shaped by water saturation gradients and biophysical processes driven by water saturation and energy gradients, with biotic communities being arrayed along longitudinal, lateral and vertical gradients. Water saturation gradients are determined by the topography, geologic materials (including soils), fluvial geomorphology and the hydrologic regime of the system. Flooding, erosion, accumulation and reworking of sediment along the channel and floodplain are the main hydrogeomorphic processes associated with the disturbance regime.

The distribution of plants laterally across a valley has been correlated to fluvial and valley landforms that are a result of hydrologic and geomorphic processes (Hupp and Osterkamp 1985; Hupp and Osterkamp 1996; Rot et al. 2000). Many abiotic processes are associated with lateral and vertical distance from the channel, including flow-related mechanical disturbance and the duration, intensity and frequency of floods (Auble et al. 1994; Scott et al. 1996), organic material and litter accumulation (Wilson and Keddy 1985), decreasing anoxia and increasing depth to groundwater (Castelli et al. 2000; Merritt and Cooper 2000). These features include depositional bars, active shelves, floodplains, terraces and hillslopes and are associated with the elevation above the active channel (Figure A.1, Appendix A) (Osterkamp and Hupp 1984).

Specific to the headwaters, Rot et al. (2000) found riparian communities are associated with four landforms (floodplains, low and high terraces, and hillslopes). The former three are alluvial and associated with height above the channel and, therefore, related to flood frequency and inundation. Specifically, the study found that floodplain vegetation communities were significantly different from communities in the other three landforms.

Riparian plants have evolved and adapted to the disturbances of fluvial systems, and Lytle and Poff (2004) demonstrated how particular flow regimes and geomorphic settings exhibit selective pressures on riparian species, which evolved to deal with these conditions through various morphological, life history and phenological adaptations.

2.2 OBJECTIVES AND HYPOTHESES

This thesis is part of a larger project which aims to understand the effects of anthropogenic influence on the Routt to aid in the development of an environmental flow strategy. The purpose of this thesis is to systematically investigate the effects of water diversions on riparian vegetation downstream from diversions. The primary objectives are to:

- Objective 1: systematically investigate whether existing flow diversions have influenced riparian communities
- Objective 2: assess which environmental variables are sensitive to diversions

These goals will be met through the investigation of multiple hypotheses:

$H_0 1$: Vegetation community composition (richness, abundances, heterogeneity, evenness) above and below diversion sites does not differ significantly.

$H_A 1$: Vegetation community composition above and below diversion sites does differ significantly.

Rationale: Naiman and Décamps (1997), Bendix and Hupp (2000), and Amoros and Bornette (2002) have shown that riparian plant communities are controlled by hydrogeomorphic processes. Stromberg and Patten (1990) and Smith et al. (1991) found reduced growth and abundance of riparian plants in response to reduced flows. Diversions reduce the amount of peak and base flow, and potentially cause streams to lose water to groundwater. Groundwater strongly influences vegetation composition and structure, as well, and can reduce the sensitivity of certain systems to decreases in streamflow through maintaining base flow (Winter 2007).

$H_0 2$: No change can be detected in species composition within lateral and vertical zones away from/above the active channel elevation.

$H_A 2$: Significant differences exist in species composition within lateral and vertical zones away from/above the active channel elevation.

Rationale: Lateral and vertical zonation of vegetation species is commonly observed in riparian areas as a result of many different processes, including flow regime and fluvial processes depositing and scouring at different frequency, duration and magnitude, depending on distance from and elevation above the channel (Merritt et al. 2009). Streamflow is often closely tied with the groundwater, and interannual fluctuations of the groundwater in riparian areas can be a direct result of changes in the discharge of the stream. Diversions can reduce duration, magnitude and frequency of peak flows and decrease base flow (Stamp and Schmidt 2006). These reductions can potentially lead to changes in the lateral and vertical zonation of the riparian vegetation community via (i) reduced groundwater recharge during flooding and base flow, (ii) increased distance from surface to groundwater, and (iii) reduced channel heterogeneity as a result of fewer disturbances and associated germination events. For example, riparian species in similar morphological settings may not be found as high above the channel, and similarly, not as far away from the active channel, along streams with flow diversion. The decreased physical heterogeneity of the system leads to vegetation encroachment and less fluvial scour and deposition, and thus fewer of the germination sites that provide successional diversity.

$H_0$3: No significant difference in species composition can be detected at identified fluvial landforms upstream and downstream from diversions.

H_A3: Species composition at identified fluvial landforms, specifically floodplains and low terraces, upstream and downstream from diversions is significantly different.

Rationale: Mechanical disturbance of the stream and riparian surfaces is a result of the flow regime and fluvial processes that erode, transport and deposit material dynamically in three dimensions. Fluvial landforms have been shown to correspond to certain types of vegetation communities (Osterkamp and Hupp 1984), and the landforms are related to the area inundated, which is a function of flood frequency. In steep, mountain streams, there are four major types of landforms associated with riparian communities; floodplain, low and high terraces, and hillslopes (Rot et al. 2000).

$H_0$4: No significant difference can be detected in the sensitivity to diversions in relation to valley confinement or plant associations.

H_A4: Sensitivity to diversions differs significantly between sites upstream and downstream from diversions in relation to valley confinement and plant associations.

Rationale: Valley confinement can control the lateral extent of riparian area, and is directly related to the degree of hillslope coupling (Polvi et al. 2011). Unconfined valley settings may have more floodplain and riparian area exposed to numerous abiotic processes, such as flow and fluvial processes, which create physical habitat heterogeneity and exert selective pressures on individuals and communities, ultimately causing these settings to respond differently than a confined setting. Plant community associations are useful for describing how plant communities vary and what species commonly occur together, and these may be a result of complex fluvial, soil and climate interactions, and may have differing sensitivities to perturbation in the system as a result of flow diversion.

In summary, riparian vegetation characteristics are influenced by hydrologic and geomorphic variables and processes. Hydrologically, flooding plays an important role in providing moisture to riparian areas, with magnitude, timing, duration and frequency being the most important flow characteristics. Surface flow is also an important medium for sediment and nutrient transport. Geomorphic processes of erosion influence the riparian areas by removing habitat through down cutting, channel migration, and scouring the channel boundaries, while deposition provides sediment to the floodplains, and forms point and channel bars. Valley morphology also plays an important role, affecting the ability of the river to move material. Narrow valleys tend to have a steeper gradient with a coarser boundary, and a narrower riparian area, whereas wide valleys often have more channel migration and more dynamic, developed alluvial features. Water diversions change the hydrologic and geomorphic variables within the stream system by reducing peak and base flow, effectively changing competency to move sediment, erode and scour the boundaries, deposit material and provide surface water to the riparian areas through flooding. Low-gradient channels, or response reaches, are geomorphically most responsive to altered water and sediment yield, due to their finer-grained boundaries, and lower ratio of sediment transport capacity to supply, when compared to high-gradient systems. Therefore, my thesis tests whether the riparian vegetation in low gradient stream segments shows a response to flow diversions.

3. STUDY AREA

The Routt National Forest (Routt) was established in 1908 and extends from north-central Colorado to the border with Wyoming. The Routt occupies an area greater than 5,200 km^2, with elevations ranging from 1900 – 3950 meters (Figure 3.1). This public land is administered by the United States Department of Agriculture (USDA) United States Forest Service (USFS), and has many land uses, including many forms of recreation, resource extraction (such as timber harvest, water withdrawals) and commercial ski operations, among others. The Routt spans both sides of the continental divide, is comprised of three mountain ranges (Park Range, Medicine Bow Range and the Gore Range), many geologic units, and differing land morphologies, making the landscape and vegetation communities unique within the Inter-mountain West. According to the water management entity, Colorado's Decision Support System (CDSS) (CDSS 2012), there are currently 68,600 diversions in the state of Colorado, and 921 within the Routt Forest boundaries (Figure 3.2).

3.1 GEOLOGY AND GEOMORPHOLOGY

The Routt National Forest exists in the Southern Rocky Mountains geomorphic province, and is primarily composed of several mountain ranges; the north-south oriented Park and northern Gore Ranges, the Sierra Madre Mountains, and the southern Medicine Bow Mountains. The Park and Gore Ranges, consisting primarily of Precambrian metamorphic and granitic basement rocks, were uplifted during the mid-Tertiary Laramide Orogeny. At the same time, volcanic activity was occurring in the Rabbit Ears Range to the southeast (Hail 1968), leaving sedimentary rock units flanking the lower elevations of the primarily granitic, gneiss and schist main range (Bunin 1975). Weathering of this parent material creates soils that are typically coarse, and with the added influence of fluvial-mechanical disturbance, are often poorly developed in the riparian areas. Depending on location of the study site, some of the soils can be finer if derived from the sedimentary units, yielding higher moisture retention and bank stability. Glaciation is responsible for scouring valleys, depositing moraines and debris, forming small basins, and can have a large impact on valley and channel morphology (Wohl 2010), completely shaping valleys and commonly reducing channel gradient upstream of terminal moraines. The study area has experienced two periods of glaciations during the Pleistocene (Atwood 1937), with the Pinedale glaciation having the most prominent and extensive visible effects on the current geomorphology (Mears 2001). The most recent glaciation terminated approximately 11,000 B.P. (Madole 1980). The lowest cirque altitude was around 3200 meters, with the lowest glacial limit being 2300 meters on the west slope and 2600 meters (Atwood 1937) on the east slope due to the orographic effect of the crest reducing moisture availability.

Topography of the study area and geomorphology of the valley bottoms is typical of the Southern Rocky Mountains, varying widely from high-gradient, confined valley cascade systems, to low-gradient unconfined valleys. I collected data on single thread, straight and meandering, alluvial channels on low to moderate gradient (<3%), pool-riffle or plane-bed systems, typically on low-order streams at middle elevations (2325-2825 meters). Valley confinement for study sites is classified as partly confined (2-10 times channel width) and unconfined (>10 times channel width). Channel substrate at study sites ranged from coarse sand (1mm) to small cobble (64-90mm), with a median size of coarse gravel (32-45mm).

Another important mechanism of alluvial valley bottom development is the activities of beaver (*Castor canadensis*). Beaver dams have ecological and geomorphic influences, including sediment and nutrient storage, and regional evidence indicates their importance for trapping sediment in montane valleys (Kramer et al. 2012). At the study sites, many of the alluvial channels and valleys had indications of beaver activity, past or current, evidenced by secondary and complex channel networks likely formed through dam backwaters, or actual beaver dam structures on terraces or channel margins.

3.1.1 HYDROLOGY AND CLIMATE

Four major rivers, the Colorado, Yampa, North Platte, and the Little Snake, have a portion of their headwaters in the Routt study region, which is primarily composed of montane and subalpine environments, making snowfall in the winter months and summer convective storms the dominant sources of precipitation. Mean annual precipitation for site basins ranges from 64 to 125.4 cm, with an average of 92.7 cm. The crests of the mountain ranges act as barriers to moisture moving west, creating moderate to strong precipitation gradients within the study region. Accordingly, the hydrograph is relatively consistent and characterized by a snowmelt peak in early to late summer, with variance in timing, duration and magnitude commensurate upon the timing of the snowmelt, magnitude of the snowpack, timing of increased solar radiation and intensity/magnitude of convective storms. All of the study sites fall within the Mountain hydrologic region, defined from Capesius and Stephens (2009) regional hydrologic analysis for the state of Colorado, and delineated based on similar climatic and physiographic characteristics: in this case, where annual peak streamflow is most commonly a result of snowmelt runoff. Watershed area for sampled sites averaged 23.2 km^2, with a minimum of 2 and a maximum of 57.1 km^2. Two year peak flow (Q_2) for study sites, based on a regional regression equation in Capesius and Stephens (2009), averaged 5.0 m^3/s, with a range from 0.6 to 12.2 m^3/s.

3.1.2 FLOW ALTERATION

The Inter-mountain west is a semi-arid environment that has extensive water infrastructure to transport and deliver water for urban and agricultural use, with over 68000 points of diversion in Colorado alone (CDSS 2012). Winter (2007) stated that it is very common in arid regions to have a loss of stream water to the ground water, making these systems more sensitive to changes, such as alteration of flow regime, which can lead to lowered groundwater levels. In areas with low seasonal precipitation, or during periods of drought, riparian vegetation is dependent upon groundwater, geomorphic setting and hydrology, and declining levels can be detrimental to individual plants and entire communities. Diversions could act as a catalyst for this stress to riparian species, through reduced peak and base flows not sustaining moist soils and groundwater levels, reducing plant access to moisture.

The majority of diversions are located at breaks in gradient, or property boundaries, yet my sites were located on similar gradients upstream and downstream, to best investigate objectives and hypotheses by reducing variance in environmental factors between paired sites. While diversions are not the cause of change in gradient or valley geometry, they are often sited there to take advantage of environmental elements. For my sites, and other observed diversions throughout the Routt National Forest, the structure, maintenance and timing and proportion of flow diverted vary widely.   The age of water rights for many of these structures is more than a century, with associated records of maintenance, and withdrawal timing or magnitude being infrequent or completely absent. Diversion structures range from concrete headgates, with the ability to completely block channel-maintaining flows and divert all flow, to peripheral structures constructed of wood or concrete that utilize rock weirs and tarps to direct flow, occupy the channel margins, and during any flow only have the capacity to take at most a moderate proportion of flow (Figure A.2, Appendix A). The maintenance interval for these structures, from field observation, ranged from multiple times a season to potentially decades, as evidenced by the state of the structure, access roads, and degree of disrepair.

3.1.3 TERRESTRIAL AND RIPARIAN VEGETATION

Terrestrial vegetation, above 2440 meters, throughout the study area consists primarily of *Pinus contorta*, *Populus tremuloides*, *Psedostuga menziesii*, and *Abies lasiocarpa-Picea engelmannii* forests, commonly with abundant herbaceous and shrubby growth in the understory, as described by Bunin (1975). Over the past two decades, *Pinus contorta* (lodgepole pine) dominated forests have been heavily affected by the mountain pine bark beetle outbreak in the Medicine Bow-Routt, White River and Arapahoe-Roosevelt National Forests, spreading to 1.6 million hectares and killing trees in large numbers (U.S. Department of Agriculture 2011).

Rocky Mountain riparian vegetation communities vary widely as a result of the lithology, topography, hydrology, channel form and natural and anthropogenic disturbance regimes. A useful unit of classification to differentiate between different communities is to identify groups of species commonly occurring together and recognizes them as plant associations, or assemblages. Kettler and McMullen (1996) developed a plant association for the Routt, sampling 195 plots and classifying five major groupings; coniferous-dominated forests and woodlands, deciduous- dominated woodlands, willow-dominated deciduous shrublands, non-willow-dominated deciduous shrublands, and herbaceous wetlands. Of these five groups, most commonly occurring in my study sites are the willow (*Salix* spp.) dominated grouping, with a few sites characterized by coniferous-dominated and herbaceous wetlands groups. In general, willows tend to occur in the low-gradient stream reaches desired for my sampling.

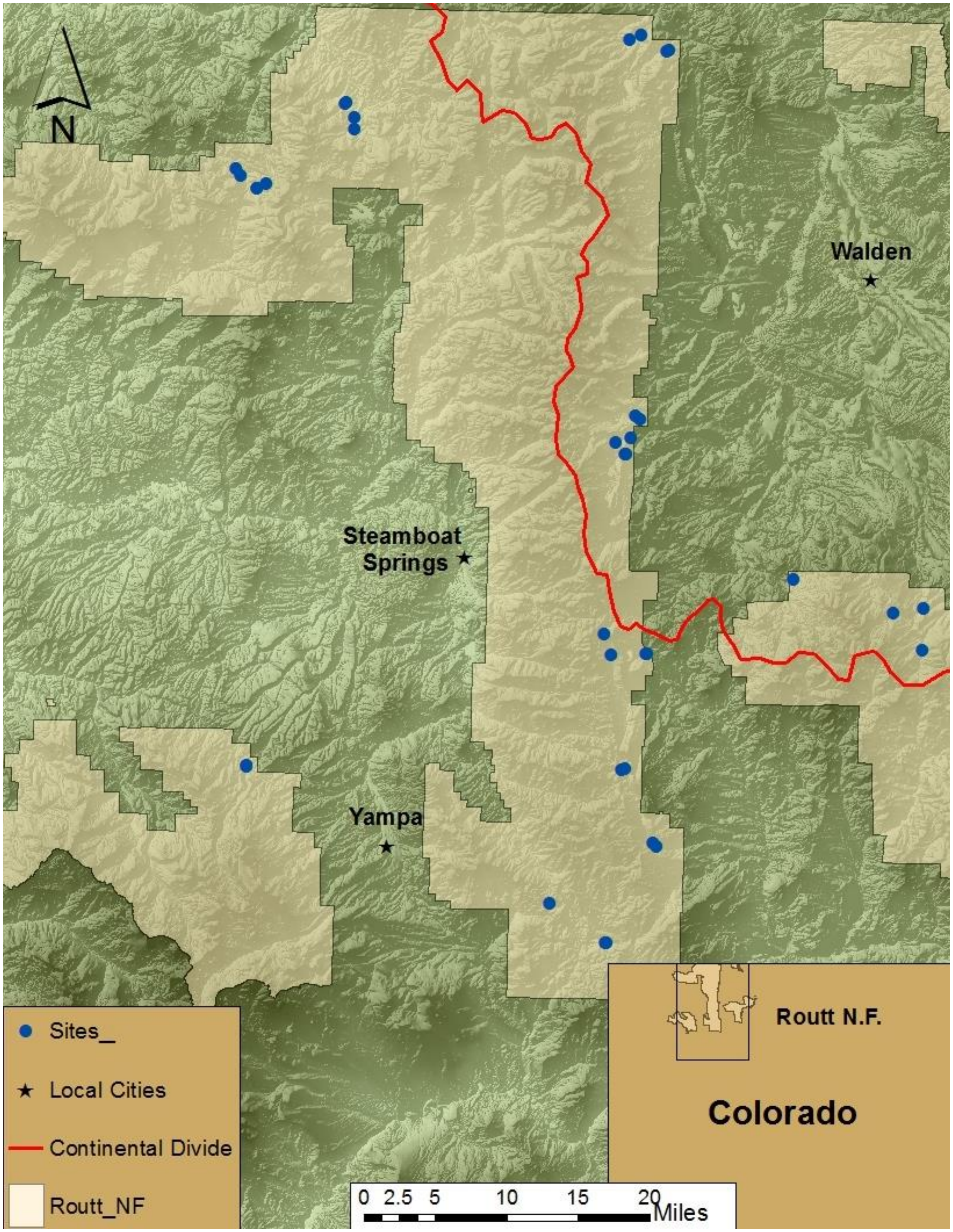

Figure 3.1: Overview map of study area. Routt National Forest land appears as tan shading.

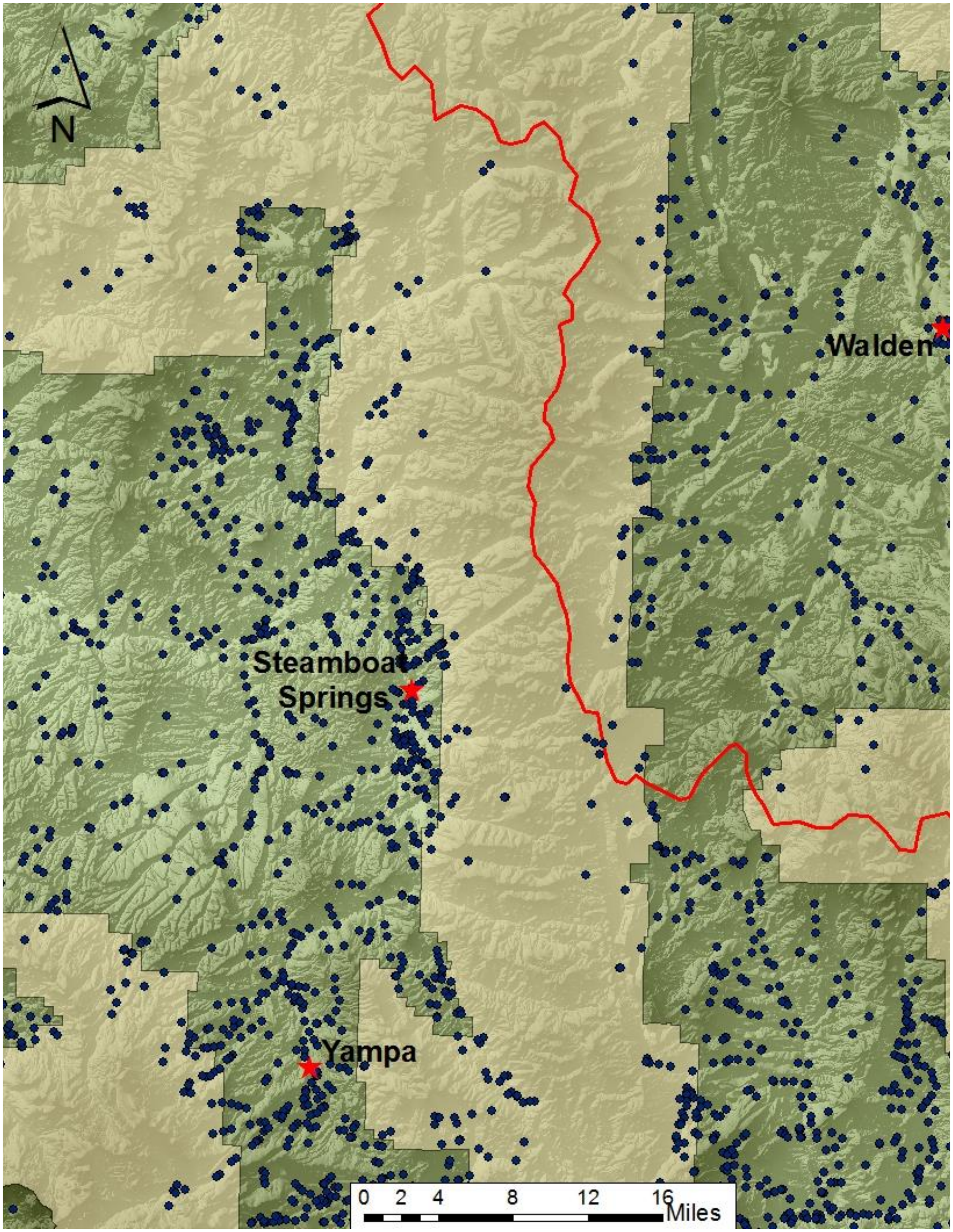

Figure 3.2: Routt National Forest, with known points of diversion in blue (CDSS 2012).

4. METHODS

The purpose of this thesis is to understand the interaction of physical processes, primarily flow, and biotic elements, as reflected in riparian vegetation communities. To achieve this goal, both geomorphic and vegetation data were collected. I focused on stream characteristics; specifically, channel gradient and geometry, and riparian vegetation communities.

Over the course of two field seasons, 38 sites were sampled: 20 downstream of diversions and 18 upstream of diversions. Sites upstream from diversions are assumed to be minimally affected by flow regulation and are designated control reaches. Sites downstream from diversions are assumed to be potentially affected by flow regulation and are designated treatment reaches. Of the 38 sites sampled, 16 were paired sites with data collected above and below a single diversion.

When possible, data were collected at 'paired' sites, but suitable, comparable reaches did not always exist. Diversions are commonly located at breaks in slope, making the upstream reach likely too steep for comparison to the downstream reach, or are located at property boundaries, causing downstream reaches to be inaccessible. In an effort to constrain environmental variables between control and treatment reaches, paired reaches were selected to minimize variability in geomorphic and hydroclimatic setting.

4.1 SITE SELECTION

Site selections of diversions were conducted through a combination of methods to identify the best sites for paired reaches, one upstream of a diversion and one downstream, with both exhibiting similar morphological characteristics (valley confinement and stream gradient). First, I started with the entire population of diversions, and used Geographic Information Systems (GIS) analysis to evaluate criteria for site selection. To determine site suitability, the criteria I used were site accessibility, relative stream gradient, valley confinement and property ownership. Disturbance history is assumed to be the same between paired upstream and downstream reaches because of their proximity to one another. Personal communication with Forest Service employees knowledgeable about diversions and streams was vital to acquiring information about low-gradient systems, operational status of diversions and best access to the site, saving many hours of reconnaissance time. Simultaneously, sites were cross-referenced with the diversion database located on Colorado's Decision Support System (CDSS) website to assess the characteristics of the desired diversion structure. This involved analyzing the amount of flow that has been taken, when the diversion was built, and timing of water extraction, deducing whether the diversion is currently operational, and incorporating comments from the water master. Sites selected in this manner as being potentially suitable were visited in the field for final selection.

4.2 DATA COLLECTION

4.2.1 RIPARIAN VEGETATION SAMPLING

The riparian vegetation sampling component was modified from the National Riparian Monitoring Protocol: Western U.S., which is currently being developed by the USDA Forest Service National Riparian Technical Team (USDA in prep). This protocol has been adjusted to best suit the purposes of this project: specifically, the orientation of the vegetation transects was altered, and the distance away from the channel was limited to 10 meters to facilitate speed of sampling.

I identified appropriate geomorphic surfaces (fluvial landforms) at each point, such as depositional bars, floodplains, secondary channels, low and high-terraces and hillslopes (Bar, FP, SC, LT, HT, and HS) (Osterkamp and Hupp 1984). During the first field season (2011), we did not associate a geomorphic surface with each point. During the second field season (2012), fluvial landform was associated with each of the points through field identification.
The line-point intercept sampling method was used to sample points along a transect (Figure 4.1) at regular intervals using a laser point sampler (USDA in prep). The laser pointer was mounted on top of a trekking pole, and then aligned directly over the sampling point (being consistent with which side of the tape the pointer is placed on) and leveled using a bubble level mounted on the frame (Figure A.3). We turned on the pointer and recorded each species from top to bottom, including ground cover (Table 4.1). We carefully moved each individual out of the way after sampling until ground cover was reached, so that each species was not recorded more than once per point unless two or more individuals of that species were present in different height classes. With dense understory, this can be difficult to not disturb individuals while moving others out of the way following identification. Similarly, with multi-layered overstory vegetation, it may be time-prohibitive or impossible to move individuals out of the way. In these cases, best judgment was used to determine species present at that vertical point in space.

Vegetation was identified to the species level in the field when possible. When not possible, multiple individuals of the unknown species were collected, tied together with flagging labeled with the name and corresponding sample point, then preserved in a plastic bag until returned to the lab for identification. If the sample could not be immediately identified back at the field station, samples were pressed individually, with unknown number, name, sample point, date and site written on the press paper, for later identification. Additionally, known species and all unknowns were photographed on a white laminated background with dry-erase pen marking to note date, name and any other notable characteristics for most efficient future identification and database reference.

Vegetation transect width was a multiple of channel width starting from active channel elevation and extending away from the channel, into the floodplain and/or terraces, perpendicular to the thalweg/channel alignment at that transect (Figure 4.1). The perpendicular orientation of the transect layout was determined to best suit the needs of the study because one of the hypotheses is that there will be a change in lateral zonation, or distance from the stream channel, of riparian communities with reduced streamflow. The transect width on each side of the channel was equal to two times (2x) the channel width, with a minimum distance of 5 m and maximum distance of 15 m. Minimum width was determined to be necessary because, for some of the smaller width streams (<1 m), riparian areas were not being adequately represented.

4.2.2 GEOMORPHOLOGY

Cross-sectional profiles: We collected 5-10 cross sections during the first field season, because the physical channel morphology component involved sampling at additional cross sections located at significant channel morphological features such as riffles, apex of meander bends and pools (Blaschak 2012). During the second season, we only surveyed cross sections along the riparian transects, totaling five per site. At these cross sections, we also identified active channel edge using new growth and erosion indicators, used to delineate a geomorphic surface below the bankfull but above late summer baseflow, typically the lowest point where riparian vegetation will grow . Additionally, bankfull was identified at each cross section using multiple indicators, such as the tops of point bars, high scour lines, and deposition of fine sediments (sand-sized or finer) or leaf litter, and roughly corresponded with a two-year flow event. Points were collected to maximize the efficiency of data collection, being placed at breaks in slope, and at other important features, such as thalweg, edge of water, bankfull and fluvial landform transition. Cross-section surveys extended to the edge of vegetation transects and, as a function of local topography, ranged from just above bankfull elevation to more than two times bankfull depth.

Stream Gradient: Points were surveyed along the thalweg at the bed surface elevation and the height of the water surface was recorded from increments on the rod. For wetted edge and bankfull locations, the cross sectional profile survey points were used to plot the longitudinal gradients of water surface slope at the active channel when sampled, and the water surface slope at bankfull elevation.

4.3 DATA ANALYSIS

Vegetation can be analyzed in a hierarchical manner, starting with individuals (traits), then populations (groups of individuals in same species), then communities (collections of species), and finally ecosystem level (structure/productivity). I focused on population and community analysis.

All vegetation data were entered into an Excel spreadsheet, where each column represents a species, and each row represents a unique vegetation data point, totaling 100 points for each site. An environmental data set was created concurrently, associating environmental variables with each point. Environmental variables include; site name, control group (above/below), distance above active channel, distance away from active channel, valley type, stream morphologic data, and others.

Statistical Assumptions and Tests: All statistical analyses were checked for compliance with assumptions associated with the test. Paired tests were used unless otherwise noted. Metrics utilizing a paired Student's t-test were evaluated for normality using the Shapiro-Wilk test, transformed if necessary, and checked again. If transformations were not successful in normalizing the data, the Wilcoxon-Signed Rank Test for paired, non-parametric data was implemented. All statistical analyses were completed in R (R Development Core Team 2011), unless otherwise noted.

Hypothesis 1: All Sites

Community Level Analysis

For community-level analysis, I examined one set of different metrics commonly used for biological diversity and another set for vegetation composition analysis.   For biodiversity, I first considered species richness, which is the most intuitive measure of biodiversity and is simply the total number of species occurring within a given sampling unit. Species richness does not give any qualitative weighting to individuals because of their perceived importance within the community, or quantitative weighting based on their relative abundance. A species richness value was calculated for all sites, and then a Student's t-test was conducted on the means of the control versus treatment groups.   Next, I examined diversity indices, a combination of evenness and richness components which in essence test heterogeneity, and are another traditional way of quantifying biodiversity. The most well-known is the Shannon index (Equation A.1, Appendix A) but more robust and meaningful (in some circumstances) is the Simpson Index (Equation A.2, Appendix A) (Magurran 2004). The Shannon index can have bias when all the species in a population are not represented in a sample, and is more weighted to species richness. The Simpson index is weighted to more abundant species in a sample (dominance), and better measures variance in species abundance distribution, where value rises as sample population becomes more even. To test the evenness, or similarity between species abundances, separate indices have been developed: those that I used are modifications of the Shannon and Simpson diversity indices used above. Pielou (1969, 1977) derived Equation A.3 from Shannon, which is more sensitive to species richness, and Simpson's evenness measure (Equation A.4) (Smith and Wilson 1996; Krebs 1999), which is not. Additionally, total abundance of species was calculated, by totaling the number of all individuals sampled at a site, and compared using a paired Student's t-test.

Species abundance distributions are another method to understand diversity and differences between sampling units, or communities. Two commonly employed examples are species accumulations curves (SAC), which generally compare the species richness of data sets, and rank/abundance models, capturing richness and evenness/dominance within the sampling unit. The SAC is a useful visual and statistical model to understand community diversity properties, such as species richness, with increasing number of samples. The accumulator models work by randomly selecting plots over a defined number of permutations, allowing every *n* (no. of samples) to have an associated mean and standard deviation. Creating the distribution through permutation provides ability to compare richness using confidence intervals derived from the standard deviation (Magurran 2004). Rank/abundance models are a very informative approach to viewing species abundance distributions because they illustrate structure of the community and retain information that 'single-figure' diversity indices lose (Kent 2011). On the y-axis is species abundance, and on the x-axis species are ranked by decreasing abundance. These plots provide good visual comparison between richness and evenness of sampled communities. Beyond basic visual comparison between sites, we used the *vegan* package in R-Cran (Oksanen et al. 2007) to find the best fit between five popular linear and non-linear models (Wilson 1991). Models were fitted using maximum likelihood estimation through the *radfit* function, in which the best model is chosen by lowest Akaike Information Criterion (AIC) value. The fits were then qualitatively compared by paired grouping, identifying pairs that have different distributions, and identifying trends towards one particular model fit. Important to note is that a particular model doesn't necessarily signify the occurrence of a specific ecological process, but the comparison is worth examining.

Population Level Analysis

I applied a chi-square analysis to test frequency of occurrence of individual species, and to determine whether this was statistically significant between upstream and downstream from diversion. Each point was considered a plot, and the total number of plots where a species was present was divided by plots absent. A significance level of 0.01 was used, to avoid Type I error by controlling the experiment-wise error rate, through applying a Bonferonni correction (Merritt and Wohl 2006). Species found to be statistically significant were investigated in terms of morphologic, life-history and other functional traits that may describe their presence or absence with respect to differing levels of water availability as a result of the flow regime.

Community Composition Analysis

To test for significant differences in species composition between groups of samples, I used analysis of similarity (ANOSIM), multiresponse permutation procedures (MRPP), and permutational MANOVA (adonis) in R-Cran. ANOSIM is based on the idea that community composition should be more dissimilar between groups than within, and is tested using a dissimilarity matrix (Clarke 1993). The dissimilarity matrix has a value for every possible site combination, and is created based upon three variables: number of shared species (*c*), number of species unique to 1st site (*a*), and number of species unique to 2nd site (*b*). There are numerous formulations of these variables, but I used Bray-Curtis for this analysis (Equation A.5,

Appendix A). MRPP is multivariate and non-parametric, and tests for statistical significance of difference between control and treatment populations by comparing dissimilarities (Mielke and Berry 2001). Lastly, to test the differences in group means, I used the Vegan function *adonis*, a non-parametric, multivariate, permutational analysis of variance based on distance matrices (Anderson 2001; Oksanen 2011). I also examined the homogeneity of groups through the *betadisper* function[1], and then used analysis of variance to test the model fit (Anderson et al. 2006). All community composition tests report p-values. Decision to reject the null was based upon α=0.05.

[1]Betadisper function is PERMDISP2 (Anderson, 2006), analogous to a multivariate Levene's equality of variances test

Filters/Groupings

I created groupings of species to help identify change in important species. Primarily, I used wetland indicator status (Lichvar et al. 2012), which is a qualitative ecological description used to rate wetland plant species based on level of occurrence in wetlands. To identify indicator species, and filter the data to identify by important groupings of plants, I associated each species with their appropriate indicator status, reducing the data set from 256 species to 5 groupings of species. Obligate species (OBL) almost always occur in wetlands. Facultative wetland species (FACW) usually exist in wetlands and are associated with near-channel, seasonally-flooded environments. I used the OBL and FACW species, which are typically hydrophytes, as general indicators of hydric, moist conditions, and as evidence of geomorphic settings where soil is saturated through flooding on a more regular basis, typical of functioning riparian environments. On the opposite side of the indicator spectrum are Facultative Upland species (FACU), commonly occurring on drier, mesic soils, and Upland species (UPL), present almost only in non-wetlands, in soils that are mesic to xeric. I used the FACU and UPL species, which are not typically hydrophytes, as indicators of geomorphic settings that are disconnected from the channel, or at the least not subject to seasonal flooding.

Similar to the analysis of the species group as a whole, I then used the richness, diversity, abundance and composition metrics to analyze only the species identified as riparian, comparing control to treatment. I examined the non-hydrophyte, upland species as a stand-alone subset, and compared the control to the treatment using the same metrics.

Hypothesis 2

Testing hypothesis 2, differences above (vertically) and away (laterally) from the stream, required each vegetation point to contain topographical coordinates for analysis. To assign values to each vegetation point, I interpolated based on known points from the survey and vegetation transects (see Appendix 0 for further description of this method). I then stratified the data by creating bins of different elevations and/or distance. For the vertical zonation, groups were created at every quarter-meter interval. For example, all points 0.25 m above active channel, all points 0.5 m above active channel, and so on. Diversity metrics, listed in Figure 4.2 above, were applied to all the points that were in a specified elevation zone, with 6 different groups up to 1.5 m above the active channel. Diversity metrics were tested for difference between upstream and downstream of diversions. To avoid bias, as there were a variable number of points in topographic groupings within the sampling unit, I used relative abundance (number of occurrences/number of points in sampling unit) for all diversity metrics, instead of absolute abundance. Distribution of points in topographical groupings between upstream and downstream was similar, with magnitude being close to 10% difference. Similarly, groupings of lateral distance away from the active channel were created, at every half meter, creating six groupings up to three meters away from the channel. These groupings were also used to test for community composition differences using ANOSIM, MRPP, and *adonis*. Chi-square analysis testing for statistical significance of species frequency was again employed. Filters were applied to highlight important groupings of species and investigate change within these indicator groups.

Logistic Regression

To investigate species and wetland indicator grouping response related to topography, I plotted the probability of species occurrence as a function of lateral and vertical distance from the active channel using logistic regression. This analysis helps indicate both the correlations between probability of species or grouping to elevation or distance to the channel, and whether this topographical relationship varies between upstream and downstream from diversions (Merritt and Wohl 2006; Polvi 2009). Based on presence-absence data for each point, I fit logistic regression equations, separately, for two topography terms, one as a function of vertical elevation above active channel (EL), and the second as a function of horizontal distance away from the active channel (DIS). To determine significance of the probability of species occurrence related to topography, the p-value associated with the topography term is evaluated. In addition to fitting the distance (DIS) or elevation (EL), I added a variable for upstream versus downstream (DIV), and an association term (DIV*DIST or EL) designed to evaluate the interaction between the control group and the topography. To understand whether the probability of occurrence of a species or indicator grouping, as a function of topography, changes between upstream and downstream from diversion, significance is evaluated using the p-value for the association term.

Curves were plotted for species of interest, and species identified as significantly different between control and treatment groups, separately for upstream and downstream of diversion. I then investigated the difference between the logistic regression curves, identifying important contrasts between the control groups, serving as potential indicators of changes in moisture availability.

Hypothesis 3

Each identified fluvial landform was compared for changes in community composition, diversity and distribution. Again, relative abundance was used (number of occurrences/number of points in sampling group) to compare heterogeneity, evenness and richness metrics. SAC were again used to compare richness, and chi-square analysis was applied to examine species frequencies, especially if contrasts were seen in rank/abundance or SAC models. Filters were applied to examine obligate riparian and upland species, identifying changes in relative abundance between upstream and downstream of diversion grouping units.

Hypothesis 4

The sensitivity of environmental variables was tested through stratifying sites by valley confinement, and precipitation regimes. Factors within these groupings, so long as the subset was greater than 2 sites, were tested for difference between upstream and downstream from diversion, using the same tests as the above hypotheses (Figure 4.2). Additionally, I selected three paired reaches with well-engineered diversion structures and evaluated differences in diversity and wetland/upland species occurrence.

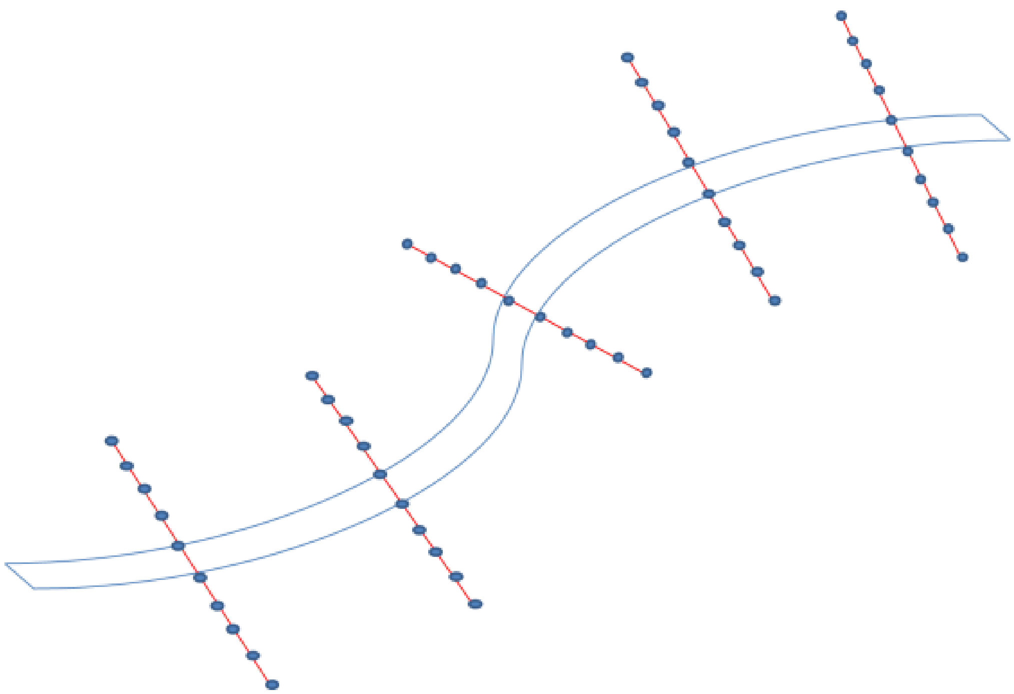

Figure 4.1: Site-level layout of line-point intercept vegetation sampling

Table 4.1: Categorical values of ground type associated with each vegetation point

Physical	Organic
Bare Soil (soil particles <2mm)	Basal vegetation
Gravel (2-64mm)	Bryophyte
Cobble (65-256 mm)	Wood
Boulder (> 256 mm)	Litter: including leaf, needle
Bedrock	litter, and other dead plant
Water	material

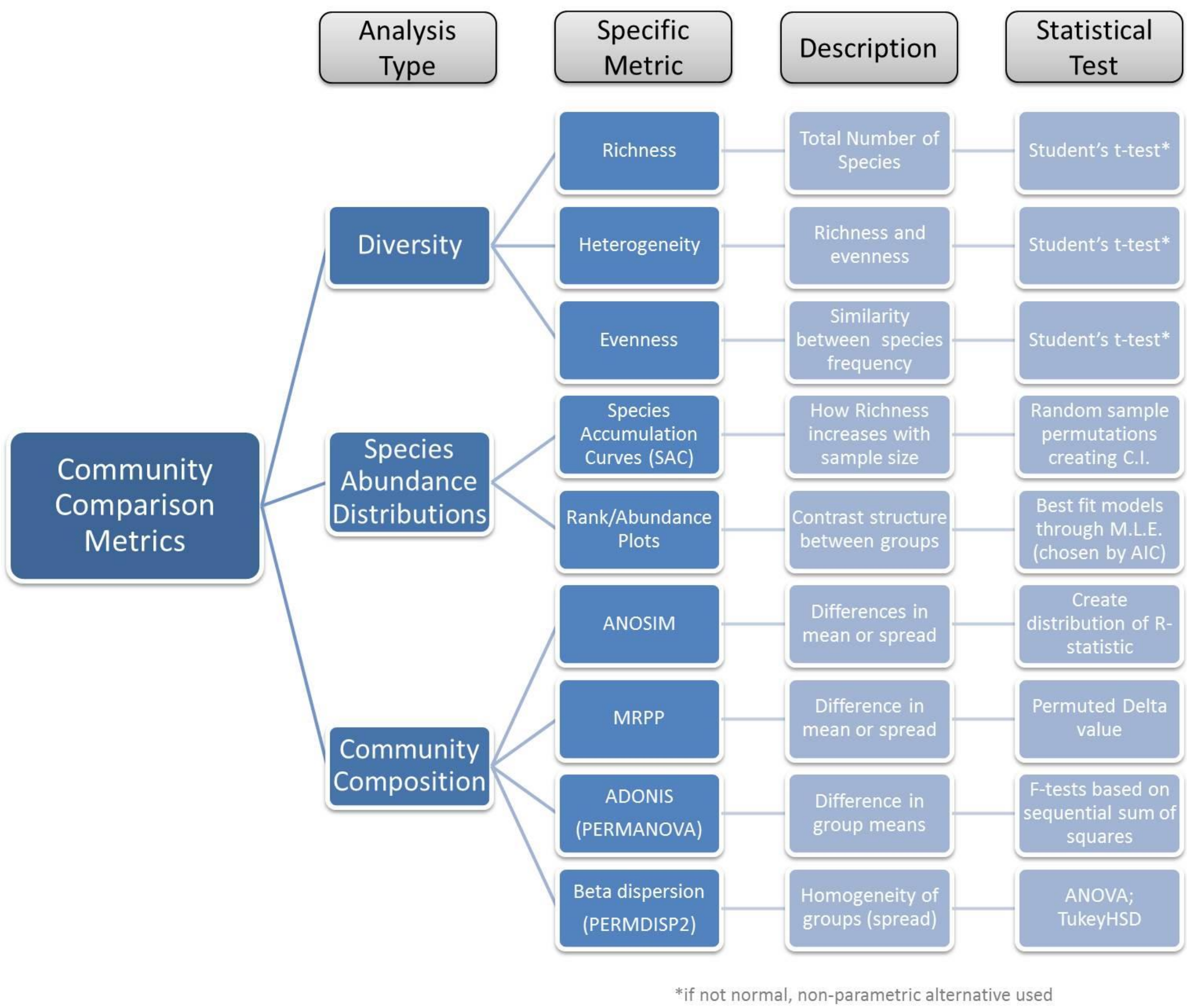

Figure 4.2: Tree diagram of community comparison analysis

5. RESULTS

From all 38 sites, encompassing 3800 sampling points, a total of 238 plant species were recorded throughout the Routt National Forest. The number of sites used in analysis was reduced from 38 to 32, as two groups (four sites) were not suitably paired, by definition of similar lithological, watershed and valley type characteristics, and one group had active beaver dams and ponds downstream of the diversion (see Appendix 0 for discussion).

5.1 HYPOTHESIS 1: ALL SITES

Community Level Analysis

The statistical analyses partially supported the alternative hypothesis of significant difference between upstream and downstream from diversions. Mean species richness was slightly higher in the downstream sites, but not statistically significant (Figure A.4, Appendix A). Species accumulation curves also show a higher richness downstream from diversions, but also were not significant (Figure A.5, Appendix A). For heterogeneity tests, the mean of the Shannon Index, Simpson Index, and Inverse Simpson Index were noticeably higher downstream from diversions (Figure A.6, Appendix A), although differences were not statistically significant. Evenness, in both the Shannon and Simpson metrics, was significantly greater downstream from diversions (Figure 5.1), based on the non-parametric Wilcoxon Signed Rank Test and Student's T-Test, respectively. The rank/abundance plots compared on a paired grouping basis indicate a general trend difference of best model fit between upstream and downstream (Figure A.7, Appendix A). Of the 16 paired groups, five change from a Mandelbrot best fit model upstream to another best-fit model.

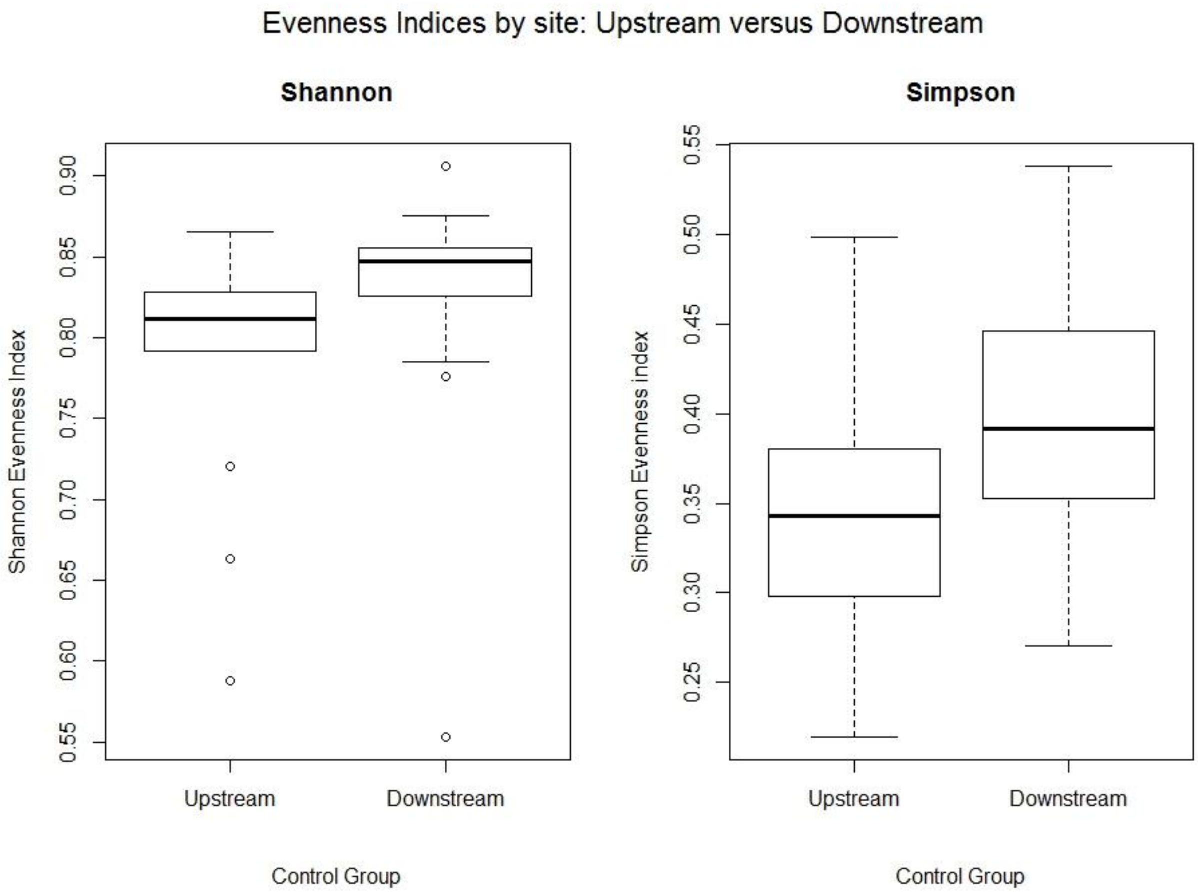

Figure 5.1: Shannon and Simpson evenness indices - upstream and downstream of diversion

Species Composition Analysis

ANOSIM, MRPP, and PERMANOVA analyses testing for species composition differences indicated statistically significant difference between upstream and downstream vegetation communities (p-value = 0.01), when analyzed at a point level. Interestingly, difference between species composition was not significant when points were aggregated into site-level data, where all 100 points for a site were distilled into one frequency value for each species.

Chi-square analysis of overall species frequency, by species, indicates that seven of the eight wetland species (OBL or FACW) had significantly higher abundances upstream from the diversion (Table 5.1). Additionally, six of the eight non-wetland, facultative upland or upland species had significantly higher abundances downstream from the diversion, with three species being in the *Salix* (willow) genera, and one *Carex*. *Taraxacum officinale*, one of the few facultative species in Table 5.1, was significantly more abundant downstream from the diversion. Significant increases of upland species downstream of diversion include forbs, grasses and conifer species. *Chamerion angustifolium* (EPAN), and *Geranium richardsonii* compose the forbs, while *Poa pratensis, Poa* spp*.,* and an unknown species make up the graminoids, with *Pinus contorta* being the only conifer significantly different upstream and downstream of diversions.

Wetland Indicator Grouping

Grouping species by wetland indicator status revealed a significantly higher frequency of wetland species upstream from diversion (p=0.03), and a marked increase (although not significant) in upland species downstream of diversion (p-value=0.12) (Figure 5.2). The mean frequency of wetland species per site for upstream of diversions was 123 individuals, and the downstream mean was 103 individuals. Mean frequency of upland species (FACU or UPL) was 36 individuals per site, whereas downstream had a markedly higher mean value of 48 individuals per site.

Table 5.1: Chi-square analysis results, sorted by wetland indicator status (arrow indicates magnitude referenced to upstream of diversion)

Species	Wetland Indicator	P-value	Freq. Above	Freq. Below	Direction of Increase
Abies lasiocarpa	FACU	0.0015	36	13	↑
Bromis inermis	FACU	0.0015	12	0	↑
Chamerion angustifolium	FACU	0.0051	8	25	↓
Geranium richardsonii	FACU	0.0086	19	40	↓
Pinus ponderosa	FACU	0.0057	12	31	↓
Poa pratensis	FACU	0	3	31	↓
Poa spp.	FACU	0	37	83	↓
Unk_195	FACU	0	0	28	↓
Ligusticum spp.	FAC	0.0077	24	8	↑
Rubus parviflorus	FAC	0.0011	15	1	↑
Taraxacum officinale F.H. Wigg.	FAC	0.003	67	106	↓
Deschampsia cespitosa	FACW	0	192	86	↑
Equisetum arvense L.	FACW	0.0001	47	94	↓
Carex utriculata Boott	OBL	0	337	222	↑
Mertensia ciliata	OBL	0.0033	34	13	↑
Salix monticola	OBL	0.0083	30	12	↑
Salix planifolia	OBL	0.0002	90	47	↑
Salix wolfii	OBL	0.0001	117	64	↑
Veronica americana	OBL	0.0044	10	0	↑

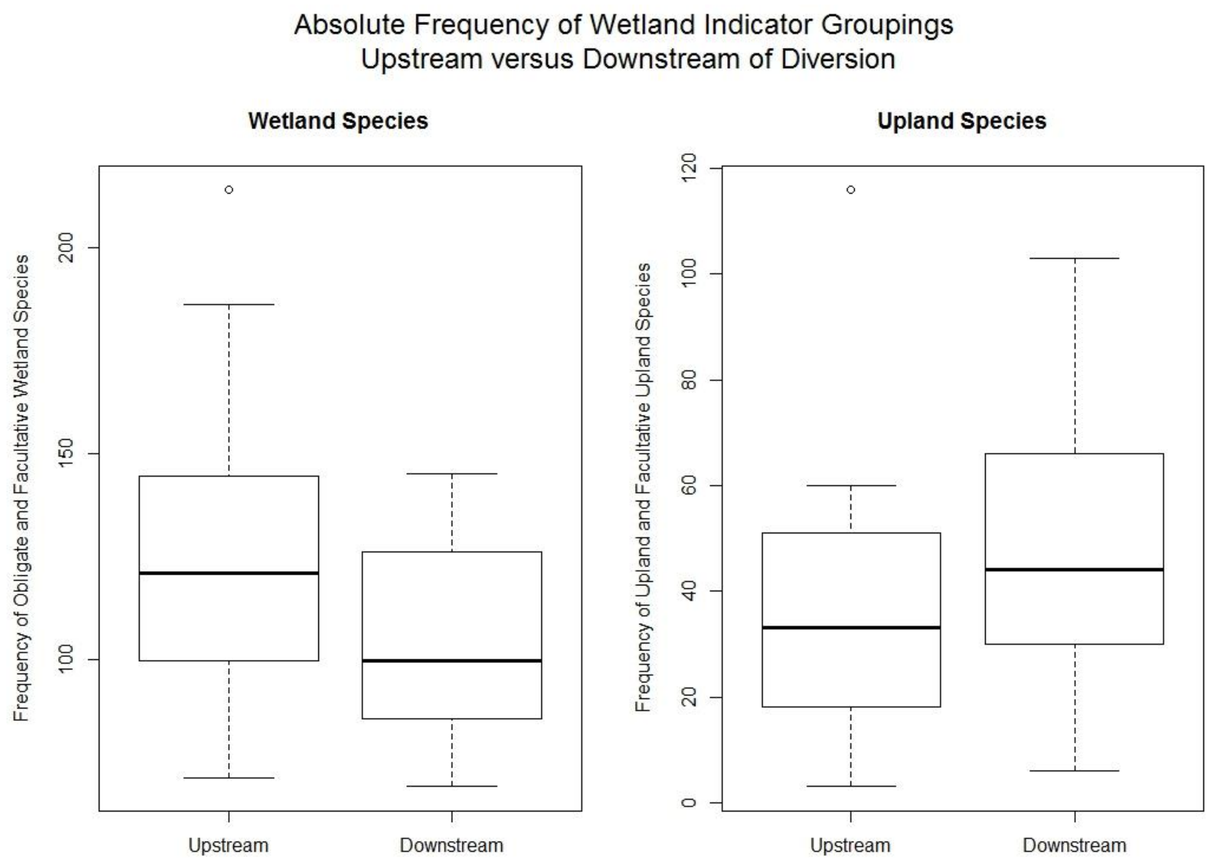

Figure 5.2: Wetland (OBL and FACW) and upland (FACU and UPL) upstream versus downstream

5.2 HYPOTHESIS 2: TOPOGRAPHIC INFLUENCE (ELEVATION AND DISTANCE)

Community Level Analysis

The statistical analyses partially supported the alternative hypothesis of significant difference between upstream and downstream from diversions, based upon lateral and vertical zonation. Diversity index was not significant in any of the groupings, although it was noticeably higher in the downstream of diversion group at the less than 100 cm above channel (elevation), and less than 300 cm away from channel (distance) (Table 5.2). Evenness was significantly greater downstream from diversion for the less than 100 cm elevation above active channel, and the less than 200, 300, and 400 cm distance away from channel groups. Relative abundance of wetland species was significantly higher above the diversions, in all elevations groups tested except for closest to the channel, and all distance groups except for 100-200 cm distance away. Upland species relative abundance was significantly higher downstream of diversion in one grouping (200-300 cm distance) and was noticeably higher, although not significant, in almost every group analyzed except for those closest in elevation and distance to the active channel.

Table 5.2: Metrics with corresponding p-values for each elevation and distance grouping analyzed (significant values, α<.05, are shown in bold with a gray background)

	Elevation-Distance Ranges (cm)	Simpsons Diversity Index	Simpsons Evenness Index	Wetland Species Relative Abundance	Upland Species Relative Abundance
Elevation above Channel	<25	0.9260	0.5034	0.3517	0.8724
	<50	0.9592	0.6939	**0.0001**	0.9784
	<75	0.1556	0.1757	**0.0119**	0.1278
	<100	0.1279	**0.0202**	**0.0187**	0.0771
	25–75	0.1471	0.3378	**0.0370**	0.2263
	75–100	0.8692	0.3142	**0.0207**	0.1165
	75–150	0.7781	0.4932	**0.0423**	0.1397
Distance Away From Channel	<100	0.5730	0.1731	**0.0225**	0.6976
	<200	0.1826	**0.0490**	**0.0193**	0.3184
	<300	0.0631	**0.0122**	**0.0091**	0.0828
	<400	0.0835	**0.0329**	**0.0079**	0.0780
	100–200	0.3329	0.3094	0.0980	0.0930
	200–300	0.1189	0.0775	**0.0048**	**0.0369**

Species accumulation curves for the elevation topography variable show a trend starting with upstream of diversion having higher species richness at less than 25 cm above the channel, then richness is increasingly greater downstream of diversion going from less than 50 cm to less than 75 cm groupings, becoming closer to even at the less than 100 cm grouping (Figure 5.3).

Species frequency analysis through chi-square testing for several elevation groupings is presented in Table A.1 (Appendix A), and indicated that at 25 cm, only one species (*Salix wolfii*) had significantly higher frequency upstream of diversions. At less than 50 cm above active channel, four species had significantly higher frequencies upstream of diversions; *Carex utriculata, Deschampsia cespitosa, Salix planifolia,* and *Salix wolfii.* No species were significantly greater downstream of diversion in this grouping. At less than 75 cm above active channel, *Pinus contorta, Poa pratensis,* and an unknown graminoid, which are all upland species, occurred only downstream from diversion and had significantly higher frequencies. Additionally, the weedy generalist species *Taraxicum officinale* has a higher abundance downstream from diversion.

Species accumulation curves for the distance groupings of less than 1 m, 2 m, 3 m and 4 m indicate a trend from higher species richness nearest to the channel upstream of diversion, to similar in the <2 m group, to slightly higher richness downstream of diversion in the <3 m grouping, and a noticeably higher richness downstream of diversion in the <4 m grouping (Figure A.8, Appendix A).

Community Composition

ANOSIM, MRPP, and PERMANOVA analyses testing for species composition differences showed no statistically significant difference between upstream and downstream vegetation communities based on vertical distance above or lateral distance away from active channel.

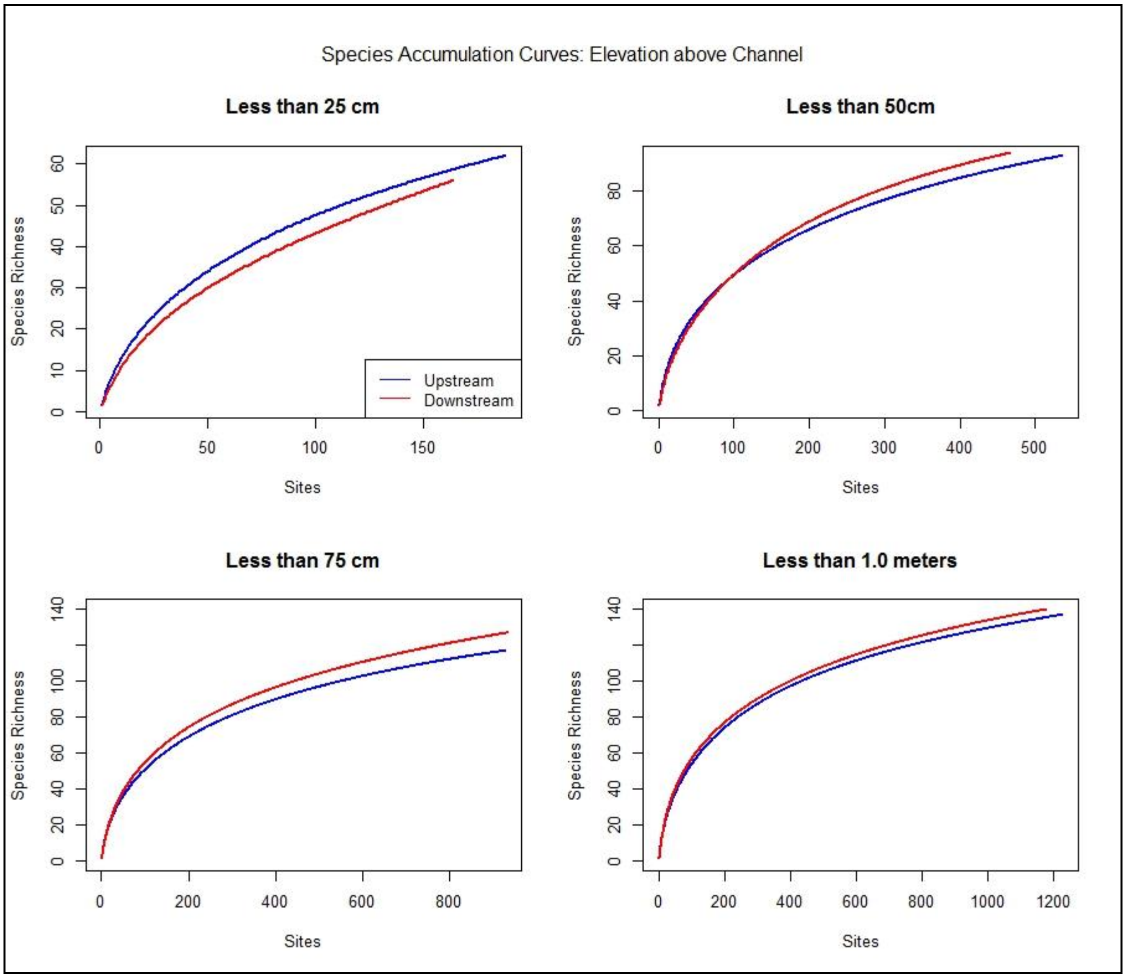

Figure 5.3: Species accumulation curves for four elevation groupings

Logistic Regression

Elevation

Logistic regression analysis indicated a higher probability of occurrence of wetland vegetation species upstream of diversions, as well as greater difference in probability closer to the channel, decreasing with increasing elevation above active channel (Figure 5.4). P-values associated with the topography variable for elevation (EL - β_1),show that all of these groupings except for UPL are significantly related to elevation above the channel, although none are significantly different between upstream and downstream of diversion, as indicated by the p-value of the association term (EL*Div – β_3) (Table 5.3). Probability of occurrence for upland species (FACU and UPL) increases at a faster rate downstream of diversion than upstream of the diversion. Although not formally analyzed, summary statistics of mean elevation above channel and standard error for upstream and downstream of diversion are presented in Table A.2 (Appendix A).

Table 5.3: Wetland indicator status logistic regression coefficients and p-values

	Intercept (β_0)	p<	Elevation (β_1)	p<	Diversion (β_2)	p<	Elev*Div (β_3)	p<
FAC	-1.7840	0.0000	0.6156	0.0004	0.3065	0.1053	-0.4798	0.0544
FACU	-1.4561	0.0000	0.8375	0.0000	0.1814	0.2850	0.2977	0.1854
FACW	-1.0560	0.0000	-0.5619	0.0034	-0.1198	0.5151	0.3005	0.2576
OBL	1.4575	0.0000	-0.4762	0.0040	-0.8281	0.0000	0.1847	0.4044
wet	1.8894	0.0000	-0.6841	0.0001	-0.7977	0.0000	0.2827	0.2289
dry	-1.4521	0.0000	0.8365	0.0000	0.2232	0.1866	0.2827	0.2076

I evaluated elevation significance of the logistic regression for all species, and 31 plant species are significantly related to elevation above the channel (Table A.3, Appendix A). Significant difference between species probability as a function of elevation above the channel between upstream and downstream of diversion was found in 14 species (Table A.3, Appendix A), and the logistic regression curves for each are plotted in Figure A.9 (Appendix A). The obligate hydrophyte and facultative wetland species *Carex aquatilis* and *Deschampsia cespitosa* both had higher probability of occurrence upstream of diversion up to 1 m above the active channel, whereas the non-hydrophyte *Achillea millefolium* had a greater probability of occurrence near the channel downstream of diversion, with zero probability of occurrence upstream below 0.4 m elevation.

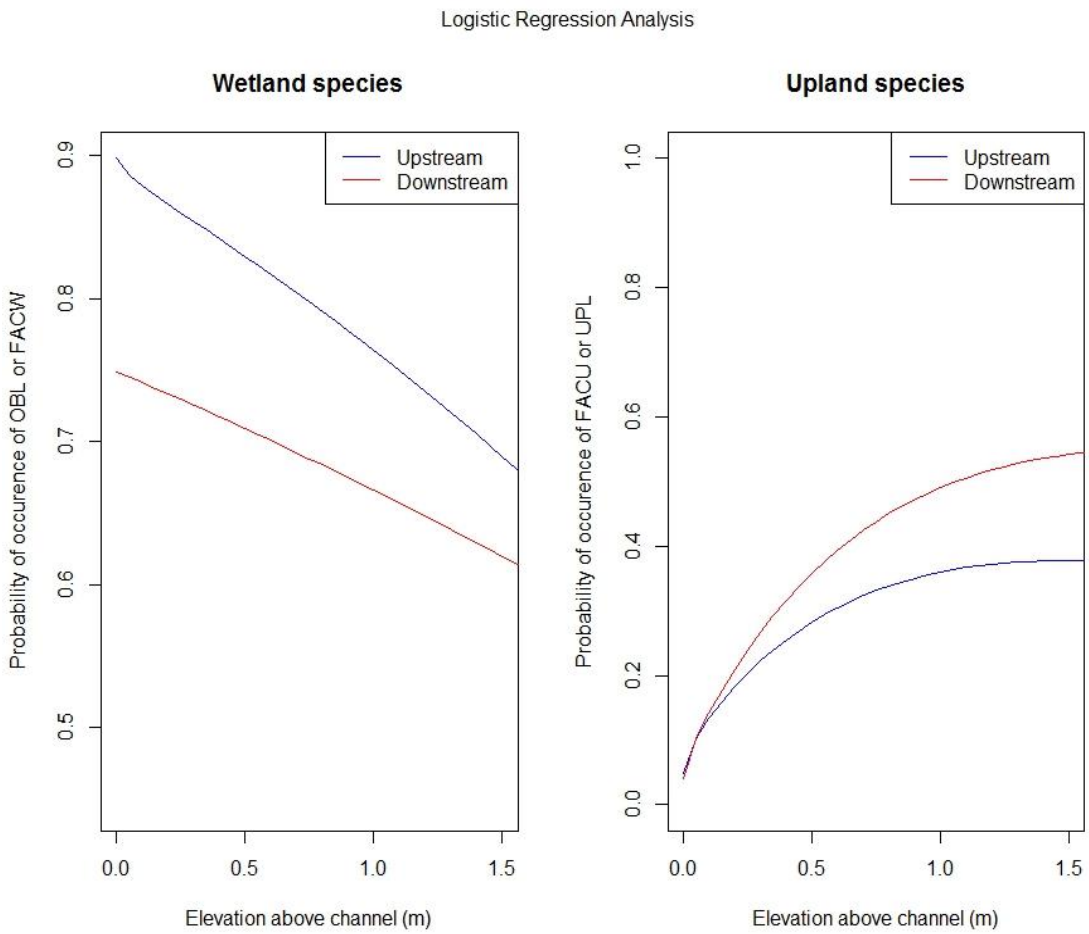

Figure 5.4: Logistic regression fit for probability of occurrence versus distance above channel

Distance

Logistic regression for distance from channel indicated that FACU, FAC and FACW had probabilities of occurrence significantly related to distance from the channel, with the hydrophytic grouping of FACW also being significantly different upstream and downstream of diversions as a function of distance from the channel (Table 5.4). Figure 5.5 indicates that the FACW grouping actually has a higher probability of occurrence as a function of distance up to 3.9 m, where the curves intersect and upstream of diversion probability becomes greater.

Summary statistics (mean distance from the channel and standard error), are provided in Table A.2 (Appendix A), and show FACW as having a mean distance further from the channel upstream of diversion. Also, the non-hydrophytic FACU have a mean distance closer to the stream downstream of diversion, although within standard error margins with the upstream mean.

Table 5.4: Logistic regression coefficients and p-values for significant wetland indicator groupings as a function of distance variable

Species	***Intercept (β_0)***	***p<***	***Distance (β_1)***	***p<***	***Diversion (β_2)***	***p<***	***DIST*Div (β_3)***	***p<***
FAC	-1.6156	0.0000	0.0722	**0.0115**	0.0658	0.6799	-0.0204	0.6165
FACU	-1.2086	0.0000	0.0920	**0.0003**	0.5586	0.0000	-0.0486	0.1668
FACW	-1.6358	0.0000	0.0812	**0.0043**	0.3908	0.0122	-0.1142	**0.0053**
dry	-1.2048	0.0000	0.0919	**0.0003**	0.5938	0.0000	-0.0502	0.1529

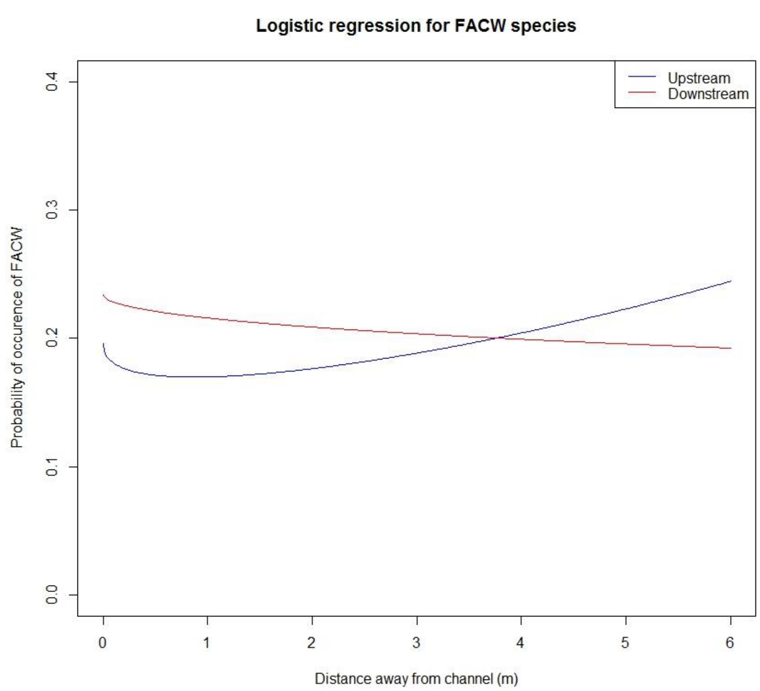

Figure 5.5: Logistic regression plot for FACW wetland species grouping, as a function of distance

5.3 HYPOTHESIS 3: FLUVIAL LANDFORMS

Community-Level Metrics

The alternative hypothesis for significant difference between upstream and downstream from diversion based on fluvial surface is partially supported. For floodplains surfaces, box plots of Shannon and Simpson Diversity Indices indicate higher mean values for downstream of diversion, although not significantly different (Figure A.10, Appendix A). Evenness differences vary between the two indices, but the more robust indicator of evenness, Simpsons Index, indicates similar mean values (Figure A.11, Appendix A). For low terrace surfaces, both diversity indices suggest higher means downstream of diversion, yet not significant (p-value=0.12) (Figure A.12, Appendix A). Evenness is also noticeably higher downstream of diversion on Low Terrace surfaces, although not significant (p-value=0.12) (Figure A.13, Appendix A).

The species accumulation curves for upstream and downstream on floodplain surfaces (Figure 5.6) indicate that as sampling intensity increases, the magnitude of difference in species richness values becomes greater, where downstream from diversion has higher species richness. The 95% confidence intervals also indicate significant difference in the values of richness at sampling size of 135 points and greater. Chi-square analysis of species frequency indicates that only one species, the hydrophytic *Deschampsia cespitosa,* was significantly different, which occurred more upstream than downstream of diversion.

A similar trend in the species accumulation curve was observed for low terrace surfaces, although not as strong, as species richness was higher downstream, although not statistically significant (Figure A.14, Appendix A). Chi-square analysis of species frequency on low terrace surfaces yielded more species as significantly different between upstream and downstream of diversion, compared to floodplain surfaces, with three non-hydrophytic FACU species occurring in greater abundance downstream of diversions, and five hydrophytic OBL and FACW species occurring more upstream of diversions (Table 5.5).

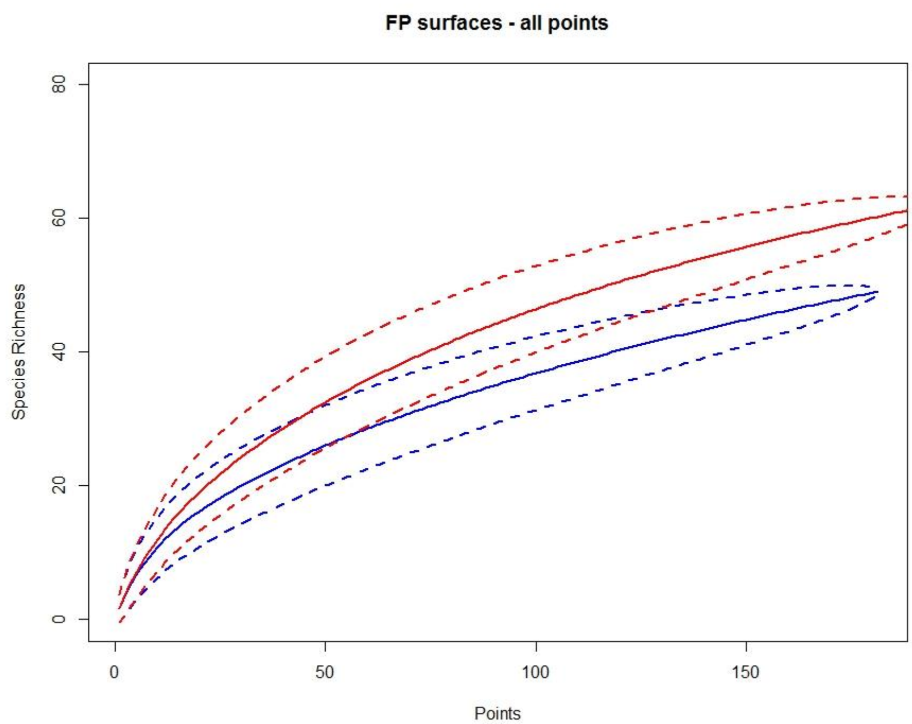

Figure 5.6: Species accumulation curve for floodplain surfaces, upstream and downstream of diversion. Dashed line indicates 95% confidence interval for values show of species richness per grouping.

Species Composition

ANOSIM, MRPP, and PERMANOVA analyses testing for species composition differences indicated statistically significant difference between upstream and downstream vegetation communities on floodplain surfaces (p-value = 0.01), when analyzed at a point level. Similar to results in hypothesis 1, difference between species composition was not significant when points were aggregated into site-level data, where all 100 points for a site were distilled into one frequency value for each species.

Table 5.5: Chi-square analysis of species frequency for low terrace surfaces for upstream versus downstream of diversion. Arrow indicates direction of magnitude towards upstream of diversion.

Species	Wetland Group	p-value	Upstream Frequency	Downstream Frequency	Direction of Change
GERI	FACU	0.0001	5	24	↓
Unk_195	FACU	0	0	21	↓
posp	FACU	0.0001	4	22	↓
TAOF	FAC	0.0087	19	33	↓
DECE	FACW	0	119	38	↑
EQAR	FACW	0.0007	15	34	↓
CAAU	OBL	0.0007	66	25	↑
CACA	OBL	0.0039	88	43	↑
CAUT	OBL	0	131	29	↑
SADR	OBL	0.0001	0	14	↓
SAGE	OBL	0.0044	95	48	↑
SAPL	OBL	0.001	34	8	↑

Wetland Indicator Status Groupings

Wetland indicator species groups found on the floodplain surfaces indicate slightly higher means of relative frequency of hydrophytic wetland species upstream of diversion, although not statistically significant (Figure 5.7). On the opposite side of the spectrum, the non-hydrophytic upland species were observed to have significantly higher means of relative frequency of occurrence downstream of diversion (p-value = 0.035). Both upland and wetland species relative frequency for upstream and downstream of diversion are shown in Figure 5.7. On low terrace surfaces, hydrophytic species were statistically more frequent upstream of diversions (p-value=0.026), while upland species were statistically more frequent downstream of diversion (p-value=0.008) (Figure 5.7).

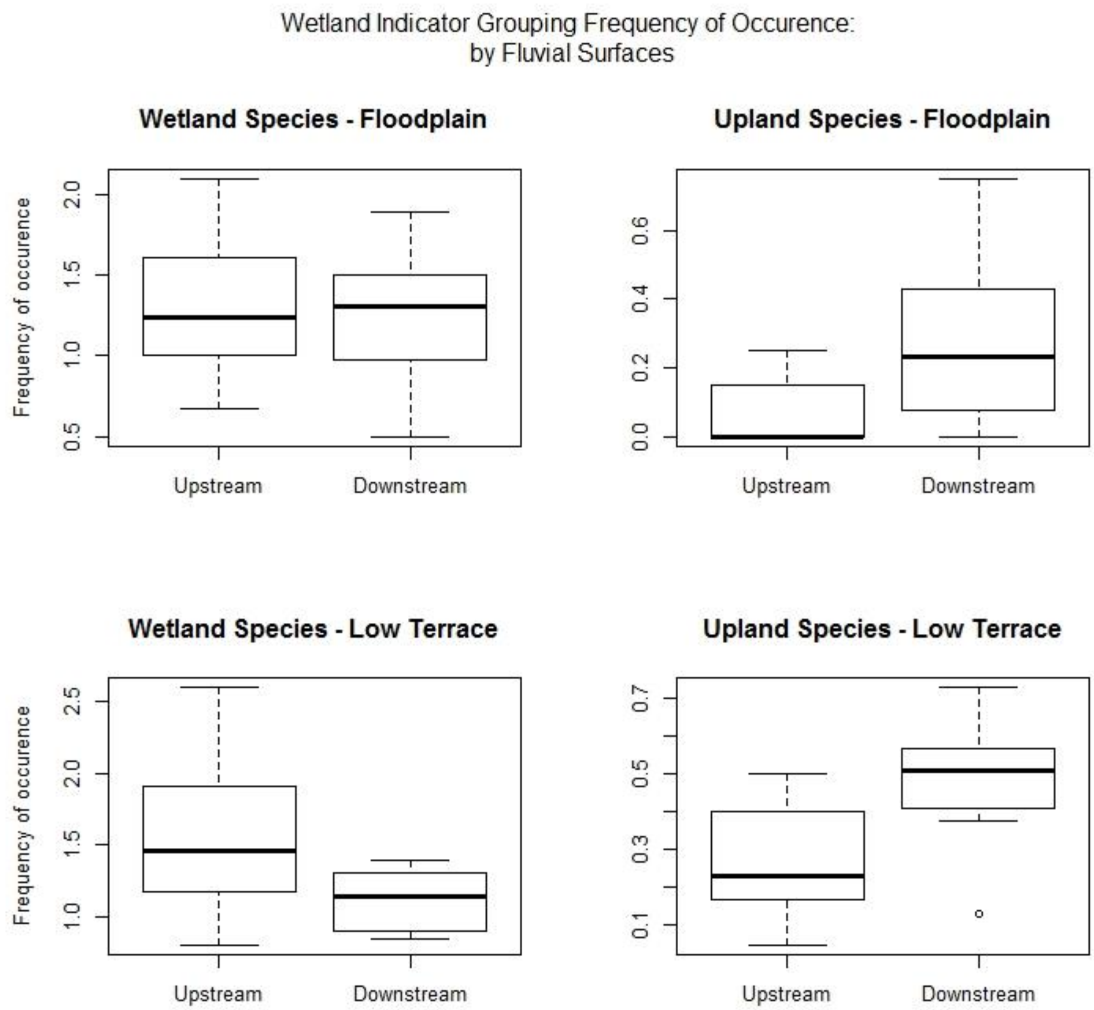

Figure 5.7: Box plots of wetland indicator groups, shown by relative frequency of occurrence, by fluvial surface for upstream and downstream of diversions. Floodplain surfaces shown on top and low terrace group on bottom.

5.4 HYPOTHESIS 4: SENSITIVITY TO ENVIRONMENTAL VARIABLES

The alternative hypothesis for sensitivity of riparian vegetation to diversions as a function of environmental variables, such as valley type and precipitation regime, is weakly supported.

Valley Type

Species richness mean is slightly higher downstream of diversion in partly confined valleys, although not significant (Figure A.15, Appendix A). Mean of the total frequency of individuals detected at the site is slightly higher upstream for both unconfined and partly confined reaches, yet not significant (Figure A.16, Appendix A). Diversity metrics show little change between upstream and downstream of diversion (Figure A.17). Evenness metrics indicated higher similarity in frequencies among species upstream of diversion, and were significant in the partly confined valleys ($p=.047$), but not in unconfined valleys (Figure A.18, Appendix A). Obligate wetland species were more prevalent upstream of diversions in the partly confined channels, which was significant at the level of $\alpha=0.1$ (p-value=0.07) (Figure A.19, Appendix A).

Precipitation Regime

I separated the sites into two precipitation regimes, lower (less than 90 cm) and higher (greater than 90 cm) which were chosen by a break in the distribution resulting in approximately half the sites in each grouping. Species richness was similar in groups upstream and downstream of diversion, in both low and high precipitation classes (Figure A.22, Appendix A). Total abundance was slightly higher upstream of diversions in the high precipitation regime, although not significant (Figure A.23, Appendix A). Shannon and Simpson diversity indices were higher downstream of diversion in high precipitation regimes, but not significant (Figure A.24, Appendix A). Evenness was higher in both precipitation regimes, not significant for both indices in low precipitation regimes, and significant for one out of the two indices for high regimes (Shannon p-value=.048, Simpson p-value=.12) (Figure A.25, Appendix A). High precipitation regimes had a significantly higher frequency of wetland species upstream of diversion at the level of α=0.1 (p-value=0.055) (Figure A.26, Appendix A), and lower frequency of upland species compared to downstream of diversion, although not significant (p-value=.15) (Figure A.27, Appendix A).

Diversion Structure

I selected three reaches based on their magnitude of diversion, and structural characteristics to investigate the differences in vegetation community composition. South Fork Big Creek, Chedsey Creek, and Grizzly Creek all had either well-engineered structures or substantial amounts of diversion potentially influencing the downstream environment. Qualitative analysis indicates that all three of these reaches had much higher wetland species occurrence upstream of the diversion, and decreased upland species occurrence downstream of the diversion (Figure A.28 and Figure A.29, Appendix A).

5.5 RESULTS SUMMARY

Focusing just on the alternative hypotheses, the statistically significant results can be summarized as follows:

> H_A1: Vegetation community composition above and below diversion sites does differ significantly.

On the whole, the results support H_A1. Evenness was significantly greater downstream of diversions. Species composition at a point level differed significantly between upstream and vegetation communities. Seven of the eight wetland species were significantly more abundant upstream of diversions, and six of the eight upland species were significantly more abundant downstream of diversions. Wetland species had a significantly higher frequency upstream of diversions.

> H_A2: Significant differences exist in species composition within lateral and vertical zones away from/above the active channel elevation.

The results partly support H_2A, in that some species typically considered wetland or upland indicators differed significantly in lateral and vertical zonation between sites upstream and downstream from diversions. Evenness was significantly greater downstream of diversion for some laterally and vertically zoned groups, but not all. Relative abundance of wetland species was significantly higher above the diversions in almost all elevation and distance groups. Upland species relative abundance was significantly higher downstream of diversion in one grouping. A few wetland species were significantly more frequent upstream of diversions, whereas three upland species were significantly more frequent downstream of diversions. Two wetland species had higher probability of occurrence upstream of diversions, whereas one upland species had a greater probability of occurrence near the channel downstream of diversions. Wetland and upland species had probabilities of occurrence significantly related to distance from the channel. Wetland species were significantly different upstream and downstream of diversions as a function of distance from the channel.

> H_A3: Species composition at identified fluvial landforms, specifically floodplains and low terraces, above and below diversions is significantly different.

The results partly support H_A3. For floodplain surfaces, as sampling intensity increases, the magnitude of difference in species richness values becomes greater, indicating higher species richness downstream of diversions at sampling size of $\geq$ 135 points. Only one wetland species occurs significantly more upstream from diversions, but upland species have significantly higher means of relative frequency of occurrence downstream of diversions. For low terrace surfaces, three upland species occurred significantly more downstream of diversion, and five hydrophytic wetland species occurred significantly more upstream of diversions. Frequency of wetland and upland indicator grouping differed significantly, with more wetland species upstream and more upland species downstream.

> H_A4: Sensitivity to diversions differs significantly between sites above and below diversions in relation to valley confinement and precipitation regimes.

H_A4 is weakly supported, in that only evenness and obligate frequency in partly confined valleys differed significantly, with higher evenness and higher prevalence of obligate wetland species upstream of diversions. For precipitation, only high precipitation regimes had significance in one of two evenness metrics downstream of diversion and greater wetland species frequency upstream of diversion.

6. DISCUSSION

Impacts on riparian vegetation as a function of flow alteration through diversions have been little studied, and the findings have been limited to mostly individual and population-level analyses in arid or semi-arid environments over two decades ago (Harris 1987; Stromberg and Patten 1990; Smith et al. 1991). My study focused on specifically low-gradient, pool-riffle reaches because these have been identified in literature as geomorphic 'response' reaches (Montgomery and Buffington 1997), and previous studies of the effects of diversions on channel morphology, substrate and macroinvertebrates found changes in these response reaches even when no changes were detected in other reach types (Ryan 1997; Rader and Belish 1999; Baker et al. 2011).

6.1 HYPOTHESIS 1: ALL SITES

Diversions that I surveyed typically have few long-term records and, based on my observations, the structure of many appear to pass high flows capable of being channel maintaining or 're-setting' events. This uncertainty and potential for periodic bypassing of the diversions by high flows, along with variability in operation of the diversions, as indicated by other studies, has made it difficult to detect changes in channel morphology and other attributes as a result of flow diversion. Despite these difficulties, I observed a clear change in riparian communities downstream of the various sizes and types of diversion structures. One of the most common measures of biodiversity, species richness, did not change significantly, although this likely reflects the increased presence of upland species in the riparian areas sampled. The next traditional measure, heterogeneity indices, often referred to as diversity indices, which factor in evenness and species richness, clearly indicates an increase in diversity downstream of diversions. Considering that species richness was not much different and further investigating the evenness aspect of diversity metrics, or the degree of similarity between all occurring species in a given sampling unit, I observed significantly higher evenness downstream of the diversions. Frequency amongst species downstream of diversions was more similar than in upstream reaches. This was supported by the fitting of ecological models to the rank-abundance data, resulting in shallower curves, evidenced by the type of best fit shifting between control and treatment groups. I inferred that this could be a result of decreased dominance of riparian species downstream of diversions, and this inference was supported by investigating the frequency of groups of wetland species.

Wetland species, defined as being hydrophytic and potential indicators of geomorphic settings associated with seasonal flooding, were significantly more frequent upstream of diversion. The change in dominance is an important indicator of systemic shift in community composition. When I further examined specific species that were changing as a result of diversion, species frequency analysis indicated seven of the eight wetland species significantly decreased in abundance downstream. On the other side of the hydrophytic spectrum, six of the eight upland species increased in abundance downstream, in addition to one weedy, invasive, generalist species (*Taraxicum officinale*). This finding further emphasizes a shift downstream of diversions towards increased frequency of upland and generalist species, and fewer wetland species. This shift in dominance and community composition from riparian or wetland species suggests a process of 'terrestrialization' of the riparian areas subject to flow alteration by diversions.

6.2 HYPOTHESIS 2: TOPOGRAPHIC INFLUENCE (ELEVATION AND DISTANCE)

Some of the important physical aspects related to hydrology and fluvial geomorphology that determine the structure and composition of riparian communities are frequency, magnitude and duration of flooding, and erosion and deposition of materials. These deterministic physical influences can then lead to important attributes that determine the presence and composition of hydrophytic riparian plant communities, such as energy and water saturation gradients. The exposure to these forces is variable as a function of elevation above or distance away from the channel. I further investigated the findings in support of H_A1 in order to identify where these changes were occurring in the riparian landscape.

Elevation

Elevation is assumed to strongly influence soil moisture. Evaluating this relationship was a primary goal, but I also examined the influence of distance from the channel, and found intriguing results in both cases. For elevation above active channel, evenness was only significant in the elevation grouping of all points less than 100 cm above the channel, suggesting that much of the shift in community might be occurring at points below that elevation. This result also potentially indicates that this is where an encroachment or increase of upland species, or a decrease in wetland species abundance, is having an impact. Wetland species relative abundance, similar to findings in the H_1 analyses, indicated significant decrease downstream in almost every elevation grouping. Interestingly, wetland species abundance was not significant in the nearest-to-channel grouping (<25 cm), and was most significant in the <75 cm grouping. This suggests that nearest the channel there is little change in prevalence of wetland species, but as elevation increases, riparian abundance decreases downstream of diversions. Upland species frequency relative abundance did not follow as striking a trend as wetland species, although upland species were significantly (at $\alpha=0.1$) more prevalent downstream of diversion at the same elevation grouping of < 100 cm. This suggests a possible threshold where riparian species are becoming less abundant, and upland species are encroaching due to changing soil moisture and a decrease in moisture availability for plants. Logistic regression also supports this finding, especially with respect to upland species, as the probability of occurrence for this functional grouping is higher downstream of diversion above 0.5 m, but continues to increase past 1 m above the channel, whereas the upstream regression curve increases at a much slower rate starting around 50 cm.

Distance

Distance from the active channel is related to elevation above the channel, position of fluvial landforms, increasing connection with terrestrial processes, and exposure to physical erosion via fluvial disturbance. While not generally viewed as being as strong a determinant in species composition patterns, analyses indicate that distance from the active channel is an important environmental gradient to consider when assessing impacts of diversion-induced flow alteration. Distance from the channel appears to be more strongly related to the composition difference of evenness between upstream and downstream of diversion, with distances less than 2, 3, and 4 m from the channel being significant, although sites closest to the channel are not different. The difference in evenness indicates that similarity in frequencies between species present at a site is changing as a result of flow diversion. This could reflect two processes related to a change in soil moisture gradients, which are not necessarily mutually exclusive. First, wetland species are being outcompeted or for other reasons not thriving. Two, upland species are encroaching because of increasing habitat suitability, likely a decrease in soil moisture. My findings suggest both of these processes. Wetland species relative frequency differences become more significant with increasing distance from the channel, with lower prevalence downstream of diversion. The species accumulation curves indicate a trend in greater species richness downstream of the diversion, with increasing distance from the channel. This difference between upstream and downstream becomes greater until peaking in the group <4 m from the channel, and is supported in that relative frequency of upland species is significantly greater at $\alpha=0.1$ downstream in the <3 m and <4 m groupings. Although distance from channel is interrelated with elevation, the findings suggest that moisture gradients downstream of diversions are likely both favoring upland species and not favoring wetland species.

6.3 HYPOTHESIS 3: FLUVIAL LANDFORMS

Fluvial landforms are formed by particular geomorphic and hydrologic processes (Hupp and Osterkamp 1985; Hupp and Osterkamp 1996; Rot et al. 2000). These landforms are uniquely related to elevation above the channel, and flow duration and frequency of flooding, and have been tied to distinct differences in riparian vegetation community. Given that these fluvial surfaces are closely linked to hydrologic characteristics of duration, frequency and magnitude of flow, and geomorphic processes of deposition and scour, I used these as a framework to evaluate the impact diversions might have because of direct alteration of some of these elements of the flow regime.

Floodplains and low terraces accounted for over 80% of the total points collected, and have distinct differences in certain aspects of the vegetation community. Floodplains are at or near bankfull elevation, commonly close to the channel but not always, and would typically be inundated seasonally or every two years. Low terraces are slightly higher than the floodplains, usually ~ 0.3-0.5 m above floodplain surfaces, and subject to less deep and frequent inundation, as well as less erosion and deposition, compared to floodplains. Both floodplains and low terraces did not show any large differences in the biodiversity metrics of evenness, or diversity, but exhibited trends similar to the rest of the data, having higher diversity and evenness downstream of diversions.

On floodplain surfaces, the species accumulation curves indicated a significant difference in species richness, being higher downstream of diversion, likely because of encroachment by non-hydrophytic individuals into more suitable habitat. Although the species richness was significantly different downstream of diversion, the relative wetland species abundance did not change, suggesting that hydrophytic wetland species were not decreasing in prevalence. This is supported in an individual species frequency analysis, indicating only one wetland species was more prevalent upstream of diversion. On the opposite side of the spectrum, more terrestrial, upland species were significantly more prevalent downstream of diversion. This implies that the conditions on floodplain surfaces are still supporting wetland species, although favoring terrestrialization. On low terrace surfaces, wetland species decreased downstream, whereas upland species increased. The individual species frequency analysis supported this finding within the functional wetland groupings, with all four FACU or FAC species occurring more frequently downstream, and six of eight wetland species decreasing downstream. This suggests an important change in the conditions on low terraces, favoring upland species, and potentially becoming less suitable for wetland species. This response could be either because of a direct change in abiotic factors (decreased flood frequency, magnitude and duration), or an indirect relationship with abiotic factors in which favorable environments are created for competing species/groups, which then outcompete the other species/group.

6.4 HYPOTHESIS 4: SENSITIVITY TO ENVIRONMENTAL VARIABLES

I examined environmental variables to detect sensitivity related to different independent variables that strongly influence species and community patterns in riparian areas. First, I examined valley type: all sites with the exception of one were partly confined or unconfined. Different valley confinements can have distinct vegetation communities, and these communities may respond in different ways to diversion-induced flow alteration. Unconfined valleys, as might be expected, tend to have wider riparian areas, and might have a greater area across which to respond to diversion-induced flow alteration, yet I did not find any difference in the metrics tested. Although downstream of diversion had higher evenness in partly confined valleys, and lower obligate wetland frequency, the relationship was not strong, indicating that this was a geomorphic condition associated with the riparian communities being more sensitive to abiotic changes.

Precipitation is an important variable partly determining discharge (Naiman et al. 2005), and hydrology can have large variation as a result of different precipitation regimes. The Routt covers a relatively large geographic area, occupying both sides of the continental divide, and has a wide range of values for mean annual precipitation. As a result of different hydrologic conditions throughout the study sites, the community composition and productivity could be different, and comparing both subsets together may limit ability to discern responses of riparian plants to flow diversion. I speculated that the reaches within the lower precipitation regime would be more sensitive to the changes in flow as a result of having less available water, but there were no differences between upstream and downstream within this subset. Also, within the higher precipitation regime subset, no substantial differences upstream and downstream of diversion were observed.

Many of the diversions structures visited were in poor condition and appeared to have little capacity to influence overall discharge during either peak or base flow. Each of the three paired reaches chosen to analyze the effect of magnitude of flow diversion had either the ability to withdraw a substantial amount from the creek, or have records supporting these types of withdrawals. Each of these three reaches indicated trends of terrestrialization, with decreasing wetland species and increasing frequency of upland species, downstream of the diversion. While qualitative, these results suggest that the magnitude of diversion may impact the downstream vegetation communities to a greater degree, with important implications for land management.

6.5 CAVEATS/LIMITATIONS

Hydrology is an important aspect of this study, as riparian vegetation composition and structure are highly correlated with flood duration, magnitude and frequency. Several aspects of other hydrologic parameters would have been helpful in describing and explaining some of the responses I observed, as well as supporting additional inference. The lack of gaged stream flow over the course of several years at any of the 38 sites prevented any investigation into the relationship of riparian areas and vegetation points to flow duration or flood frequency. Relating these hydrologic parameters to the vegetation points would have been an additional step beyond examining relationships between vegetation and elevation, distance and fluvial landform, and perhaps have provided a more robust and direct indicator than elevation, distance and landform. The feasibility of this is questionable with respect to length of time and effort, as I would need at least several years of data that included wet and dry years, as well as the time spent to instrument study sites. Regarding historical hydrologic data, some of these diversions have been in place in one form or another for over a century, yet the records of timing and magnitude of withdrawal are often incomplete, inconsistent, and sometimes non-existent. Having these data, even in the form of a contemporary subset that could be used as a proxy for previous years, would allow more inference regarding the timing and/or magnitude that is most affecting riparian vegetation communities. In terms of management implications, it would be very powerful to have a threshold of response defining a significant increase in impact beyond a certain amount of withdrawal or withdrawal during a certain time of the year.

A year of abundant snowpack and a year of drought – the two field seasons of data collection, summer 2011 and 2012, could not have been more different in terms of hydrology. 2011 set near-records for the amount of snowpack in June, with all three major basins (Colorado, North Platte, and Yampa), having greater than 250% of average snowpack at the date of measurement. In stark contrast, during 2012 the three basins had a June snowpack at 6% of average. The 2011 snow year made it difficult to access sites, let alone conduct geomorphic channel surveys. In terms of geomorphology, a year like this could act as a ‘resetting’ event, scouring channel margins, inundating fluvial surfaces and elevations above the channel that may only be inundated once every twenty years or longer. Few if any of the diversions are capable of diverting large quantities of a snowmelt peak flow of this magnitude. This has the potential to make it especially difficult to detect geomorphic changes. More relevant to this thesis, high flows make it difficult to detect changes in species that reflect shorter term changes in flow regime, such as annuals which complete their lifecycle in one growing season, versus a perennial species that might reflect longer term change (or respond at a slower rate). Fortunately for this study, these diversions have been in place longer than a few years and likely influence an overall community structure that reflects a prolonged period of flow alteration. In contrast, 2012 had little to no overbank flow during the peak snowmelt runoff. These drought-like conditions presumably impact vegetation communities, but similarly may only manifest on a short time scale in individual traits of a species such as annuals or other species that may respond to seasonal or annual variations in flow regime.

Diversions were commonly located at breaks in gradient, at property boundaries, or between distinct process domains or valley types. One of my goals with site selection, to increase robustness of analyses, was to constrain environmental variables between paired sites by only using reaches that were similar in valley type, hydrology, land use, watershed area and stream gradient. Although there are over 850 diversions in the Routt, finding suitable sites proved difficult.

Soil type was not controlled for in my study, and likely varied between sites across the Routt study area. But, within a paired site, the assumption was that upstream and downstream soil types were the same because of their proximity. Also, soil saturation is an important attribute that controls the presence of hydrophytic vegetation (Naiman et al. 2005). In riparian areas, this can result from overbank flow, overland runoff, hillslope-influenced subsurface flow, or base flow from the channel. I assumed the abiotic factors overbank and base flow to be the controlling influence because of proximity to the channel. I did not characterize soil wetness at a site or point-level basis. Quantifying this variable could have accounted for some paired-site differences, potentially leading to a better understanding of whether groundwater (subsurface flow from adjacent hillslope topography) was contributing to the presence of hydrophytic species at the site. This inference may have been possible during the summer of 2012, because there were little to no overbank flow, and overbank flow would have occurred much before sampling. In summer 2011, however, I saw sites that experienced overbank flows upstream and downstream of a diversion, sometimes into the month of August. Nevertheless, soil wetness could be an important variable in explaining some of the variability between plant communities.

Another important aspect of this research is the temporal component of the data collection and analysis. I want to emphasize that these results are a snapshot in time, where I am using space (upstream versus downstream) as a surrogate for time. This introduces some uncertainty, with an example being longer-lived plants, which can survive dry spells and obscure interpreted trends. As a result, short-term trends may be harder to interpret, but most of the diversions sampled for this study have existed for a century or more.

6.6 MANAGEMENT IMPLICATIONS

The findings support the interpretation that diversion-induced flow alteration is impacting riparian communities, but the question remains as to how this affects land management. Bunn and Arthington (2002) state that natural patterns of lateral and longitudinal connectivity are integral for sustaining populations of many riverine species. Homogenization of vegetation is occurring downstream of these diversions on low-gradient streams, similar to the homogenization of flow, fish and wetlands across the globe. Specifically, hydrophytic, wetland species are decreasing in abundance downstream of diversion, which could have adverse impacts on conditions such as allochthonous energy inputs as well as instream temperatures. If diversions currently exist, or are proposed for future development, in streams or watersheds that have been identified as higher priority, land managers should evaluate carefully whether these diversions should be allowed, and, if so, what species are present and how will the timing/magnitude of withdrawal impact these species in the context of the element(s) that are deemed important. The magnitude of withdrawal over the course of total discharge should be understood and amounts withdrawn overseen, as riparian areas have species uniquely adapted to the conditions present prior to alteration.

Altered flow regimes can also help increase the success of exotic and introduced species (Bunn and Arthington 2002), and in this study the weedy, generalist species *Taraxacum officinale* was observed to have increased downstream of diversions. Land managers from numerous agencies often deal with the issue of invasive species. The observed increased prevalence could suggest the importance of specifying certain areas where this may already be a problem or have a high potential to be a problem, and influence management decisions regarding withdrawals accordingly. Impacts of invasive species can potentially be mitigated by reducing the amount of discharge withdrawn, or identifying aspects of the flow regime that the present plants need to outcompete specific invasive species.

Climate change, predicted to increase temperatures and trigger an earlier snowmelt peak, could also have an impact on riparian plant communities. Many species have life cycles that are adapted to certain timing of peak flows, either for dispersal, germination or other reproductive traits, and could be selectively excluded as a result. In an already sensitive environment, the change to the hydrologic cycle caused by climate change could be further exacerbated by diversions, specifically those lacking restrictions during certain times of the year, or by simply taking a large proportion of the flow.

From a land management perspective, it is significant that the habitat downstream of diversions is decreasing in suitability for hydrophytic species. Whether this continues farther downstream needs further attention, to understand whether the impacts observed in this study are attenuated by downstream hydrologic inputs, changes in process domain, or other signals controlling response to a greater degree.

Ultimately, as a result of diversions being so widespread, land managers should look closely at the timing and magnitude of withdrawals from the system. Because both flood duration and magnitude, and base flow, are important components determining soil wetness and therefore presence of hydrophytic species, the percentage of these particular components of the flow regime that diversions extract, as well as duration of flow extraction, should be examined closely and evaluated for potential significant effects. If a diversion is reducing peak flow by a noticeable amount every year, in many years this could likely make the difference between floodplains being inundated or not, and accordingly have an effect on the plant communities and successional stages of species population. In terms of base flow, if a diversion is extracting a significant amount of water and/or for long periods during this season, subsurface flow gradients could be directly impacted, lowering the groundwater table and soil wetness in the riparian areas, potentially leading to the impacts I observed in this study.

Management of diversions, and mitigation of their effects, could be addressed in three manners. First, focusing on the timing, magnitude and duration of withdrawals and comparing the hydrograph upstream and downstream of a diversion or in similar, unaltered watersheds with a more natural flow regime can support a professional judgment on whether diversion impacts may be significant. If long-term records exist, a hydrologic alteration analysis, such as Indicators of Hydrologic Alteration (IHA) (Mathews and Richter 2007), could be used as defensible support for interpretations regarding which withdrawal regulations could be imposed. Second, identifying key areas of biodiversity, such as partly confined and unconfined valleys with low-gradient reaches downstream of a diversion, or multiple diversions, and/or sensitive areas, can be used as justification for high priority sites to target with mitigation or conservation efforts. Third, ensuring that proper oversight of diversion withdrawals is occurring, and working with water districts or overseeing the water agency to ensure records are being kept, especially during periods when hydrograph triggers are most important for riparian communities, is critical. This may be most important with diversion structures that have the capacity to block all flow, regulate amount withdrawn, and/or capture a significant amount of flow otherwise going down the natural channel.

6.7 FUTURE WORK

Understanding some of the finer scale differences in riparian vegetation above and below flow diversions could be achieved with the combination of research focusing on hydrology as a primary driver of the system, and more intense sampling at a site-level basis. Details of flow alteration by the diversions were largely unknown for this study. Many of these diversions have water rights dating back to the early 20th century, or even earlier, and the records for withdrawal amounts are in many cases non-existent, negligible, or not interpretable. Understanding the withdrawal timing and magnitude has the potential to develop thresholds of response necessary to sustain riparian vegetation populations and communities. Timing of withdrawal, either during snowmelt runoff peak flow, or late season base flow, could favor certain species better adapted to these conditions, whether wetland or upland, exotic or native. Similarly, magnitude of withdrawal, in combination with timing, could create thresholds that help dictate soil wetness, an important attribute in determining presence of hydrophytic plant species. Likely, response thresholds will be along a gradient as a function of other environmental variables such as channel and floodplain morphology, groundwater influences, and climate, but these could be constrained through more in-depth monitoring of hydrology, relating riparian surfaces to flooding frequency, determining soil wetness at different times of the year, and measuring hillslope-groundwater influences (even if only as a rough characterization). On the opposite side of the spectrum, compared to the focus on a large sample size in this study, many of these objectives could be achieved by focusing sampling on several pairs of upstream/downstream reaches, and revisiting these sites multiple times a year to characterize hydrology, hillslope connection, individual and population ecology, and ecosystem ecology or productivity.

The findings suggest, overall, that frequency of riparian, hydrophytic species is decreasing downstream of diversions, potentially indicating a change in the overall biomass of the riparian systems. From an ecosystem ecology perspective, measurement of the biomass of communities could have important implications, with diversions potentially reducing the overall productivity of riparian areas.

7. CONCLUSIONS

Many of the word's rivers are affected by direct flow alteration, primarily by dams and diversions, yet the impacts of the latter on riparian plant community composition and diversity have received little attention and are not well understood. Diversions extract water from streams without impounding flow, not necessarily altering the shape of a hydrograph, yet can reduce peak and base flow, thereby changing the abiotic factors to which the stream has adjusted. Riparian vegetation communities have adapted to the unique abiotic conditions of the timing, magnitude and duration of the flow regime, implying that changes in flooding disturbance and water availability could lead to decrease in suitable habitat and species invasion (Bunn and Arthington 2002; Naiman et al. 2005). Developing an understanding of the effects on riparian vegetation by diversion-induced flow alteration is important for land managers and future researchers to: better understand how to manage flow regimes (withdrawal timing, magnitude and duration); sustain plant communities and beneficial ecosystem services; and focus future study to investigate other regions and specific thresholds of hydrologic alteration resulting in community change.

My research indicates that diversions influence both the community composition and diversity of the riparian communities through reducing the overall discharge downstream of the point of diversion. Field observations indicated that evenness increased downstream from diversions in low-gradient, montane riparian areas through decreased dominance of wetland indicator species groupings, as well as an increase in frequency of several upland indicator species. These results support my first hypothesis that species composition changes downstream of diversion, taking into account all points collected. This provides support for the 'terrestrialization' hypothesis, where habitat is becoming more suitable for upland species, as shown by decreasing wetland species and increasing upland species downstream of diversion.

Elevation is an important determining variable in presence and prevalence of hydrophytic species, as it is inversely related to exposure to shear forces, deposition and scour, and magnitude and duration of flooding. Examination of species composition at defined elevations above the active channel indicated a threshold: decrease in wetland species and increase in upland species became most apparent downstream of diversion at ~1 m above the channel. A similar trend was also shown in the logistic regression curves, supporting my second hypothesis. Distance from active channel edge, the other topographic variable, showed a similar trend in decreasing wetland species abundance and increasing upland species abundance downstream from diversion, becoming more pronounced with greater distance from the channel. Although this can often be interrelated with elevation, the results suggest that the greater the distance from the channel, the more important the natural patterns of flow regime are to sustaining plant communities.

Fluvial surfaces, either floodplain or low terrace, have distinct relationships to hydrologic and geomorphic processes, and, in support of my third hypothesis, have significant changes in species composition downstream of diversion. Floodplains, commonly annually inundated surfaces, had significantly higher species richness downstream of diversion, yet only had significantly higher wetland species abundance, whereas the upland species frequency remained similar. This suggests that the habitat is becoming more suitable for encroachment by other species, although they are not thriving. Low terraces are features higher above and/or farther away from the channel that are inundated much less frequently than floodplains, potentially being more dependent on base flow for sustaining natural riparian plant communities. These surfaces have both decreased wetland species frequency and increased upland species frequency downstream of diversions, suggesting that the abiotic conditions downstream of diversion are supporting this process of ‘terrestrialization.’ Because these surfaces are more temporally removed from overbank flow, the wetland plant communities may be more adapted to soil wetness determined by base flow, which might be the abiotic factor causing these surfaces to have a more pronounced response to diversion-induced flow alteration.

Many studies have examined the effects of dams on riparian areas, but this work is the first to investigate changes in plant community composition as a result of diversion, quantifying effects as a function of topography (elevation and distance) and fluvial surface. More intensive, site-level studies quantifying the hydrology and functional characteristics of the plants are necessary to characterize the particular aspects of the flow-regime necessary to sustain healthy riparian plant communities and populations, as well as identifying the response thresholds at which effects of altered hydrology significantly influence the composition and functioning of these ecosystems.

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A. APPENDIX A: ADDITIONAL FIGURES

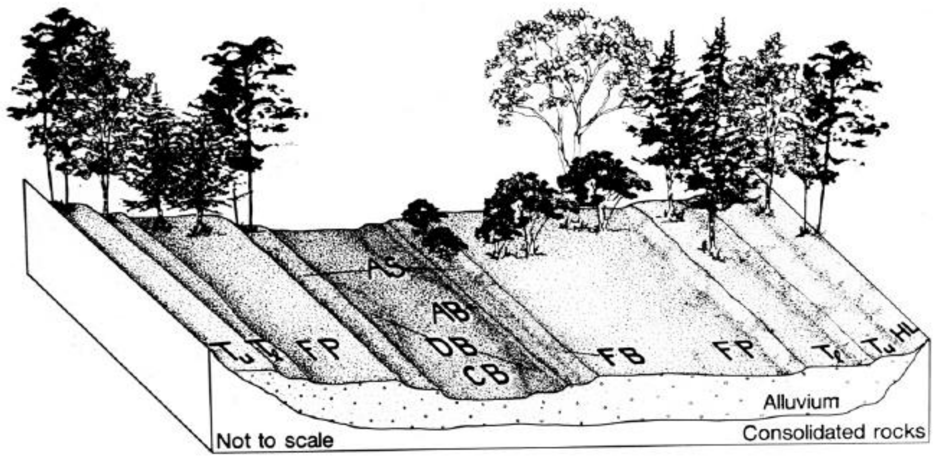

Fig. 1. Block diagram showing alluvial surfaces of perennial streams of northern Virginia; from the lowest, the surfaces are CB, channel bed; DB, depositional bar; AB, active-channel bank; AS, active-channel shelf; FB, flood-plain bank; FP, flood-plain; T_l, lower terrace; and T_u, upper terrace (from Osterkamp and Hupp, 1984).

Figure A.1: Figure showing the different fluvial landforms, relative height above the channel, and associated vegetation community. (From Osterkamp and Hupp, 1984, Figure 1)

Figure A.2: Examples of diversion structures on Routt National Forest (modified from Blaschak (2012))

Clockwise from top right. (1) Service Creek Diversion - Levee obstructing all flow, acting as a dam, diverting into canal in upper right of photo. (2) Beaver Creek Diversion – rock weir perpendicular to flow raising base level and directing flow towards log headgate structure. (3) East Fork Williams Fork Ditch – Another rock weird but metal headgate, most typical structure for diversions in study. (4) Little Muddy Creek Diversion - Structure composed of two concrete headgates, one regulating flow to natural channel (foreground) and the other regulating flow to the canal (background). 1 and 4 are both capable of blocking all but very large events (~ > 50 yr recurrence interval). Photos taken by Simeon Caskey and Tyanna Schlomm during 2011 and 2012

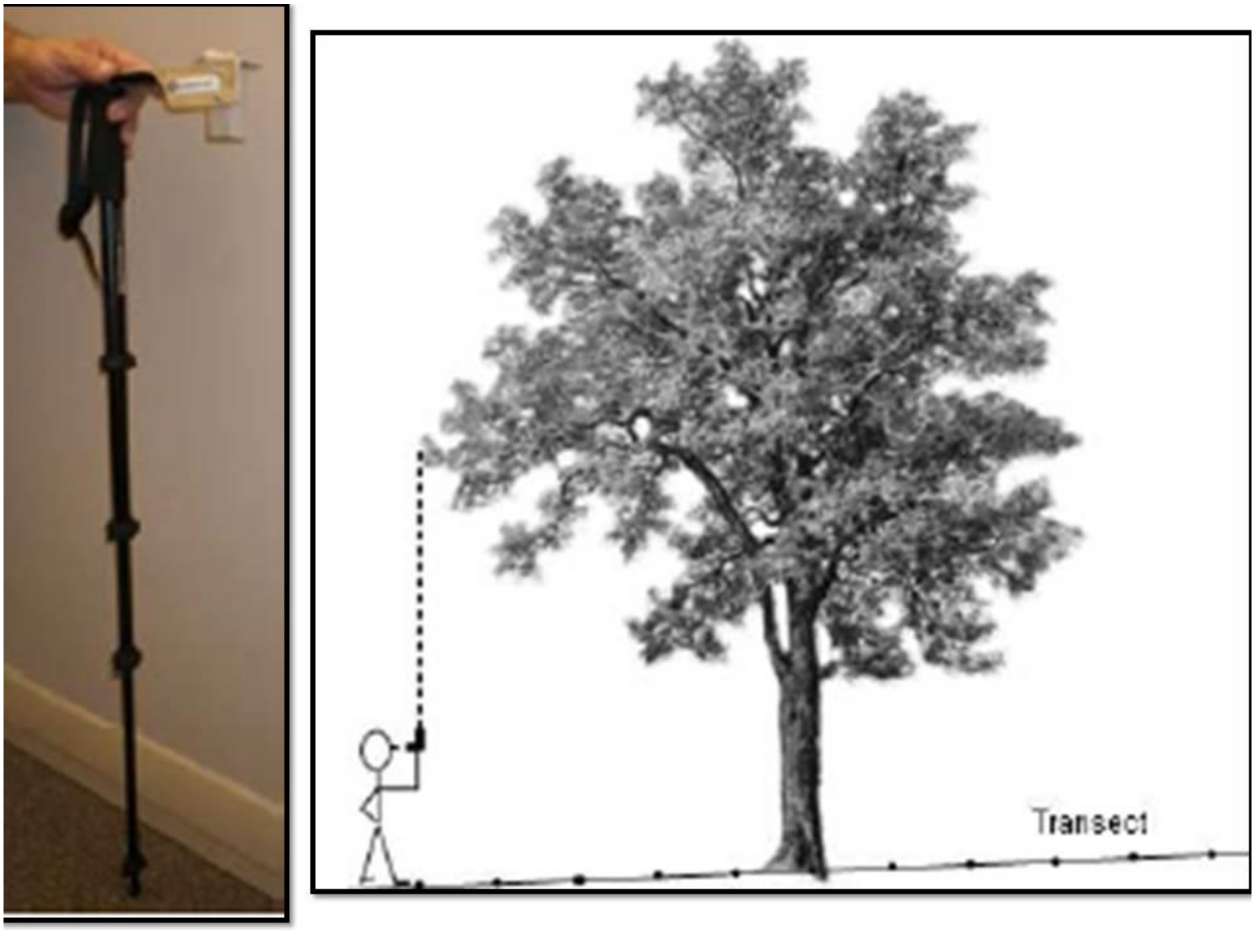

Figure A.3: Graphics of laser pointer and its use.

(1) Picture of pointer mountain on trekking pole (from countgrass.com). (2) Example of laser pointer use, measuring vegetation above user (from USDA in prep).

A.1 DATA ANALYSIS METHODS – ADDITIONAL DISCUSSION AND EQUATIONS

Equations

$$H' = -\sum p_i ln p_i$$

Equation A.1: Shannon's Diversity Index (p_i = proportion of individuals for i^{th} species)

$$D = \sum\left(\frac{(n_i[n_i - 1])}{(N[N - 1])}\right)$$

Equation A.2: Simpson's Diversity Index (n_i= # of individuals in i^{th} species, and N = total # of individuals)

$$J' = \frac{H'}{lnS}$$

Equation A.3: Shannon Evenness Measure (H' = Shannon Diversity Index, and S = species richness for given sampling unit)

$$E_{\frac{1}{D}} = \frac{\left(\frac{1}{D}\right)}{S}$$

Equation A.4: Simpson's Evenness Measure (D = Simpsons Diversity, and S = species richness)

$$B = \frac{A + B - 2 * J}{A + B}$$

Equation A.5: Bray-Curtis Dissimilarity Index (for binary data)

Diversity Metrics

The Shannon Diversity metric was chosen as one of two primary diversity indices to use for analysis, mainly because it is a time-honored and commonly used index to characterize the heterogeneity of many different types of communities. In researching the best use of biodiversity measurements, it appears that the Shannon method is biased towards higher species richness, such that the index value will be greater given more species at a given sampling unit. For that reason, I chose to also use the Simpson index, which has been touted as a more robust alternative, less sensitive to species richness biases mentioned above, with evenness playing a larger role in the ultimate metric. The combination of the two methods commonly indicated similar trends in the data, probably because the species richness values for the compared sites was similar enough not to make the bias of Shannon influence the resulting values. For evenness metrics, I also used two indices, both derived from the above-mentioned diversity metrics, for the same reasons. The majority of the time, as with the heterogeneity metric results, the evenness metrics trended in the same direction, although in the case where they did not agree, I deferred to the Shannon evenness values because of less sensitivity to species richness.

Community Composition Analysis

Three different multivariate community composition tests were used to examine the vegetation data. The adonis function, analogous to permutational MANOVA, has been touted as a more robust alternative to both the ANOSIM and MRPP tests (Oksanen 2011). ANOSIM has been shown to have difficulty regarding the interpretation differences of dispersion within groups and between groups (Warton et al. 2012), and the MRPP function will show significance as a result of there being a difference in means *or* dispersion between groups. Adonis tests specifically for differences between the means of different groups, using a method that is analogous to permutational MANOVA, and can be complemented with the use of the betadisper function, which models the differences in spread between groups with a given dissimilarity index.

A.1.1 ELEVATION INTERPOLATION

Assigning elevation values for each vegetation point proved difficult, as in total I sampled approximately 3800 points at 38 reaches. To maximize efficiency in the field, I surveyed points along transects at significant topographic elements (i.e., breaks in gradient, midslope, high points, low points, etc.). This resulted in not occupying and collecting the exact location of every vegetation point. For each transect, I had a known starting and ending point for the topography and vegetation, and therefore could associate one with the other. Then, also having measured and recorded the distances along the transect where each vegetation point was located, I could interpolate the elevation for that distance along the surveyed line. To achieve this, I used the Matlab tool ‘interp1q’, and systematically assigned elevations for each vegetation point.

A.2 ADDITIONAL RESULTS

A.2.1 SMITH-BRIGHTON: BEAVER IMPACTED REACH

The Smith Creek Brighton Diversion site was affected by current beaver presence to a great degree. Upstream and downstream of the diversion contrasted with each other, as the upstream water level was well below bankfull, or even active channel edge, whereas downstream the water level was near or at bankfull due to active beaver impoundments. This was an especially stark contrast as the site was visited in late summer, during a significant drought year. The geomorphic contrasts I observed were supported by some basic vegetation characteristic analyses. The genera *Salix* was almost twice as abundant downstream, growing much more densely than upstream. The introduced and more upland generalist species *Trifolium pretense* was significantly more common upstream of the diversion, occurring 34 times, compared to 2 times downstream. The hydrogeomorphic evidence, as well as the cursory vegetation analyses, suggest that riparian vegetation of Smith Creek immediately below the diversion is being primarily influenced by the water table height as a function of active beaver damming.

A.2.2 HYPOTHESIS 1: ALL DATA

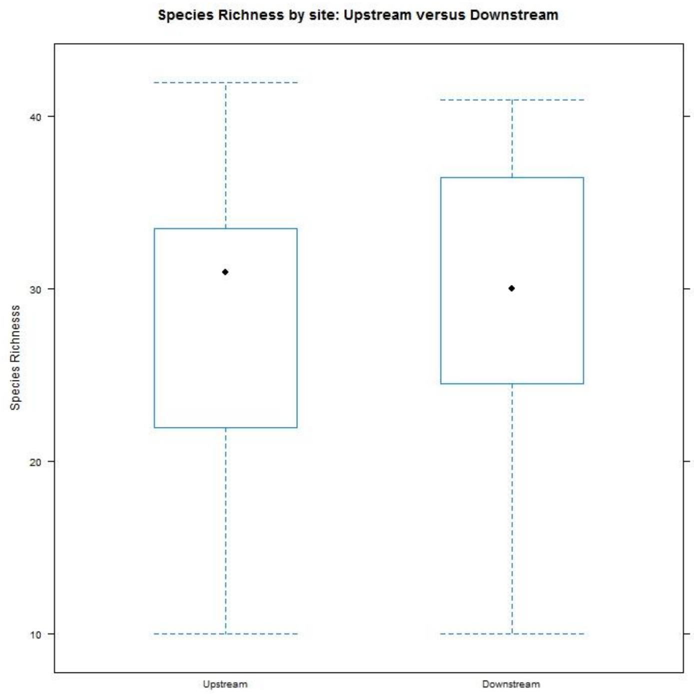

Figure A.4: Richness upstream and downstream

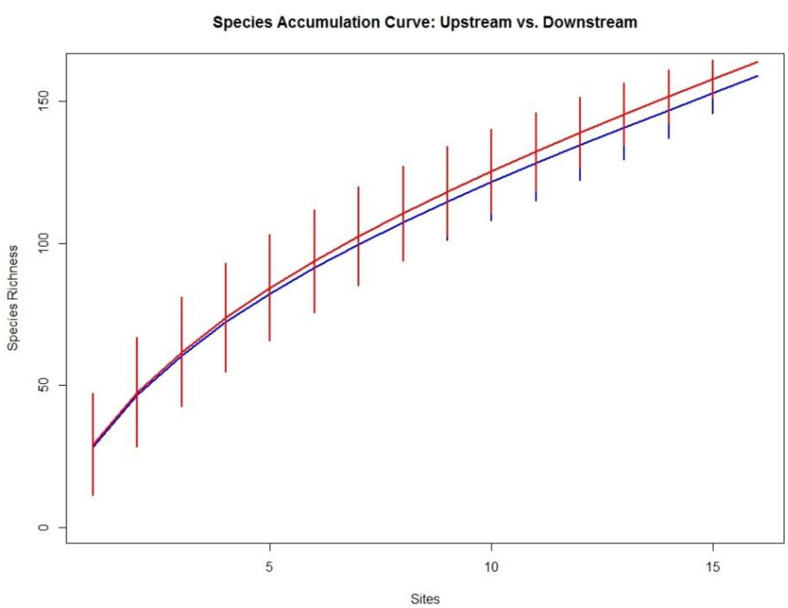

Figure A.5: Species accumulation curve - upstream versus downstream

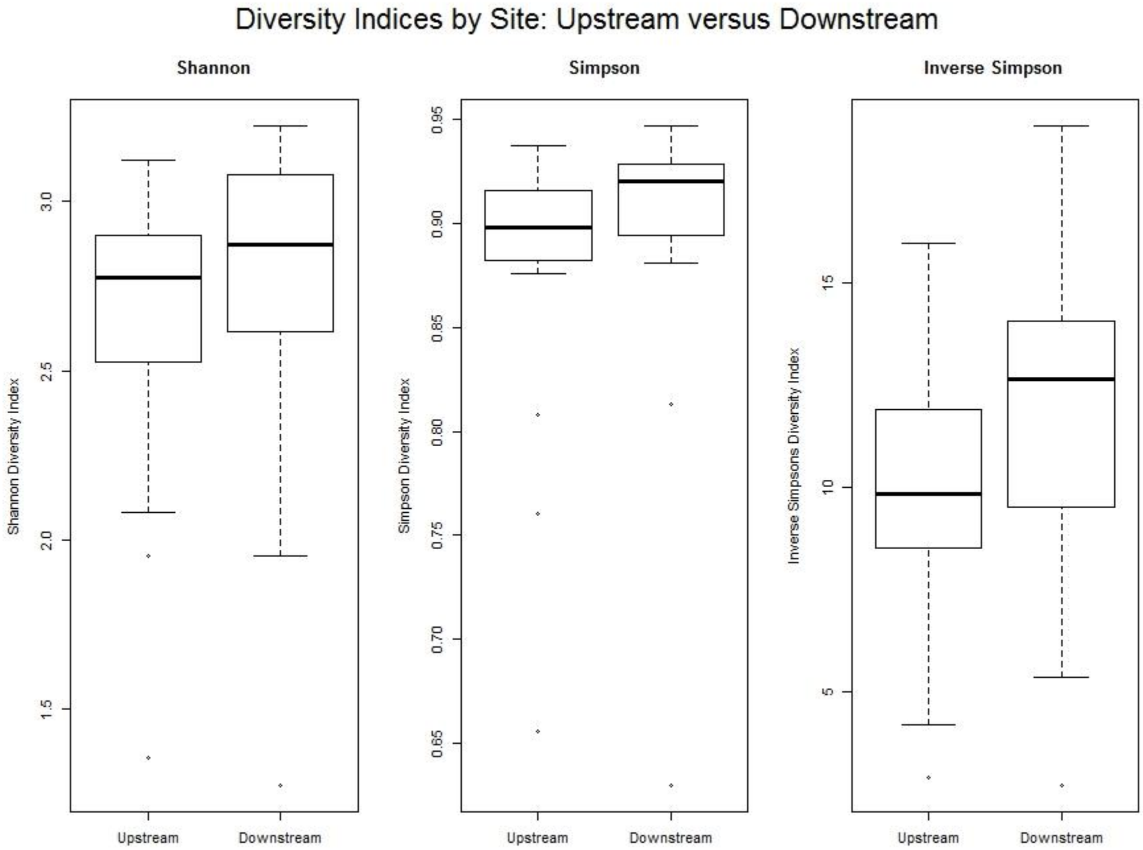

Figure A.6: Box plot of diversity indices upstream versus downstream of diversion

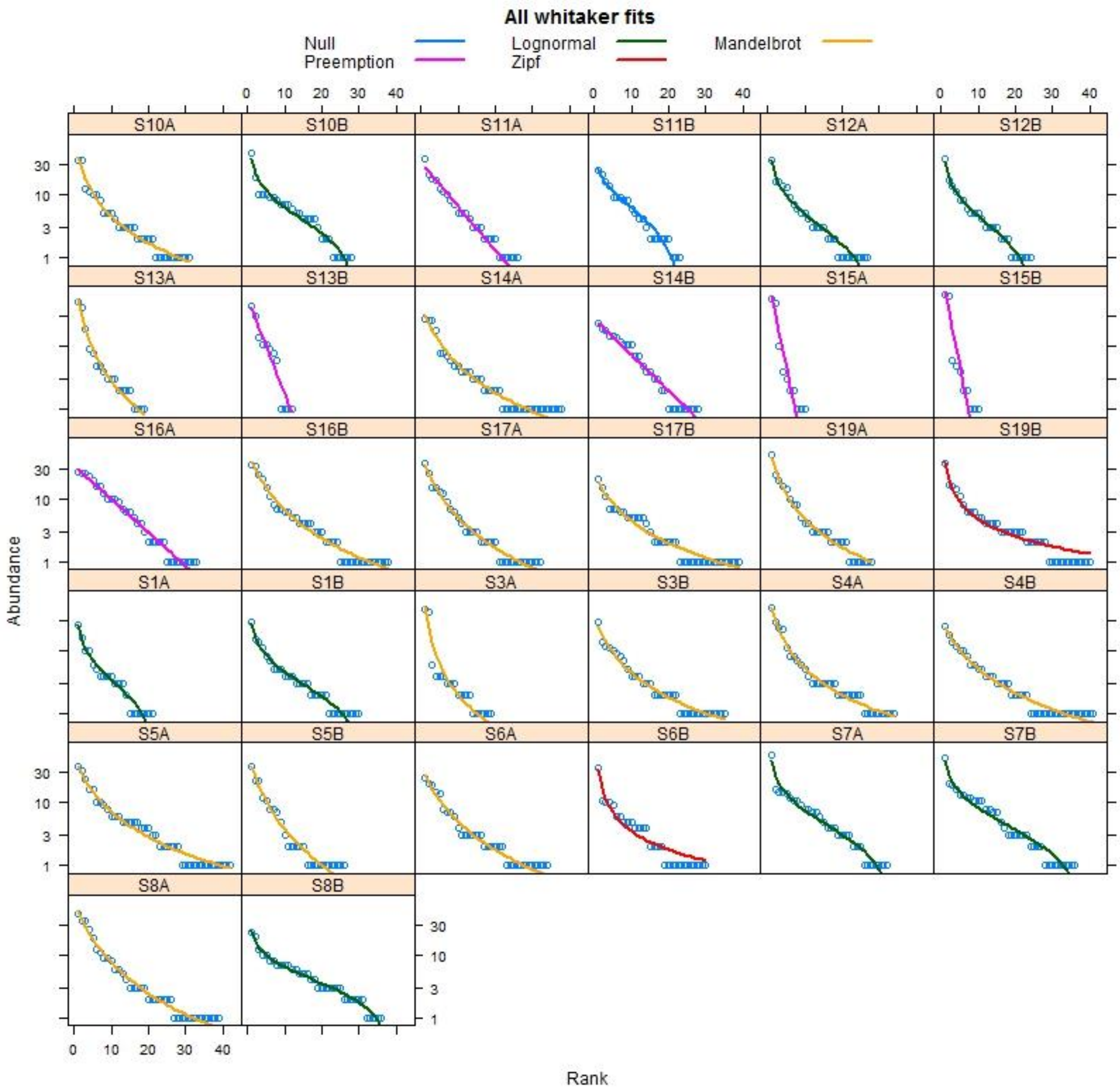

Figure A.7: Whitaker plots of all sites

A.2.3 HYPOTHESIS 2: LATERAL AND VERTICAL ZONATION

Table A.1: Species frequency analysis of elevations groups of less than 25cm, 50cm, and 75 cm above active channel. Functional status, p-value, frequency and direction of change oriented towards upstream.

	Species	Wetland Group	p-value	Upstream Freq	Downstream Freq	Direction of Change
<25	SAWO	OBL	0.0059	25	7	↑
<50	DECE	FACW	0	96	20	↑
	CAUT	OBL	0.0065	115	68	↑
	SAPL	OBL	0.0051	35	12	↑
	SAWO	OBL	0.0009	50	18	↑
<75	ABLA	FACU	0.005	18	4	↑
	BRIN	FACU	0.0073	9	0	↑
	PIPO	FACU	0.0009	0	13	↓
	POPR	FACU	0.0026	0	11	↓
	Unk_195	FACU	0	0	22	↓
	LIPO	FAC	0.0055	14	2	↑
	TAOF	FAC	0.0015	36	69	↓
	DECE	FACW	0	146	44	↑
	EQAR	FACW	0.0016	40	74	↓
	POFR	FACW	0.0022	2	16	↓
	CAUT	OBL	0	185	103	↑
	SAPL	OBL	0	73	31	↑
	SAWO	OBL	0.0006	79	42	↑

Table A.2: Tables of mean elevation above channel, and mean distance from channel, for wetland indicator groupings upstream and downstream of diversion. Direction of change indicates direction toward upstream.

		Upstream		Downstream		
	Wetland Indicator Grouping	Mean Elevation (m)	Standard Error	Mean Elevation (m)	Standard Error	Direction of Change
Elevation	UPL	0.59	0.07	0.63	0.05	↓
	FACU	0.69	0.02	0.75	0.02	↓
	FAC	0.67	0.02	0.67	0.02	↑
	FACW	0.55	0.02	0.63	0.02	↓
	OBL	0.59	0.01	0.64	0.01	↓
	FACW & OBL	0.59	0.01	0.64	0.01	↓
	UPL & FACU	0.69	0.02	0.75	0.02	↓

		Upstream		Downstream		
	Wetland Indicator Grouping	Mean Distance (m)	Standard Error	Mean Distance (m)	Standard Error	Direction of Change
Distance	UPL	2.67	0.40	2.38	0.56	↑
	FACU	3.28	0.11	3.18	0.10	↑
	FAC	3.25	0.13	3.26	0.13	↓
	FACW	3.28	0.13	2.91	0.13	↑
	OBL	2.95	0.07	3.10	0.08	↓
	FACW & OBL	2.95	0.06	3.05	0.07	↓
	UPL & FACU	3.28	0.11	3.17	0.10	↑

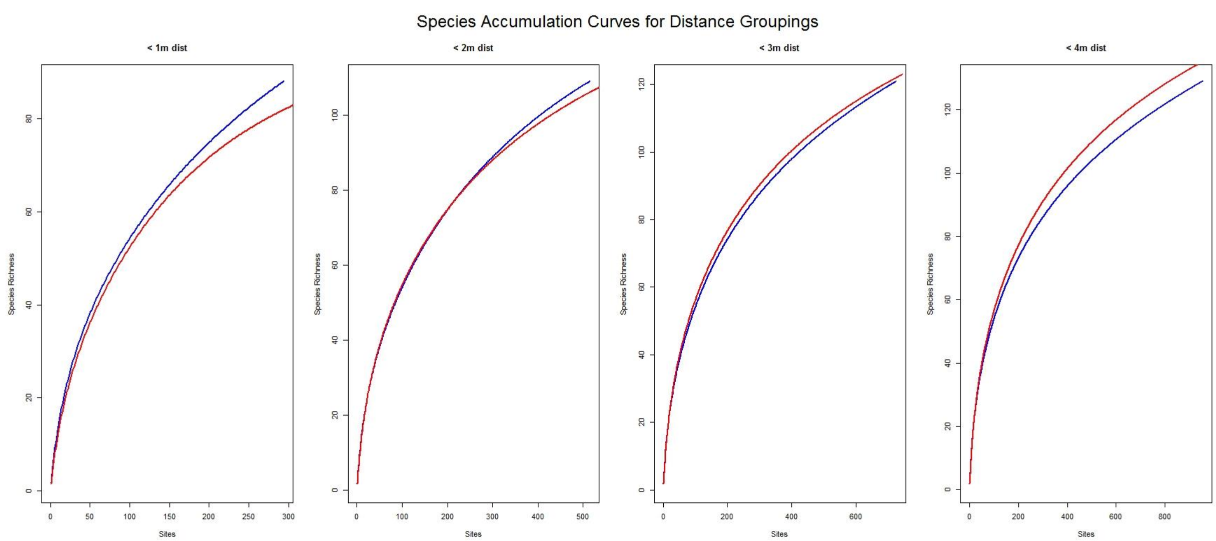

Figure A.8: Species accumulation curves for distance groupings (<1m,<2m, <3m, and <4m)

Table A.3: Logistic regression coefficients and associated p-values for species significantly related to elevation above the channel

Species	***Intercept (β_0)***	***p<***	***Elevation (β_1)***	***p<***	***Diversion (β_2)***	***p<***	***EL*Div (β_3)***	***p<***
ACCO	-5.8956	0.0000	1.5894	0.0081	1.3816	0.0645	-1.1707	0.1536
ACMI	-6.0796	0.0000	2.1505	0.0000	1.5978	0.0180	-1.5220	0.0269
ALIN	-2.2051	0.0000	-2.3136	0.0000	0.0131	0.9718	-0.6191	0.4247
ARCA	-7.2770	0.0000	2.0396	0.0219	0.3216	0.8027	-0.1982	0.8605
ASFO	-3.2099	0.0000	-1.8712	0.0081	-0.4816	0.3301	2.0491	0.0132
BRCI	-5.0086	0.0000	1.2190	0.0119	1.1536	0.0412	-1.0136	0.1284
CAAU	-0.9367	0.0000	-1.7566	0.0000	-0.8014	0.0006	0.8906	0.0195
CAPR	-5.2448	0.0000	1.2021	0.0277	1.6916	0.0100	-2.4600	0.0065
casp	-4.0083	0.0000	1.2083	0.0001	-0.0904	0.8307	-0.3301	0.4865
CAUT	-0.8163	0.0000	-1.0279	0.0000	-0.6574	0.0028	-0.3561	0.3202
DECE	-1.5472	0.0000	-0.6410	0.0059	-1.7049	0.0000	1.2952	0.0004
EQAR	-2.3111	0.0000	-2.2630	0.0000	0.2635	0.4238	1.3007	0.0333
FRVA	-3.5290	0.0000	0.9940	0.0004	0.0150	0.9673	-0.4956	0.2585
GATR	-5.5124	0.0000	1.3854	0.0135	0.4072	0.6881	-2.2547	0.1240
JUSA	-3.4292	0.0000	-2.8244	0.0033	-0.2144	0.7520	0.0369	0.9799
lisp	-5.1059	0.0000	1.3938	0.0026	0.5568	0.4888	-2.4181	0.0406
MUAN	-6.4702	0.0000	1.6839	0.0241	-16.0959	0.9951	-1.6839	0.9996
PIPO	-6.4981	0.0000	2.1515	0.0002	1.6195	0.0299	-0.7178	0.2956
PIPU	-5.7314	0.0000	1.8403	0.0002	1.2867	0.0359	-0.8025	0.1932
POFR	-6.1914	0.0000	2.2040	0.0000	1.9071	0.0048	-1.6803	0.0140
RILA	-6.2152	0.0000	1.5284	0.0345	1.3343	0.1346	-1.1016	0.2620
RUPA	-5.8948	0.0000	1.7535	0.0014	-1.2616	0.5466	-1.8798	0.5032
SABO	-3.1470	0.0000	1.3911	0.0000	0.5324	0.0351	-0.4487	0.1285
SALA	-3.1925	0.0000	-2.0227	0.0055	-0.1368	0.7968	0.8725	0.3633
TAOF	-3.6468	0.0000	0.8577	0.0062	1.0741	0.0012	-0.7723	0.0624
TRHY	-3.9687	0.0000	-3.6327	0.0086	-1.7584	0.0525	4.4364	0.0055
unk_149	-11.8669	0.0007	4.3104	0.0372	-12.6992	0.9986	-4.3104	0.9996
Unk_265	-9.0355	0.0000	3.1403	0.0032	-14.5306	0.9973	-3.1403	0.9996
URDI	-6.1695	0.0000	1.7081	0.0075	0.4260	0.6592	-0.8835	0.3859
VIMA	-3.5476	0.0000	-3.2884	0.0026	-19.0184	0.9942	3.2884	0.9992
VIOB	-7.4880	0.0000	2.4257	0.0020	-16.0780	0.9970	-2.4257	0.9997

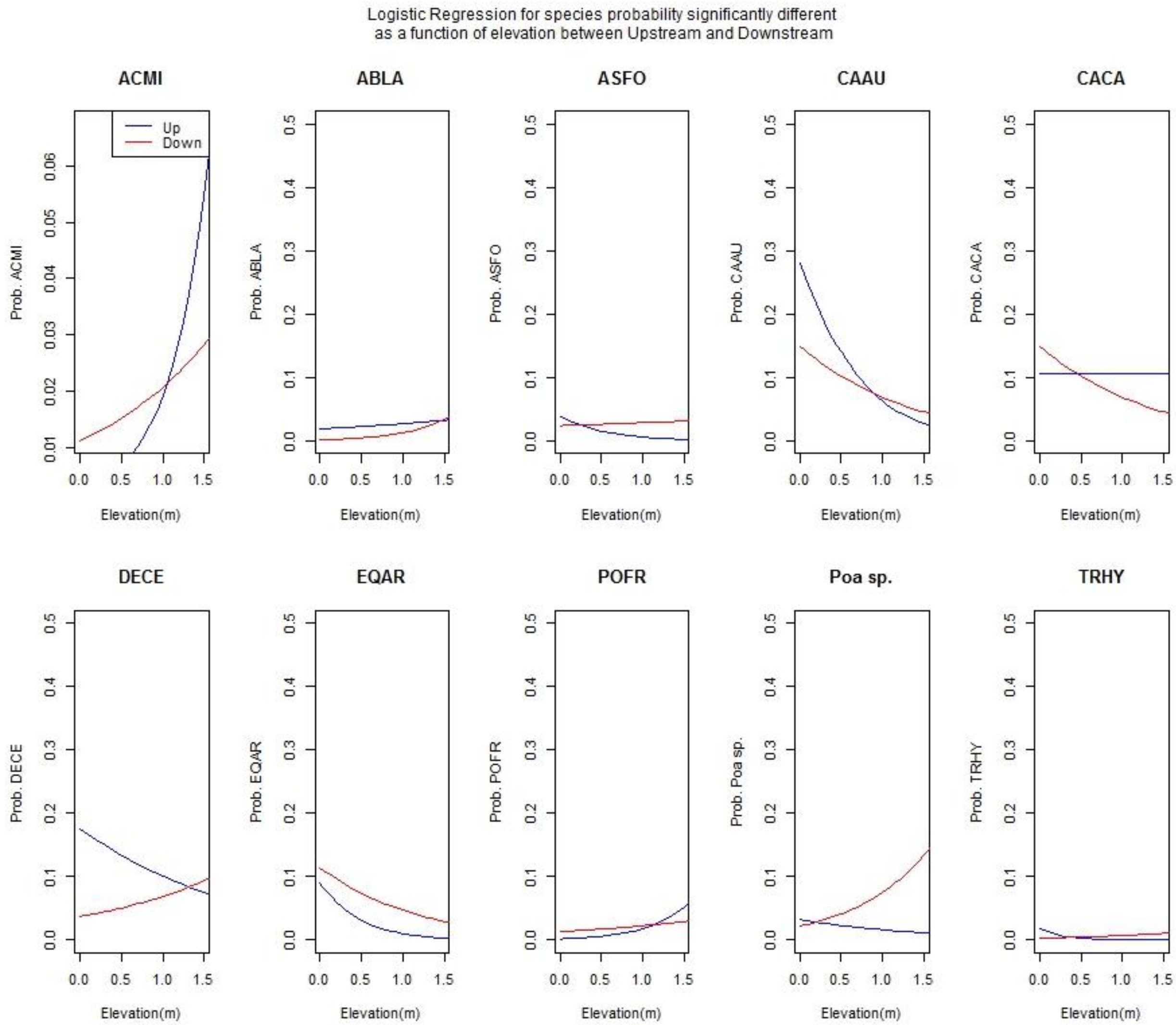

Figure A.9: Plotted logistic regression curves for species significantly different between upstream and downstream of diversion as a function of elevation.

Table A.4: Logistic regression coefficients and associated p-values for species significantly different between upstream and downstream of diversion as a function of elevation above the channel

	Intercept (β_0)	p<	Elevation (β_1)	p<	Diversion (β_2)	p<	Elev*Div (β_3)	p<
ABLA	-3.9341	0.0000	0.3620	0.4185	-2.3654	0.0004	1.6073	0.0142
ACMI	-6.0796	0.0000	2.1505	0.0000	1.5978	0.0180	-1.5220	0.0269
ASFO	-3.2099	0.0000	-1.8712	0.0081	-0.4816	0.3301	2.0491	0.0132
CAAU	-0.9367	0.0000	-1.7566	0.0000	-0.8014	0.0006	0.8906	0.0195
CACA	-2.1376	0.0000	0.0088	0.9700	0.3761	0.1267	-0.8335	0.0213
CAPR	-5.2448	0.0000	1.2021	0.0277	1.6916	0.0100	-2.4600	0.0065
DECE	-1.5472	0.0000	-0.6410	0.0059	-1.7049	0.0000	1.2952	0.0004
EQAR	-2.3111	0.0000	-2.2630	0.0000	0.2635	0.4238	1.3007	0.0333
gasp	-6.3683	0.0000	1.2199	0.1892	1.9274	0.0922	-4.0671	0.0309
lisp	-5.1059	0.0000	1.3938	0.0026	0.5568	0.4888	-2.4181	0.0406
LOIN	-4.6549	0.0000	0.2966	0.6494	1.0634	0.1254	-2.4749	0.0313
POFR	-6.1914	0.0000	2.2040	0.0000	1.9071	0.0048	-1.6803	0.0140
posp	-3.4000	0.0000	-0.6931	0.1973	-0.3809	0.3606	1.9692	0.0010
TRHY	-3.9687	0.0000	-3.6327	0.0086	-1.7584	0.0525	4.4364	0.0055

Table A.5: Logistic regression coefficients and p-values for all species sampled (elevation variable)

	Intercept (β_0)	p<	Elevation (β_1)	p<	Diversion (β_2)	p<	Elev*Div (β_3)	p<
ABLA	-3.9341	0.0000	0.3620	0.4185	-2.3654	0.0004	1.6073	0.0142
ACCO	-5.8956	0.0000	1.5894	0.0081	1.3816	0.0645	-1.1707	0.1536
ACMI	-6.0796	0.0000	2.1505	0.0000	1.5978	0.0180	-1.5220	0.0269
agsp	-5.7487	0.0000	-3.7261	0.2550	0.9949	0.4984	3.0727	0.3713
ALIN	-2.2051	0.0000	-2.3136	0.0000	0.0131	0.9718	-0.6191	0.4247
ANPI	-24.5661	0.9971	0.0000	1.0000	16.8827	0.9980	0.6359	0.9999
ANAR	-23.5661	0.9954	0.0000	1.0000	18.1763	0.9964	-0.3751	0.9999
ANNE	-24.5661	0.9971	0.0000	1.0000	15.4402	0.9982	2.1654	0.9998
ARCA	-7.2770	0.0000	2.0396	0.0219	0.3216	0.8027	-0.1982	0.8605
ASAS	-23.5661	0.9954	0.0000	1.0000	14.9505	0.9971	2.6328	0.9996
ASFO	-3.2099	0.000	-1.8712	0.008	-0.4816	0.330	2.0491	0.013

		0		1		1		2
		0.000		0.305		0.643		0.929
assp	-2.5276	0	-0.3196	8	-0.1464	2	0.0403	4
		0.000		0.190		0.997		0.999
BEGL	-7.3826	0	1.5997	8	-16.1835	0	-1.5997	8
		0.000		0.011		0.041		0.128
BRCI	-5.0086	0	1.2190	9	1.1536	2	-1.0136	4
		0.000		0.307		0.994		0.999
BRIN	-5.3040	0	0.7343	9	-17.2620	7	-0.7343	8
		0.000		0.000		0.000		0.019
CAAU	-0.9367	0	-1.7566	0	-0.8014	6	0.8906	5
		0.000		0.158		0.883		0.875
CABE	-4.4536	0	-1.7776	5	-0.1461	2	0.2832	4
		0.000		0.970		0.126		0.021
CACA	-2.1376	0	0.0088	0	0.3761	7	-0.8335	3
		0.000		0.325		0.646		0.949
CACO	-4.4616	0	-0.9821	4	-0.4535	2	0.1002	8
		0.000		0.777		0.994		0.999
CALE	-4.8500	0	-0.2596	9	-17.7161	6	0.2596	9
		0.000		0.431		0.336		0.276
CAMI	-5.4150	0	0.6310	4	-0.8761	6	1.0683	5
		0.000		0.361		0.821		0.718
CAOC	-4.9944	0	-1.3222	7	0.2649	6	-0.7843	4
		0.000		0.027		0.010		0.006
CAPR	-5.2448	0	1.2021	7	1.6916	0	-2.4600	5
		0.000		0.000		0.830		0.486
casp	-4.0083	0	1.2083	1	-0.0904	7	-0.3301	5
		0.000		0.000		0.002		0.320
CAUT	-0.8163	0	-1.0279	0	-0.6574	8	-0.3561	2
		0.000		0.127		0.829		0.980
CIAR	-5.1511	0	0.9237	1	-0.1643	8	-0.0214	2
		0.000		0.058		0.581		0.914
cisp	-6.4788	0	1.5400	8	-0.7091	8	0.1287	4
		0.995		1.000		0.996		1.000
CRDO	-23.5661	4	0.0000	0	17.5149	6	0.2994	0
		0.000		0.005		0.000		0.000
DECE	-1.5472	0	-0.6410	9	-1.7049	0	1.2952	4
		0.000		0.625		0.132		0.652
DEGL	-7.1782	0	0.8382	8	2.3581	6	-0.8574	5
		0.000		0.071		0.145		0.915
EPAN	-6.2321	0	1.4079	4	1.2367	1	-0.0932	8
		0.000		0.898		0.193		0.491
EPCI	-5.2798	0	-0.1380	4	-2.0876	5	1.2469	0
epsp	-5.1303	0.000	-2.2087	0.257	0.6494	0.592	0.0445	0.985

		0		0		3		4
EPSP	-26.5661	0.9988	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000
EQAR	-2.3111	0.0000	-2.2630	0.0000	0.2635	0.4238	1.3007	0.0333
EQPR	-5.6414	0.0000	-4.1962	0.1884	-18.9247	0.9979	4.1962	0.9996
eqsp	-24.5661	0.9971	0.0000	1.0000	15.4485	0.9982	2.1585	0.9998
ERGL	-24.5661	0.9971	0.0000	1.0000	17.1836	0.9979	0.2165	1.0000
FRVA	-3.5290	0.0000	0.9940	0.0004	0.0150	0.9673	-0.4956	0.2585
GABO	-26.5661	0.9988	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000
gasp	-6.3683	0.0000	1.2199	0.1892	1.9274	0.0922	-4.0671	0.0309
GATR	-5.5124	0.0000	1.3854	0.0135	0.4072	0.6881	-2.2547	0.1240
GEAL	-24.5661	0.9971	0.0000	1.0000	18.1909	0.9978	-1.5379	0.9999
GEMA	-4.8464	0.0000	0.3959	0.5621	0.5552	0.4279	-0.3791	0.6813
GERI	-4.5053	0.0000	0.2391	0.7012	0.5312	0.3472	0.4105	0.5742
HEMA	-4.0424	0.0000	0.6443	0.1182	-0.3345	0.5468	-0.3501	0.6150
JUBA	-26.5661	0.9988	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000
JUBI	-6.2598	0.0000	1.0819	0.2561	0.0941	0.9608	-3.0797	0.3594
JUFI	-5.6592	0.0000	0.2273	0.8371	0.4474	0.6985	-0.5938	0.7119
JUSA	-3.4292	0.0000	-2.8244	0.0033	-0.2144	0.7520	0.0369	0.9799
jusp	-4.6596	0.0000	-1.6590	0.2199	-0.9162	0.4884	0.7130	0.7480
LAOC	-23.5661	0.9954	0.0000	1.0000	17.8613	0.9965	0.1200	1.0000
LEVU	-6.7904	0.0000	0.2738	0.8852	-16.7757	0.9969	-0.2738	1.0000
LIPO	-4.3703	0.0000	0.1863	0.7554	-1.9789	0.0245	1.1949	0.2038
lisp	-5.1059	0.000	1.3938	0.002	0.5568	0.488	-2.4181	0.040

		0		6		8		6
		0.995		1.000		0.996		0.999
LITE	-23.5661	4	0.0000	0	19.2556	2	-2.1332	7
		0.000		0.649		0.125		0.031
LOIN	-4.6549	0	0.2966	4	1.0634	4	-2.4749	3
		0.000		0.898		0.940		0.679
LUAR	-5.6059	0	0.1431	3	-0.1037	7	-0.8471	7
MAR		0.000		0.691		0.695		0.339
A	-6.5905	0	0.5828	9	0.7523	5	-3.4123	0
		0.000		0.052		0.809		0.906
MEAR	-4.0941	0	-2.3399	1	-0.2179	2	0.2102	6
		0.000		0.586		0.177		0.976
MECI	-3.9231	0	0.2546	1	-0.8946	8	-0.0252	6
		0.000		0.662		0.386		0.448
MIST	-5.8148	0	0.4646	0	0.9596	7	-1.1757	1
MUA		0.000		0.024		0.995		0.999
N	-6.4702	0	1.6839	1	-16.0959	1	-1.6839	6
		0.000		0.213		0.706		0.390
PEGR	-4.4679	0	-1.4396	4	-0.3394	4	1.2500	4
		0.000		0.559		0.532		0.340
PHPR	-3.0613	0	0.1885	6	0.2170	4	-0.4587	7
		0.000		0.000		0.029		0.295
PIPO	-6.4981	0	2.1515	2	1.6195	9	-0.7178	6
		0.000		0.000		0.035		0.193
PIPU	-5.7314	0	1.8403	2	1.2867	9	-0.8025	2
		0.000		0.222		0.996		0.999
PLDI	-5.2859	0	-2.9173	0	-18.2802	6	2.9173	6
		0.000		0.300		0.998		0.999
POBI	-8.8901	0	2.0358	0	-15.6759	2	-2.0358	8
		0.000		0.000		0.004		0.014
POFR	-6.1914	0	2.2040	0	1.9071	8	-1.6803	0
		0.000		0.255		0.726		0.150
POGR	-5.7487	0	-3.7261	0	-0.5365	5	4.8588	5
		0.998		1.000		1.000		1.000
POOC	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
		0.000		0.207		0.026		0.369
POPR	-7.3431	0	1.5545	2	2.8879	4	-1.2189	2
		0.000		0.450		0.998		0.999
POPU	-8.4782	1	1.5935	4	-16.0879	2	-1.5935	9
		0.000		0.197		0.360		0.001
posp	-3.4000	0	-0.6931	3	-0.3809	6	1.9692	0
		0.000		0.511		0.775		0.381
potsp	-6.8257	0	0.9109	0	-0.4073	6	1.3218	5
PYAS	-4.7755	0.000	-1.8164	0.223	-18.7905	0.996	1.8164	0.999

		0		5		5		7
PYMI	-23.5661	0.9954	0.0000	1.0000	17.3938	0.9966	0.7687	0.9999
pysp	-7.6351	0.0000	1.4205	0.3573	0.6057	0.8077	-1.7506	0.5884
RILA	-6.2152	0.0000	1.5284	0.0345	1.3343	0.1346	-1.1016	0.2620
RIOX	-6.1097	0.0000	-0.1720	0.9173	-1.8692	0.2573	2.3037	0.2217
ROWO	-7.0414	0.0000	1.7912	0.0521	-16.5247	0.9969	-1.7912	0.9998
RUID	-7.0554	0.0003	-0.4419	0.8818	0.9745	0.6390	1.5164	0.6219
RULA	-23.5661	0.9954	0.0000	1.0000	16.6327	0.9967	1.0762	0.9999
RUPA	-5.8948	0.0000	1.7535	0.0014	-1.2616	0.5466	-1.8798	0.5032
RUSA	-8.3637	0.0001	1.4611	0.4992	2.2665	0.3303	-1.0962	0.6610
SABO	-3.1470	0.0000	1.3911	0.0000	0.5324	0.0351	-0.4487	0.1285
SADR	-5.1578	0.0000	-0.3485	0.7540	0.9947	0.2598	-0.0167	0.9898
SAGE	-1.6094	0.0000	-0.0399	0.8389	-0.0233	0.9101	-0.1701	0.5544
SAIR	-5.7515	0.0000	-1.6826	0.4720	-17.8146	0.9967	1.6826	0.9998
SALA	-3.1925	0.0000	-2.0227	0.0055	-0.1368	0.7968	0.8725	0.3633
SAMO	-4.3086	0.0000	0.6404	0.1711	-1.8971	0.0070	1.1592	0.0943
SAPL	-2.4362	0.0000	-0.5439	0.0949	-1.1112	0.0025	0.8317	0.0966
SAWO	-2.2091	0.0000	-0.4451	0.1179	-0.5835	0.0670	0.0371	0.9366
SESE	-6.8110	0.0000	1.2641	0.2616	1.6266	0.1901	-1.0403	0.4636
SETR	-3.8327	0.0000	-1.1716	0.1334	-0.3433	0.6149	0.6152	0.5721
sosp	-5.5612	0.0000	0.6881	0.4107	-17.0049	0.9948	-0.6881	0.9998
SYFO	-24.5661	0.9971	0.0000	1.0000	18.9233	0.9977	-3.4284	0.9997
TAOF	-3.6468	0.000	0.8577	0.006	1.0741	0.001	-0.7723	0.062

		0		2		2		4
		0.000		0.869		0.621		0.652
THFE	-4.9148	0	-0.1486	8	0.4342	4	-0.5902	6
		0.000		0.008		0.052		0.005
TRHY	-3.9687	0	-3.6327	6	-1.7584	5	4.4364	5
		0.000		0.051		0.344		0.592
TRPR	-3.1974	0	-1.0889	7	0.4046	5	0.3737	2
		0.000		0.192		0.922		0.374
trsp	-4.8432	0	-2.2044	0	0.1032	3	1.7307	1
unk_1		0.000		0.792		0.998		0.999
03	-7.7448	1	0.6606	3	-16.8213	1	-0.6606	9
unk_1		0.997		1.000		0.998		0.999
07	-24.5661	1	0.0000	0	16.8994	0	0.6138	9
unk_1		0.997		1.000		0.997		0.999
09	-24.5661	1	0.0000	0	18.3043	8	-1.7812	8
unk_1		0.997		1.000		0.997		0.999
10	-24.5661	1	0.0000	0	19.1609	7	-4.3691	6
unk_1		0.997		1.000		0.998		1.000
11	-24.5661	1	0.0000	0	17.0228	0	0.4456	0
unk_1		0.995		1.000		0.996		1.000
13	-23.5661	4	0.0000	0	17.1108	6	-0.1378	0
unk_1		0.995		1.000		0.996		0.999
16	-23.5661	4	0.0000	0	16.5412	7	0.6828	9
unk_1		0.997		1.000		0.997		0.999
17	-24.5661	1	0.0000	0	17.7107	9	-0.6240	9
unk_1		0.997		1.000		0.997		1.000
19	-24.5661	1	0.0000	0	17.4679	9	-0.2188	0
unk_1		0.995		1.000		0.996		1.000
20	-23.5661	4	0.0000	0	17.5812	5	-0.2400	0
unk_1		0.995		1.000		0.996		1.000
22	-23.5661	4	0.0000	0	16.8751	7	0.2200	0
unk_1		0.997		1.000		0.998		0.999
24	-24.5661	1	0.0000	0	16.0030	1	1.6522	9
unk_1		0.997		1.000		0.997		0.999
25	-24.5661	1	0.0000	0	18.8543	7	-1.4742	9
unk_1		0.997		1.000		0.998		1.000
26	-24.5661	1	0.0000	0	16.9626	0	0.5286	0
unk_1		0.995		1.000		0.996		0.999
27	-23.5661	4	0.0000	0	18.3421	4	-1.6450	8
unk_1		0.997		1.000		0.997		0.999
28	-24.5661	1	0.0000	0	18.1861	8	-1.5279	9
unk_1		0.997		1.000		0.997		0.999
29	-24.5661	1	0.0000	0	17.7959	9	-0.7743	9
unk_1	-26.5661	0.998	0.0000	1.000	0.0000	1.000	0.0000	1.000

3		8		0		0		0
unk_1		0.997		1.000		0.997		1.000
31	-24.5661	1	0.0000	0	17.6557	9	-0.5293	0
unk_1		0.998		1.000		0.999		0.999
32	-25.5661	1	0.0000	0	13.7593	0	3.8512	8
unk_1		0.997		1.000		0.998		0.999
33	-24.5661	1	0.0000	0	14.4241	3	2.9081	8
unk_1		0.997		1.000		0.998		0.999
35	-24.5661	1	0.0000	0	17.0235	0	1.3091	9
unk_1		0.997		1.000		0.997		0.999
36	-24.5661	1	0.0000	0	17.2788	9	1.0134	9
unk_1		0.997		1.000		0.998		0.999
38	-24.5661	1	0.0000	0	15.8928	1	1.7600	9
unk_1		0.995		1.000		0.996		0.999
39	-23.5661	4	0.0000	0	16.7149	7	1.3136	8
unk_1		0.997		1.000		0.998		0.999
40	-24.5661	1	0.0000	0	16.7736	0	1.5757	9
unk_1		0.997		1.000		0.998		0.999
41	-24.5661	1	0.0000	0	16.1072	1	1.5466	9
unk_1		0.997		1.000		0.998		0.999
42	-24.5661	1	0.0000	0	16.0661	1	2.2251	8
unk_1		0.997		1.000		0.998		0.999
43	-24.5661	1	0.0000	0	16.2340	1	1.4130	9
unk_1		0.000		0.320		0.996		0.999
48	-5.4745	0	-2.3735	8	-18.0915	7	2.3735	7
unk_1		0.000		0.037		0.998		0.999
49	-11.8669	7	4.3104	2	-12.6992	6	-4.3104	6
unk_1		0.998		1.000		1.000		1.000
5	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_1		0.000		0.080		0.996		0.999
52	-4.7350	0	-3.3907	0	-18.8310	5	3.3907	5
unk_1		0.000		0.649		0.998		0.999
54	-8.0375	1	1.0583	9	-16.5286	1	-1.0583	9
unk_1		0.000		0.728		0.996		0.999
55	-6.5456	0	0.5172	1	-17.0205	9	-0.5172	9
unk_1		0.000		0.499		0.998		0.999
56	-8.3637	1	1.4611	2	-16.2024	2	-1.4611	9
unk_1		0.000		0.985		0.996		1.000
58	-6.5969	0	-0.0360	6	-16.9691	9	0.0360	0
unk_1		0.997		1.000		0.998		0.999
64	-24.5661	1	0.0000	0	16.8648	0	1.4809	9
unk_1		0.998		1.000		1.000		1.000
7	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_1	-24.5661	0.997	0.0000	1.000	17.4631	0.997	-0.2110	1.000

70		1		0		9		0
unk_1		0.997		1.000		0.998		1.000
72	-24.5661	1	0.0000	0	17.0012	0	0.4756	0
Unk_		0.000		0.501		0.996		0.999
176	-5.5401	0	-1.2514	1	-18.0260	7	1.2514	8
Unk_		0.000		0.390		0.997		0.999
178	-5.9877	1	-2.8952	3	-18.5784	9	2.8952	8
Unk_		0.000		0.511		0.997		0.999
179	-6.2299	1	-2.2114	4	-18.3362	9	2.2114	8
unk_1		0.998		1.000		1.000		1.000
8	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.000		0.267		0.998		0.999
181	-9.0003	0	2.1459	2	-15.5658	3	-2.1459	8
Unk_		0.000		0.346		0.998		0.999
182	-8.7490	0	1.8899	7	-15.8171	2	-1.8899	8
Unk_		0.000		0.915		0.998		1.000
183	-7.4911	2	0.2844	4	-17.0750	1	-0.2844	0
Unk_		0.000		0.974		0.996		1.000
189	-6.2441	0	0.0514	4	-17.3220	8	-0.0514	0
unk_1		0.998		1.000		1.000		1.000
9	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.000		0.409		0.419		0.634
190	-6.0251	1	-2.7814	8	1.3849	7	-1.9255	1
Unk_		0.997		1.000		0.997		1.000
192	-24.5661	1	0.0000	0	17.4826	9	-0.2423	0
Unk_		0.995		1.000		0.996		0.999
193	-23.5661	4	0.0000	0	18.4742	4	-1.9362	7
Unk_		0.995		1.000		0.996		0.999
194	-23.5661	4	0.0000	0	17.1007	6	0.4764	9
Unk_		0.988		1.000		0.990		0.999
195	-21.5661	5	0.0000	0	17.0917	9	0.8250	7
Unk_		0.997		1.000		0.998		0.999
196	-24.5661	1	0.0000	0	15.8869	1	1.7657	9
Unk_		0.997		1.000		0.998		0.999
197	-24.5661	1	0.0000	0	15.0865	2	2.9391	8
Unk_		0.997		1.000		0.997		0.999
198	-24.5661	1	0.0000	0	19.7396	6	-3.8605	7
Unk_		0.997		1.000		0.998		0.999
199	-24.5661	1	0.0000	0	14.6912	2	2.7304	8
unk_2		0.998		1.000		1.000		1.000
0	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.997		1.000		0.997		0.999
203	-24.5661	1	0.0000	0	19.9092	6	-4.6172	6
Unk_	-24.5661	0.997	0.0000	1.000	18.9507	0.997	-3.5219	0.999

204		1		0		7		7
Unk_		0.997		1.000		0.997		0.999
205	-24.5661	1	0.0000	0	19.2185	7	-4.6691	6
Unk_		0.997		1.000		0.997		0.999
206	-24.5661	1	0.0000	0	19.6675	7	-3.5954	7
Unk_		0.997		1.000		0.997		0.999
207	-24.5661	1	0.0000	0	19.3386	7	-5.5879	5
Unk_		0.997		1.000		0.997		0.999
208	-24.5661	1	0.0000	0	19.3539	7	-5.7955	5
Unk_		0.000		0.148		0.997		0.999
209	-5.5788	0	-4.5256	1	-18.9872	9	4.5256	6
unk_2		0.998		1.000		1.000		1.000
1	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.000		0.558		0.998		0.999
210	-8.2312	1	1.3022	7	-16.3349	2	-1.3022	9
Unk_		0.000		0.419		0.997		0.999
211	-7.5180	0	1.2788	4	-16.0481	0	-1.2788	8
Unk_		0.000		0.571		0.998		0.999
213	-8.2027	1	1.2673	8	-16.3634	2	-1.2673	9
Unk_		0.000		0.072		0.997		0.999
214	-5.4677	0	-5.3760	8	-19.0984	9	5.3760	5
Unk_		0.000		0.620		0.998		0.999
215	-8.1000	1	1.1386	0	-16.4661	2	-1.1386	9
Unk_		0.000		0.282		0.997		0.999
217	-7.7937	0	1.6048	5	-15.7723	1	-1.6048	8
Unk_		0.000		0.676		0.998		0.999
218	-7.9828	1	0.9867	3	-16.5833	1	-0.9867	9
unk_2		0.998		1.000		1.000		1.000
2	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.997		1.000		0.998		0.999
222	-24.5661	1	0.0000	0	15.0606	2	2.4657	8
Unk_		0.997		1.000		0.997		0.999
223	-24.5661	1	0.0000	0	18.7911	8	-1.3455	9
Unk_		0.997		1.000		0.998		0.999
224	-24.5661	1	0.0000	0	15.4595	2	2.1492	8
Unk_		0.997		1.000		0.998		0.999
226	-24.5661	1	0.0000	0	15.3384	2	2.2491	8
Unk_		0.000		0.941		0.996		1.000
233	-6.5296	0	-0.1487	4	-17.0365	8	0.1487	0
Unk_		0.000		0.064		0.997		0.999
234	-5.4570	0	-5.5100	6	-19.1090	9	5.5100	5
Unk_		0.997		1.000		0.997		0.999
236	-24.5661	1	0.0000	0	19.6720	7	-3.6111	7
Unk_	-23.5661	0.995	0.0000	1.000	17.0450	0.996	0.5526	0.999

237		4		0		6		9
Unk_		0.997		1.000		0.998		0.999
238	-24.5661	1	0.0000	0	16.9702	0	1.3678	9
Unk_		0.000		0.759		0.996		0.999
239	-6.2430	0	-0.6598	6	-17.3231	8	0.6598	9
unk_2		0.998		1.000		1.000		1.000
4	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
Unk_		0.000		0.090		0.997		0.999
240	-5.4931	0	-5.1220	9	-19.0730	9	5.1220	6
Unk_		0.000		0.984		0.996		1.000
241	-6.6423	0	0.0385	4	-16.9238	9	-0.0385	0
Unk_		0.995		1.000		0.996		0.999
246	-23.5661	4	0.0000	0	16.3453	8	1.7014	8
Unk_		0.997		1.000		0.998		0.999
248	-24.5661	1	0.0000	0	16.7105	0	0.8585	9
Unk_		0.997		1.000		0.998		0.999
249	-24.5661	1	0.0000	0	16.4745	0	1.8676	8
Unk_		0.995		1.000		0.996		0.999
250	-23.5661	4	0.0000	0	16.6327	7	1.0762	9
Unk_		0.997		1.000		0.998		0.999
253	-24.5661	1	0.0000	0	16.6951	0	0.8778	9
Unk_		0.997		1.000		0.997		1.000
254	-24.5661	1	0.0000	0	17.2112	9	0.1761	0
Unk_		0.000		0.708		0.580		0.831
255	-6.6656	3	-1.1980	6	1.2108	7	-0.8385	3
Unk_		0.997		1.000		0.997		0.999
256	-24.5661	1	0.0000	0	19.5188	7	-3.1107	7
Unk_		0.000		0.660		0.548		0.519
260	-6.0797	0	-0.9767	8	1.0095	8	-2.0650	1
Unk_		0.995		1.000		0.996		0.999
261	-23.5661	4	0.0000	0	17.3948	6	-0.6070	9
Unk_		0.000		0.080		0.997		0.999
262	-5.4786	0	-5.2588	7	-19.0875	9	5.2588	6
Unk_		0.000		0.567		0.996		0.999
263	-6.7494	0	0.8072	7	-16.8166	9	-0.8072	9
Unk_		0.000		0.090		0.996		0.999
264	-6.8778	0	1.6092	1	-16.6883	9	-1.6092	8
Unk_		0.000		0.003		0.997		0.999
265	-9.0355	0	3.1403	2	-14.5306	3	-3.1403	6
Unk_		0.000		0.239		0.998		0.999
266	-9.1028	0	2.2456	6	-15.4633	3	-2.2456	8
Unk_		0.000		0.126		0.998		0.999
267	-9.7093	1	2.7881	2	-14.8568	3	-2.7881	8
unk_3	-7.7093	0.000	0.6098	0.809	-16.8568	0.998	-0.6098	0.999

7		1		7		1		9
unk_3		0.000		0.870		0.998		1.000
8	-7.0308	3	-0.4863	7	-17.5353	0	0.4863	0
unk_3		0.000		0.853		0.998		1.000
9	-6.9914	3	-0.5583	0	-17.5747	0	0.5583	0
unk_4		0.000		0.698		0.998		0.999
1	-7.9360	1	0.9246	9	-16.6301	1	-0.9246	9
unk_4		0.000		0.817		0.996		1.000
2	-6.1182	0	0.3082	4	-17.4479	8	-0.3082	0
unk_4		0.000		0.529		0.998		0.999
4	-8.2957	1	1.3804	4	-16.2704	2	-1.3804	9
unk_4		0.000		0.529		0.998		0.999
5	-8.2957	1	1.3804	4	-16.2704	2	-1.3804	9
unk_4		0.000		0.822		0.998		0.999
7	-6.9223	3	-0.6873	1	-17.6438	0	0.6873	9
unk_5		0.000		0.741		0.996		0.999
1	-6.5290	0	0.4927	5	-17.0371	8	-0.4927	9
unk_5		0.000		0.738		0.998		0.999
4	-7.8543	1	0.8137	8	-16.7118	1	-0.8137	9
unk_5		0.000		0.629		0.998		0.999
6	-8.0792	1	1.1121	9	-16.4868	1	-1.1121	9
unk_5		0.000		0.645		0.998		0.999
8	-8.0459	1	1.0692	9	-16.5202	1	-1.0692	9
		0.998		1.000		1.000		1.000
unk_7	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_8		0.998		1.000		1.000		1.000
9	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_9		0.998		1.000		1.000		1.000
0	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_9		0.998		1.000		1.000		1.000
1	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_9		0.998		1.000		1.000		1.000
2	-26.5661	8	0.0000	0	0.0000	0	0.0000	0
unk_9		0.000		0.388		0.997		0.999
4	-5.9840	1	-2.9065	3	-18.5821	9	2.9065	8
unk_9		0.000		0.110		0.996		0.999
5	-4.6577	0	-2.7138	4	-18.9084	5	2.7138	6
unk_9		0.000		0.123		0.996		0.999
6	-5.0835	0	-3.6073	5	-18.4826	6	3.6073	5
unk_9		0.000		0.146		0.996		0.999
7	-4.9029	0	-2.8439	2	-18.6631	5	2.8439	6
unk_9		0.000		0.405		0.997		0.999
8	-6.0175	1	-2.8042	9	-18.5485	9	2.8042	8
unk_9	-7.6531	0.000	1.4419	0.348	-15.9129	0.997	-1.4419	0.999

9		0		2		1		8
		0.000		0.007		0.659		0.385
URDI	-6.1695	0	1.7081	5	0.4260	2	-0.8835	9
		0.000		0.082		0.723		0.562
VAOC	-4.7425	0	-3.3644	5	0.3779	4	1.3576	8
		0.000		0.508		0.665		0.637
VETE	-8.3437	1	1.4376	0	1.2554	2	-1.6721	3
VEW		0.000		0.285		0.738		0.586
O	-5.1836	0	-2.0724	8	0.4046	5	1.2247	8
		0.000		0.789		0.762		0.244
VIAM	-5.0442	0	0.2187	4	-0.2308	8	1.0942	8
		0.000		0.002		0.994		0.999
VIMA	-3.5476	0	-3.2884	6	-19.0184	2	3.2884	2
		0.000		0.002		0.997		0.999
VIOB	-7.4880	0	2.4257	0	-16.0780	0	-2.4257	7

A.2.4 HYPOTHESIS 3: FLUVIAL SURFACE

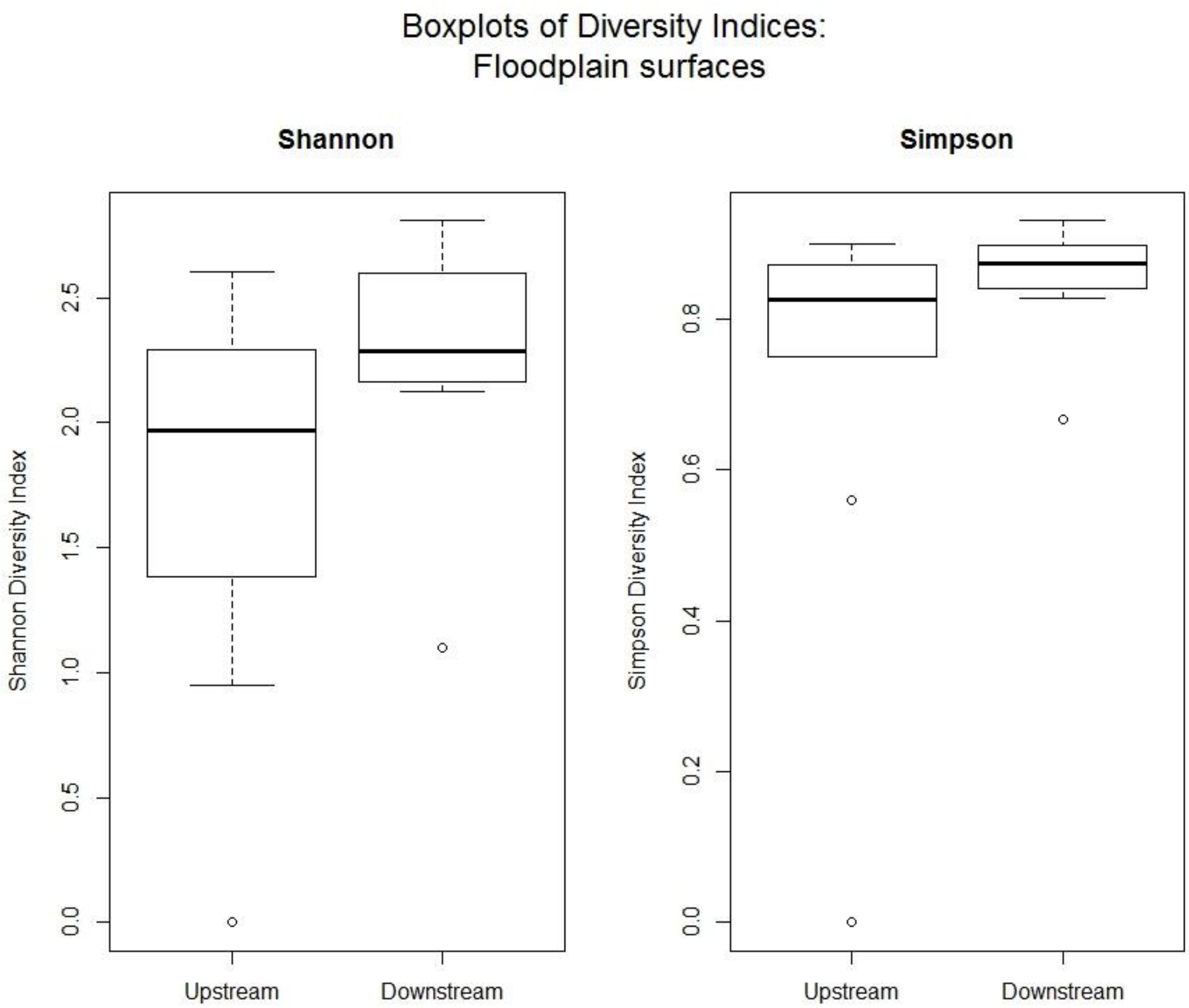

Figure A.10: Box plots of diversity indices upstream and downstream of diversion

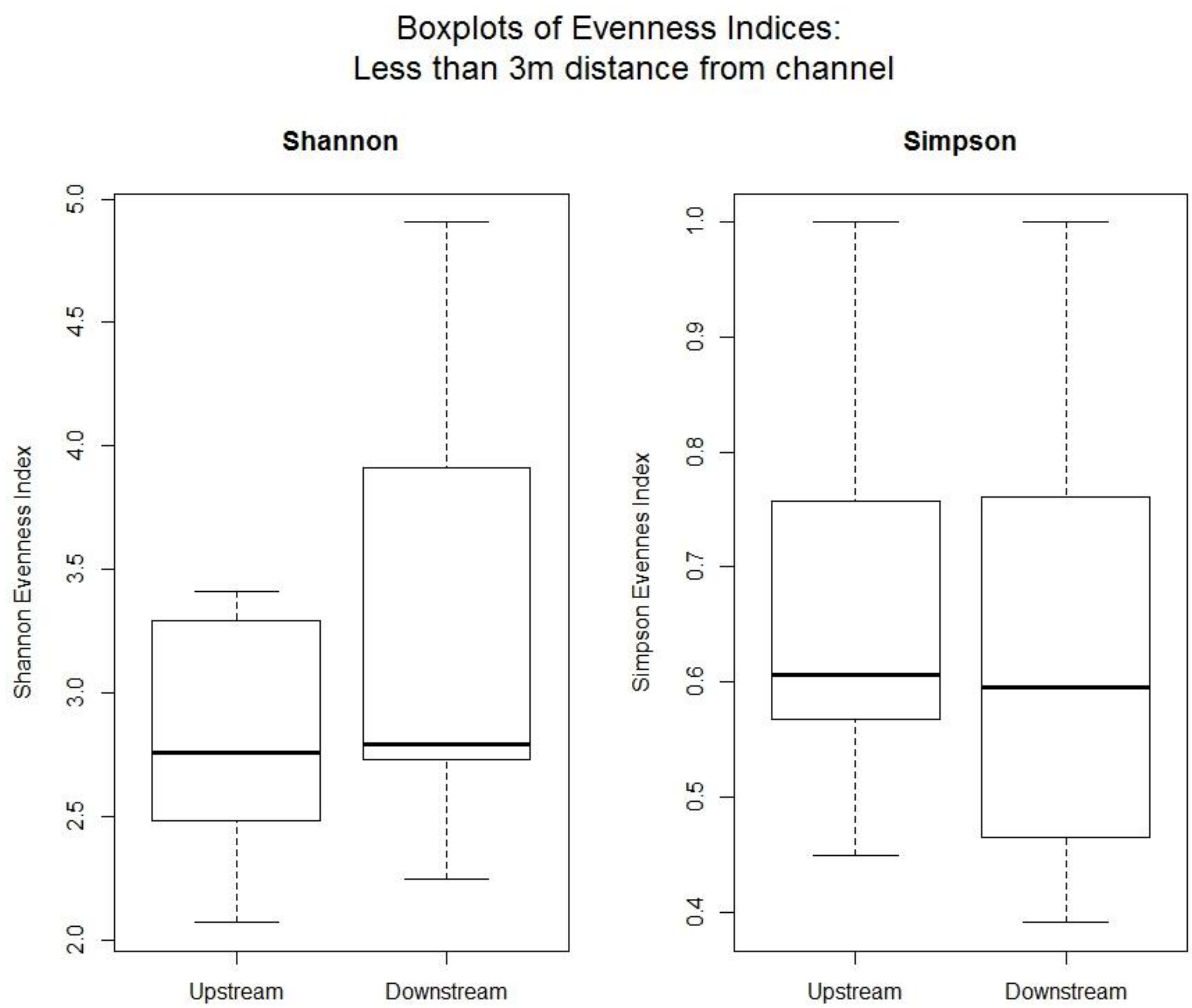

Figure A.11: Box plots of evenness indices upstream and downstream of diversion

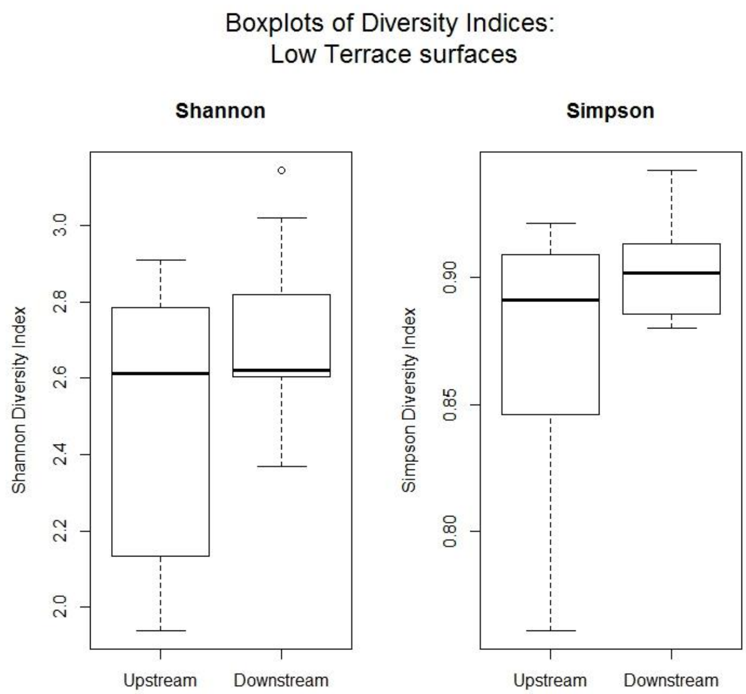

Figure A.12: Box plots for diversity indices on low terrace surfaces - upstream versus downstream of diversion

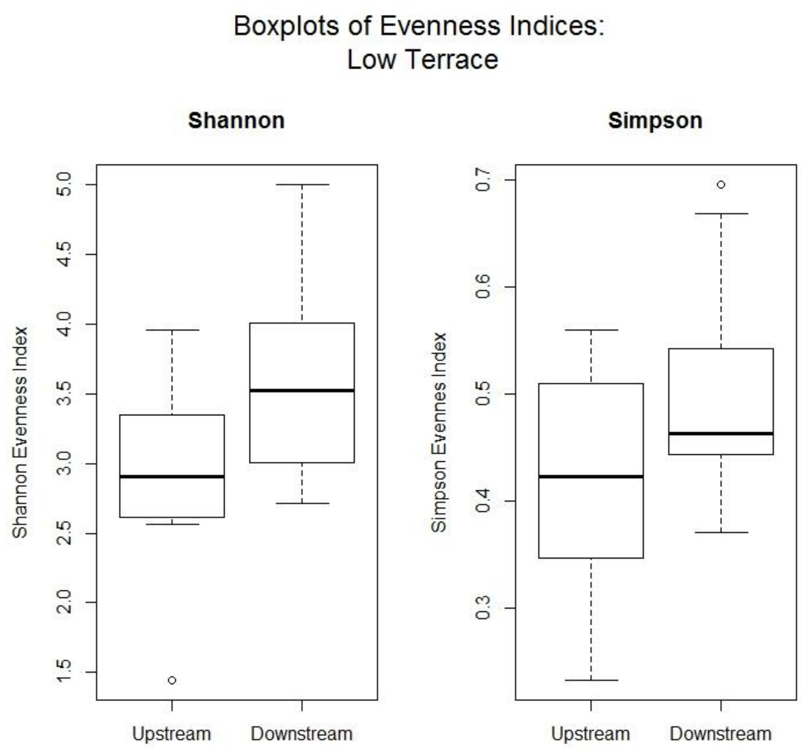

Figure A.13: Box plots of evenness indices on low terrace surfaces - upstream versus downstream of diversion

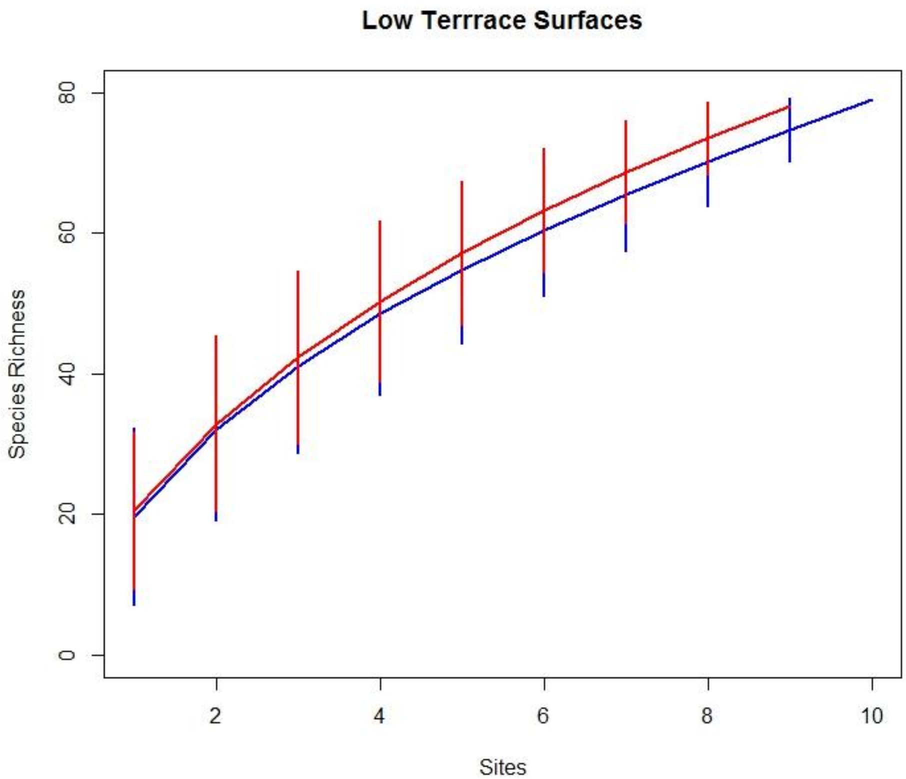

Figure A.14: Species accumulation curves on low terrace surfaces - upstream versus downstream of diversion

A.2.5 HYPOTHESIS 4: SENSITIVITY OF RIPARIAN VEGETATION AS A FUNCTION OF ENVIRONMENTAL VARIABLES

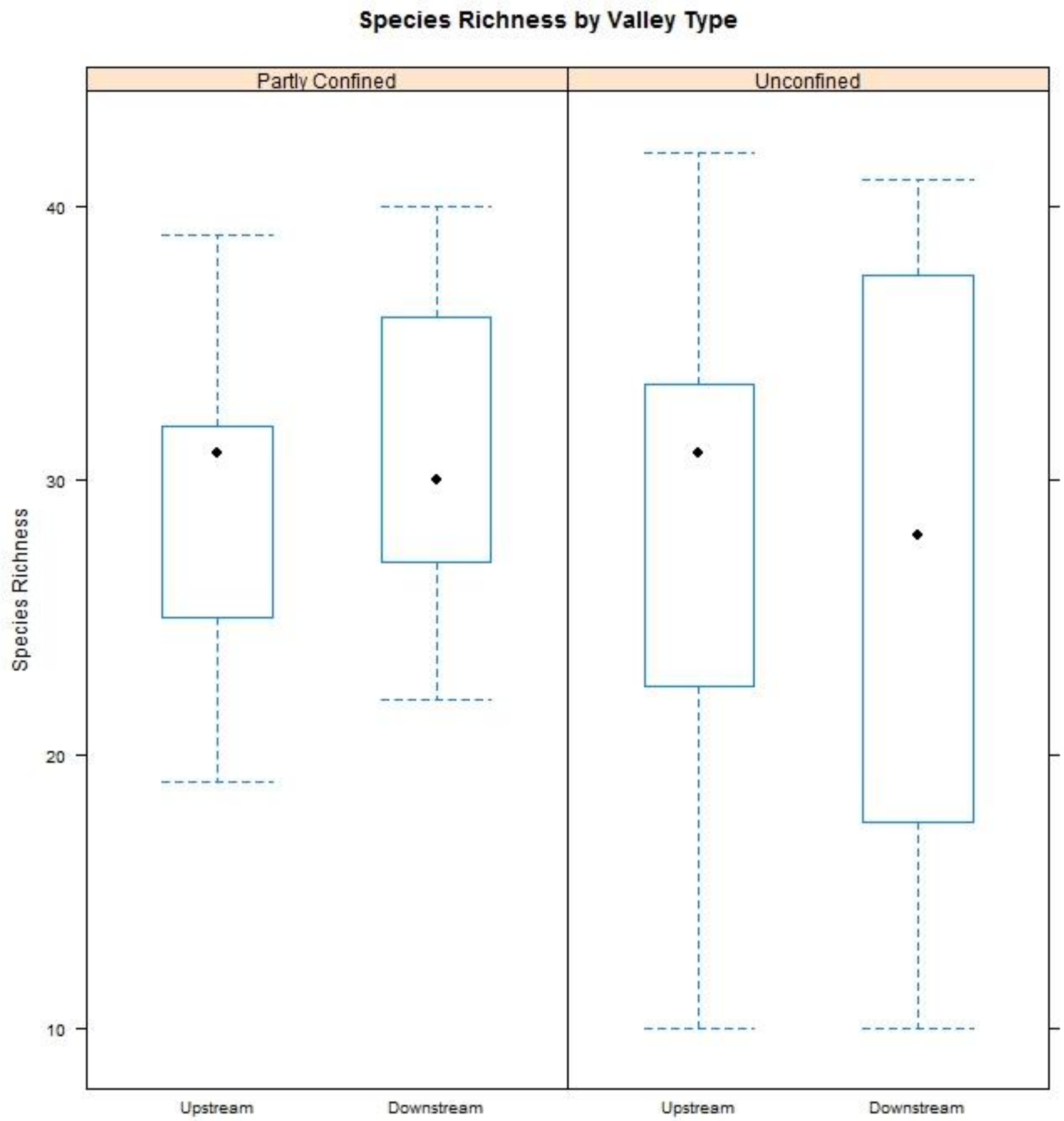

Figure A.15: Species richness by valley type

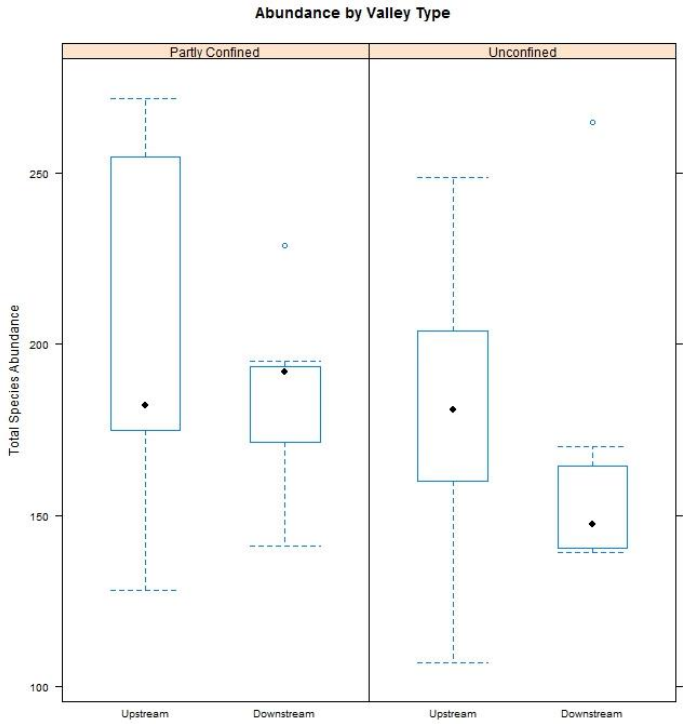

Figure A.16: Abundance by valley type

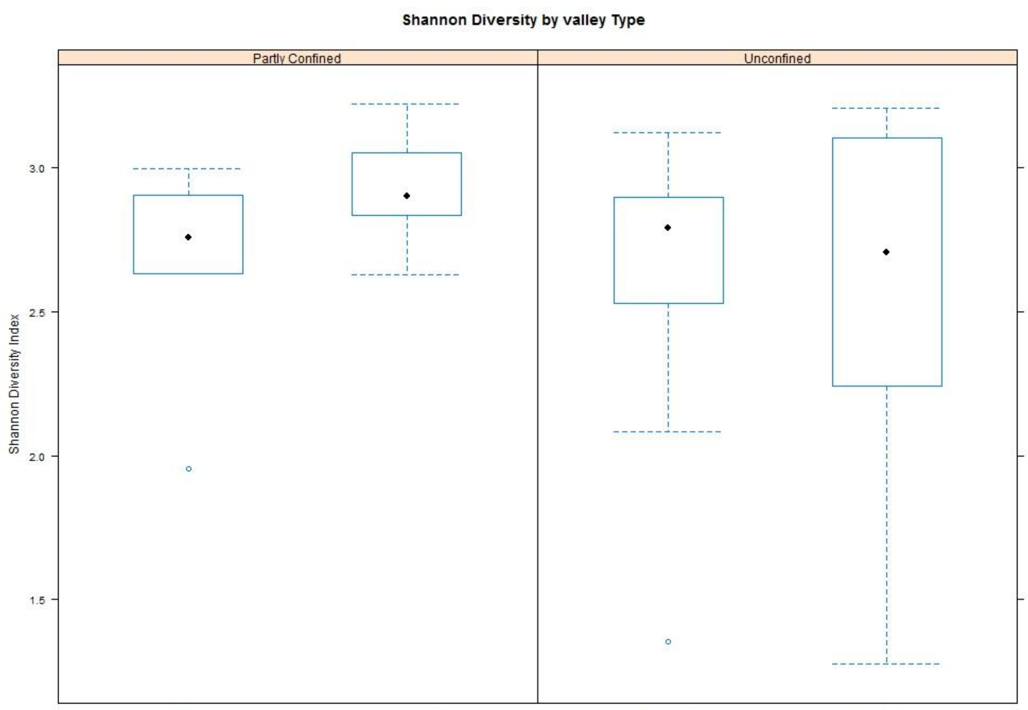

Figure A.17: Shannon Diversity by valley type

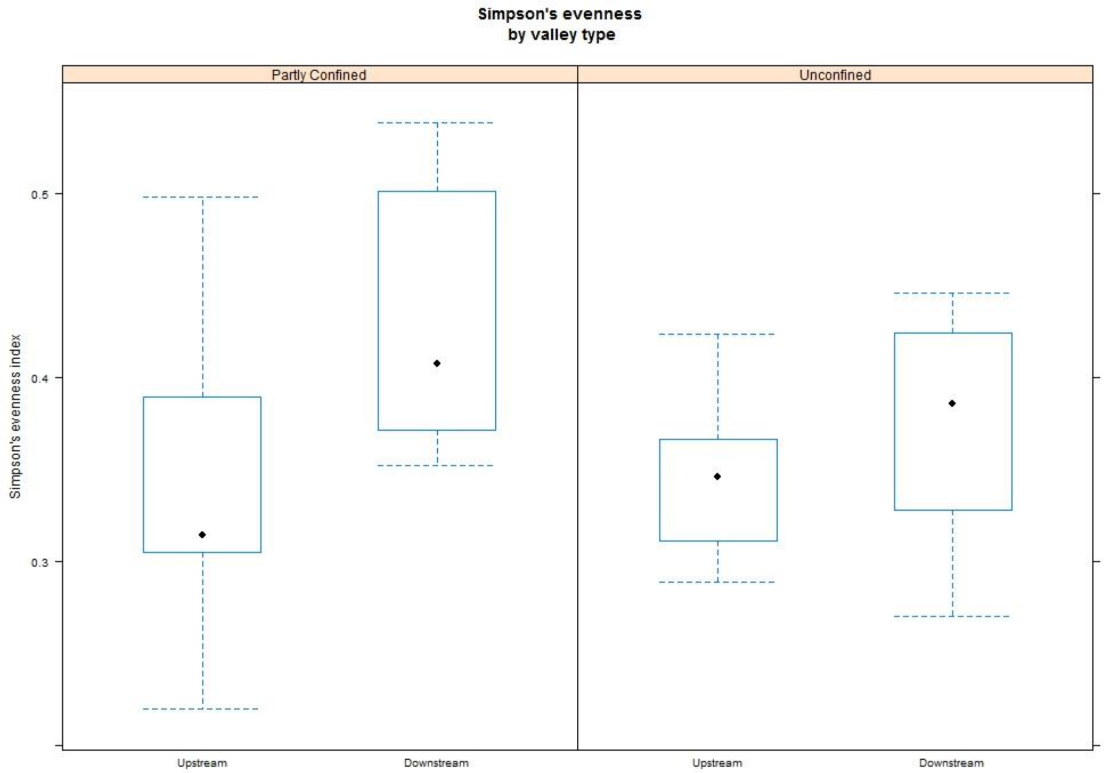

Figure A.18: Simpson's Evennness by valley type

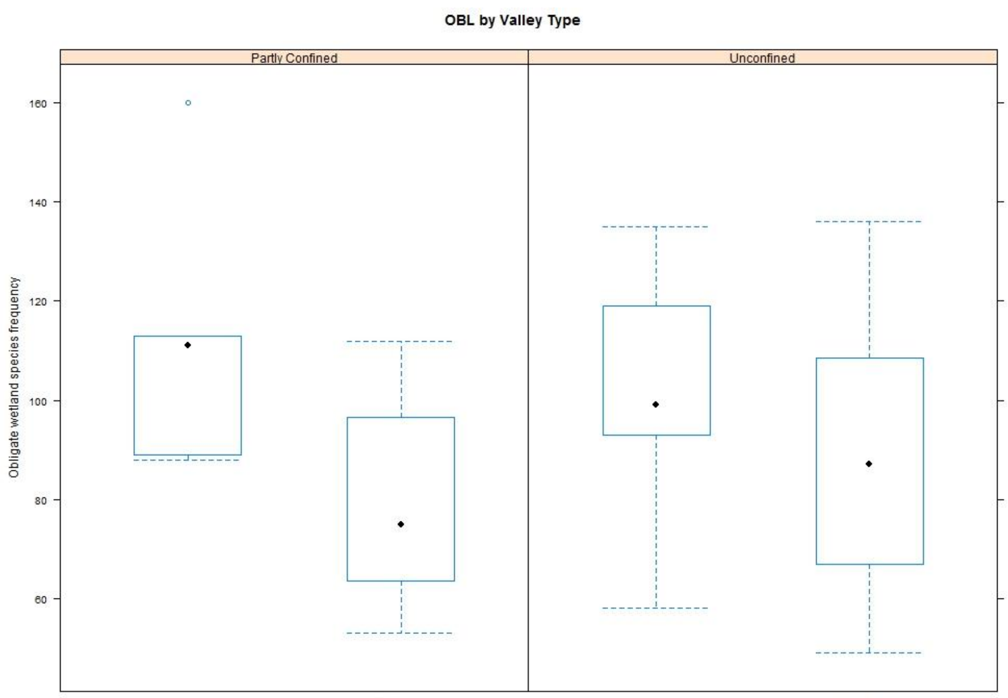

Figure A.19: Obligate frequency by valley type

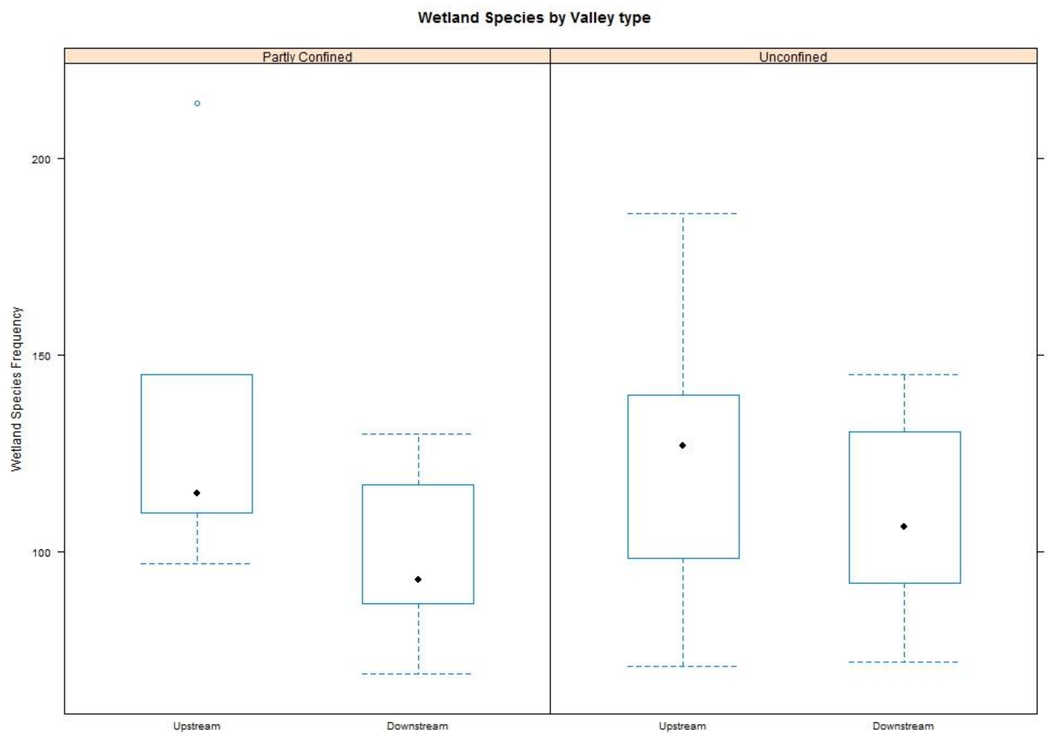

Figure A.20: Wetland species by valley type

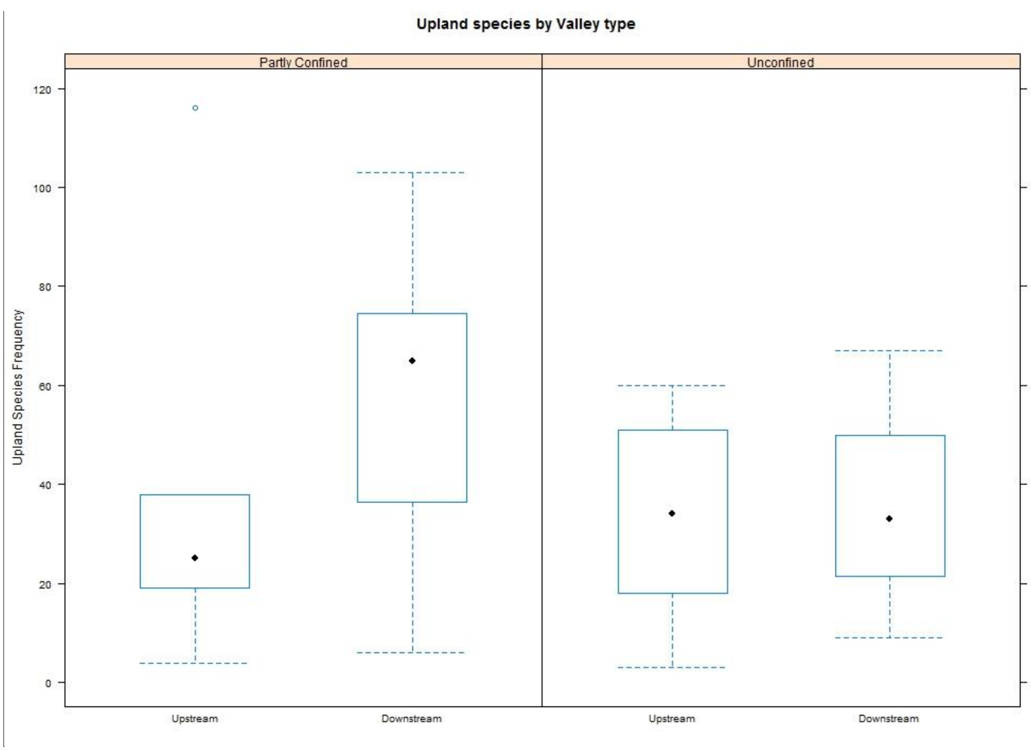

Figure A.21: Upland species by valley type

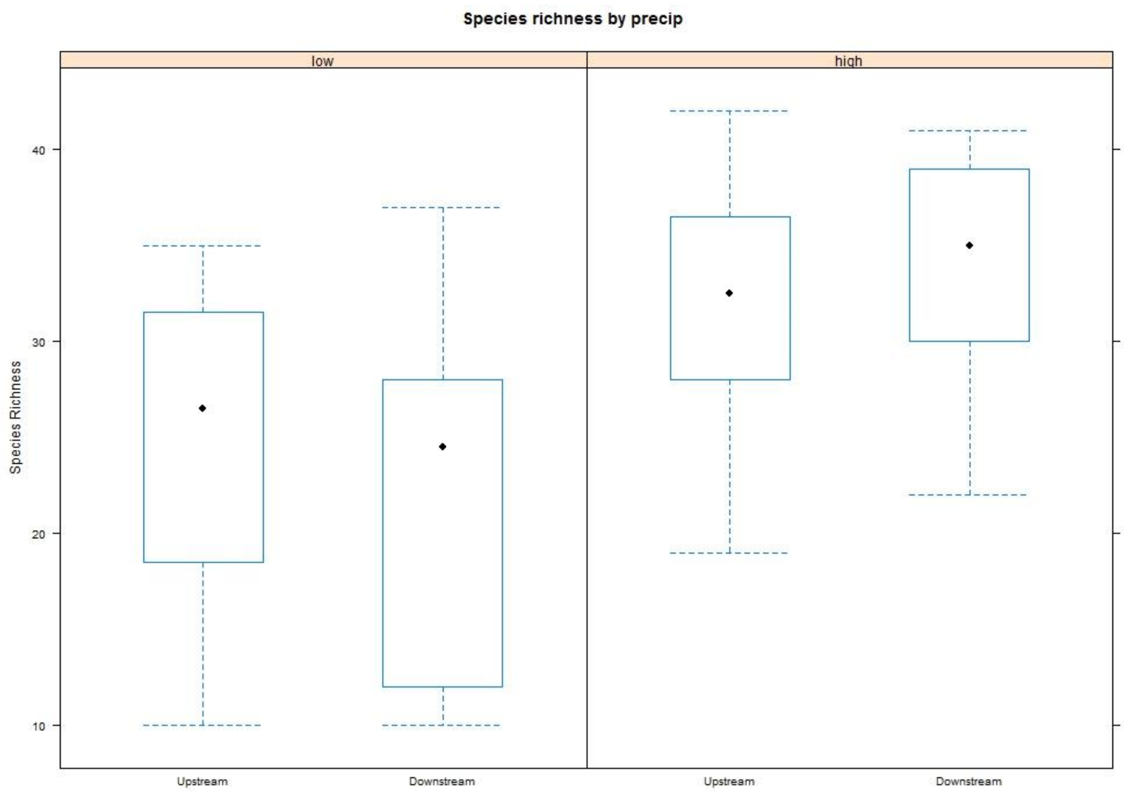

Figure A.22: Species richness by precipitation regime

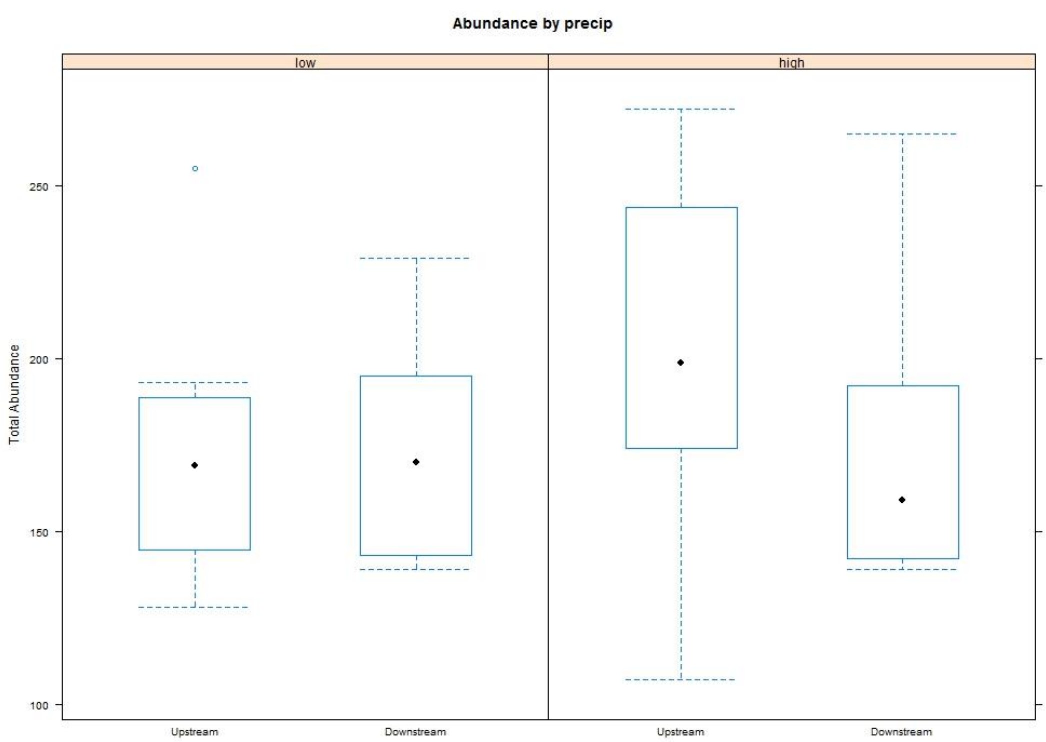

Figure A.23: Total species abundance by precipitation regime

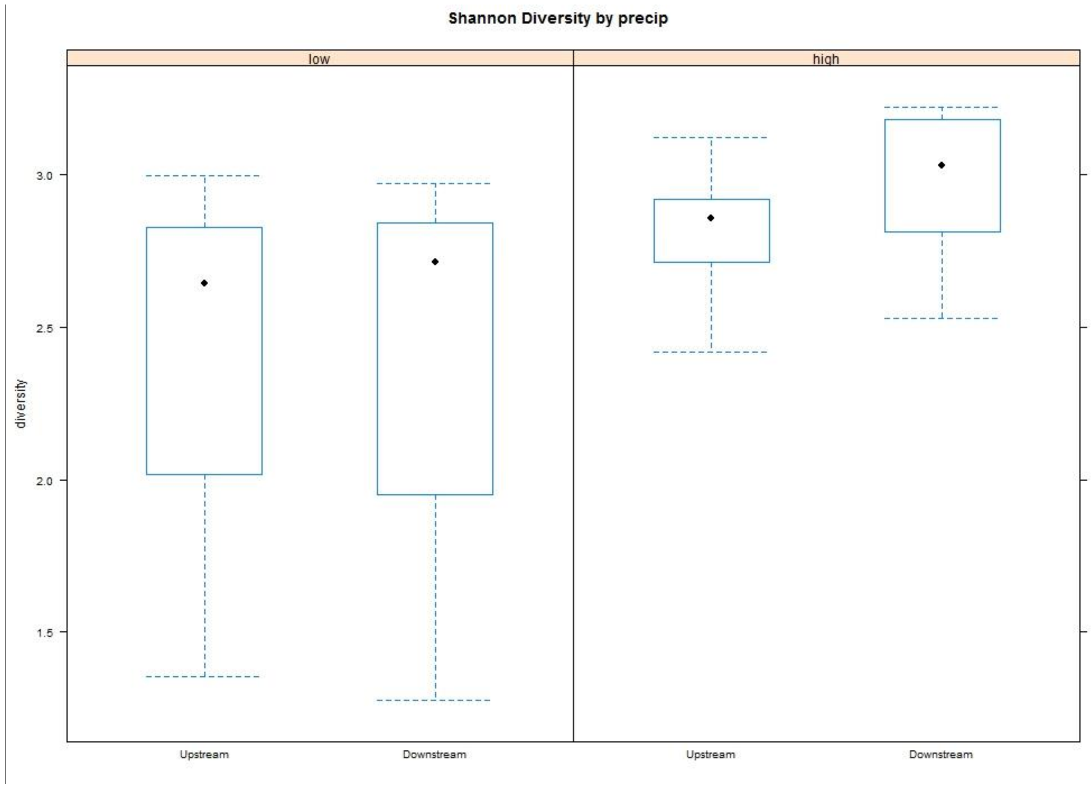

Figure A.24: Shannon Diversity by precipitation regime

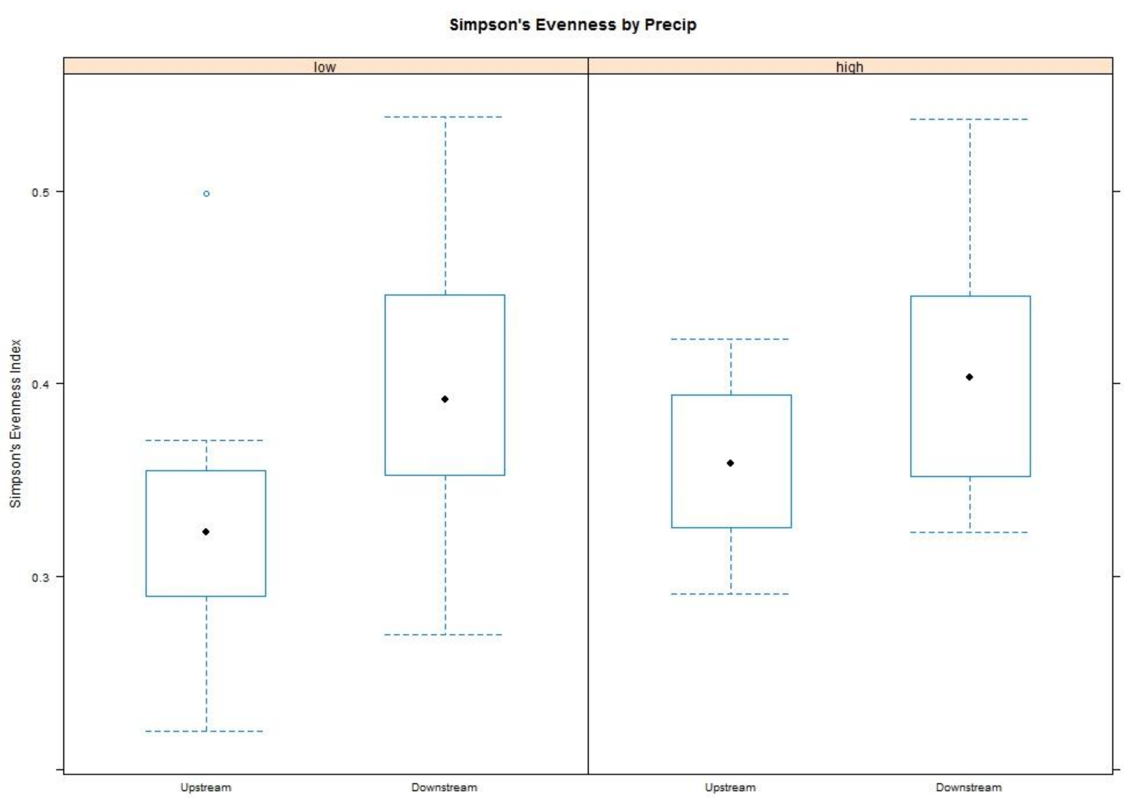

Figure A.25: Simpson's Evenness by precipitation regime

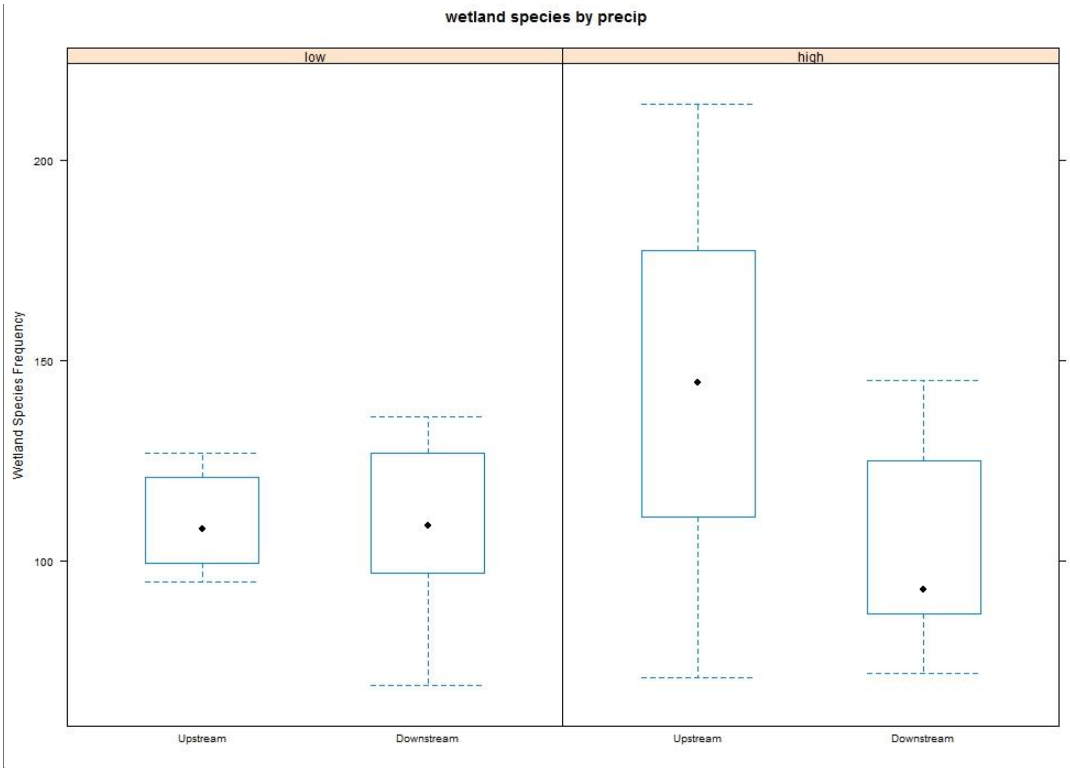

Figure A.26: Wetland species by precipitation regime

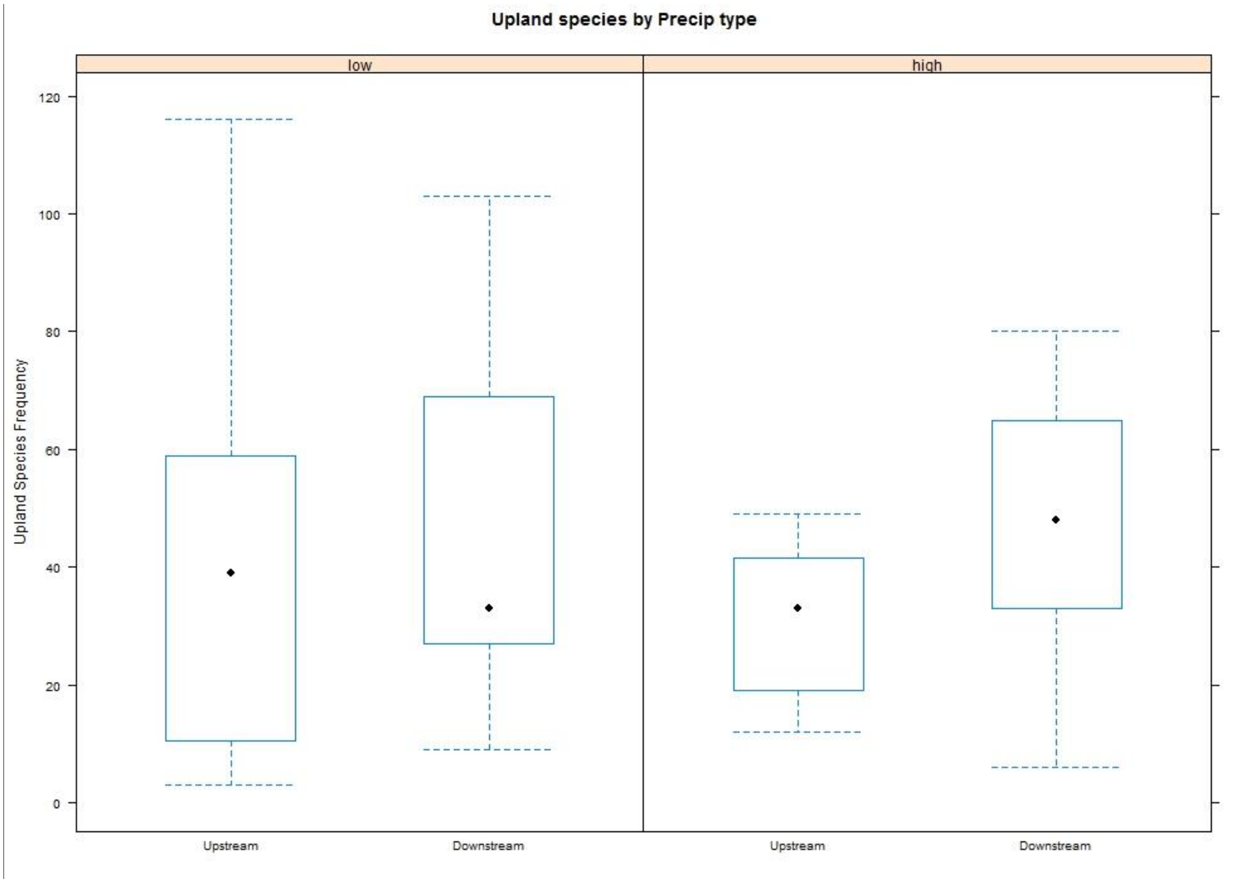

Figure A.27: Upland species by precipitation regime

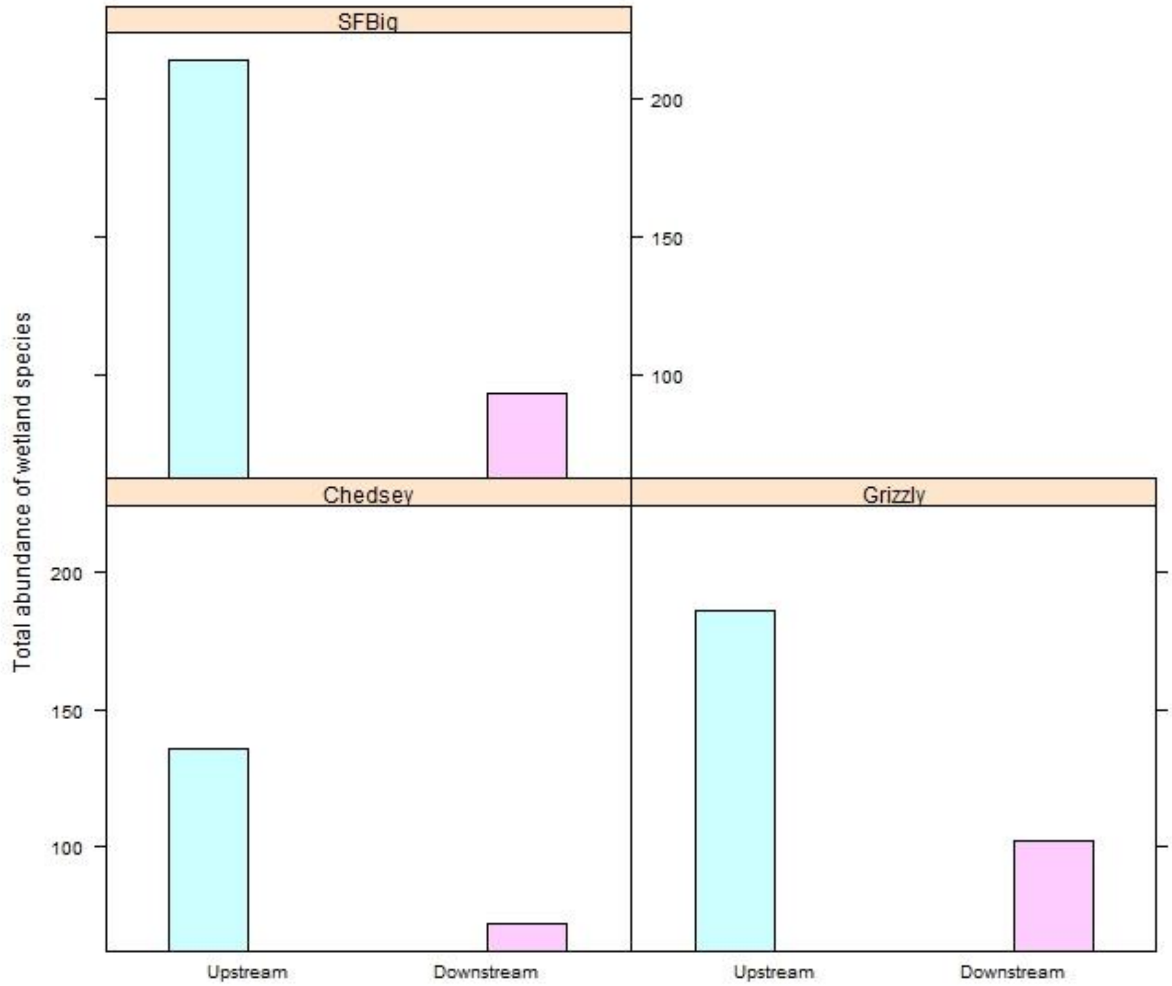

Figure A.28: Abundance frequency of wetland species for well-engineered diversion structures

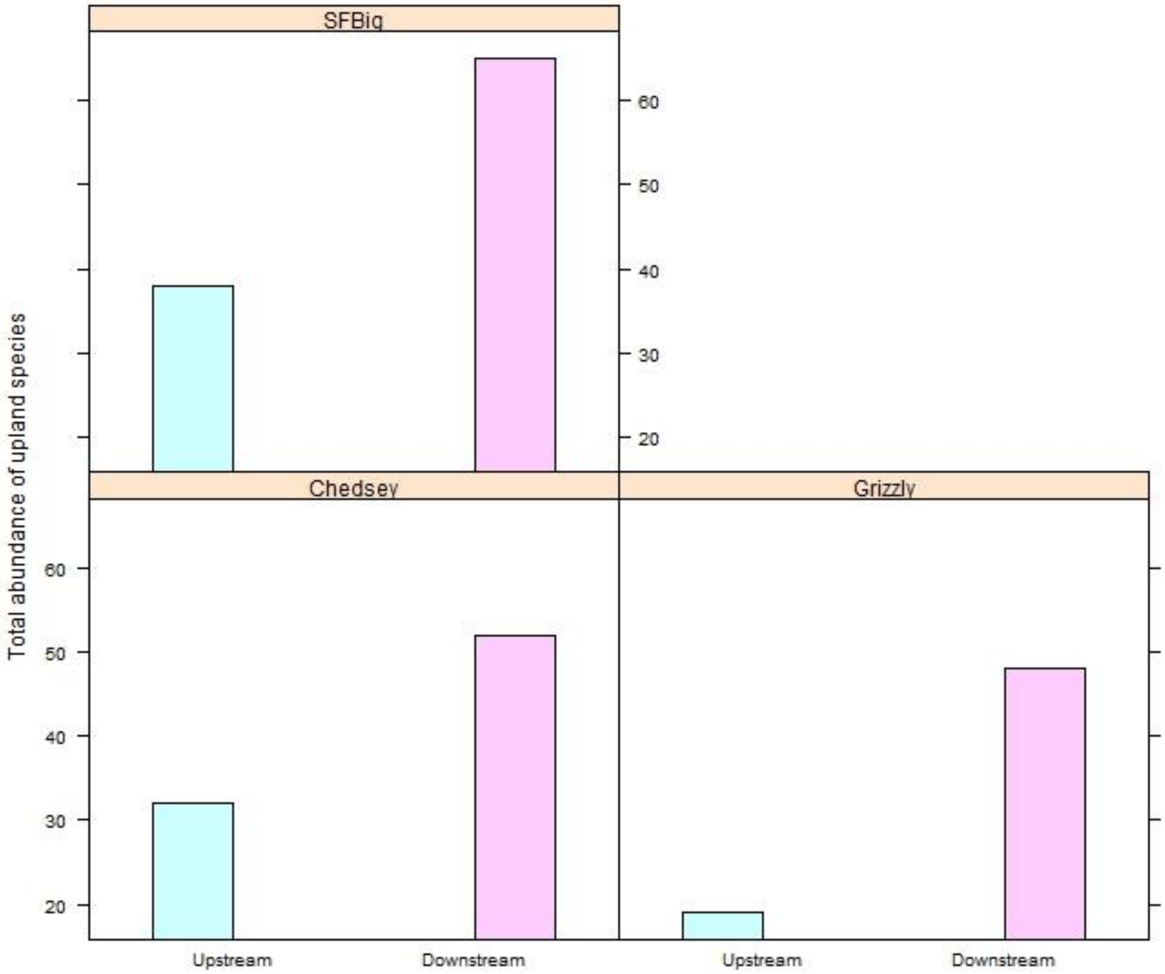

Figure A.29: Abundance frequency for upland species for paired reaches at well-engineers structures or substantial diversion amounts