SB14-195 Report to the Colorado Legislature
South Platte Phreatophyte Study

December 31, 2016

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Summary of Findings and Recommendations

This summary provides an overview of findings and recommendations related to effects of the 2013 flood on the riparian forest of the South Platte River in northeast Colorado. For supporting documentation and a more detailed summation, please see pages 5-35. Appendices are included on the online version found at http://www.cwi.colostate.edu to provide additional detail on research methodology and findings.

Forest composition and future trajectory:

- Riparian forest composition and extent in the South Platte basin have likely been under continuous change since water development began in the mid-19th Century. This process is driven by both short- and long-term patterns of river discharge within the system.

- Phreatophytes are deep-rooted plants, such as cottonwoods or willows that access a substantial portion of their water needs from groundwater sources. They are associated with all riparian corridors to various degrees, but non-native and invasive phreatophytes are a source of concern for both water users and environmental interests.

- The riparian forest along the South Platte River is dominated by Plains cottonwood, in terms of basal area, stem density, and canopy cover. The second most common mature tree species is the Peach-leaf willow. Currently, the most common non-native phreatophytes in the study area are Russian olive and Siberian elm. We estimate that non-native phreatophytes make up between 4% and 10% of the riparian forest on a per-area basis.

- Maintenance of cottonwood and willow forests depends upon periodic flooding and disturbance patterns that allow for both seedling establishment and long-term survival. In the absence of appropriate levels of disturbance, vegetation dynamics will likely follow one of two possible trajectories:

    1) Forest succession could result in a shift in forest composition from cottonwood-willow to non-pioneer species such as green ash, Siberian elm and Russian olive, or

    2) Mortality of cottonwoods could result in a shift to grassland conditions.

- The issue of whether removing phreatophytes increases water supply has been studied for many years, and little empirical evidence exists that tree removal will sustainably increase water supply.

Effects of flooding on Phreatophytes:

- A conservative estimate of the result of scouring, erosion, and/or temporary inundation from the 2013 flood and subsequent high water years in 2014 and 2015 is that at least 8.5% of the forest, on an area basis, died in this interval.

- The flood opened up new areas for cottonwood seedling germination and establishment that occurred during 2014 and 2015. We do not yet know whether these seedlings will survive to become saplings or mature trees.

Effects of flooding on shallow ground water levels:

The effect of the 2013 flood on shallow ground water levels was short in duration. Ground water levels followed river flows, and receded in most areas as river flows returned to normal levels 3 – 5 weeks after the flood. Thus, long-term changes in phreatophyte evapotranspiration (ET) are not due to flood effects on groundwater levels.

Abundance of Colorado State Listed weeds in the study area:

- Listed weed species are common, but percent cover is generally low within the study area. The disturbance associated with removal has the potential to greatly increase the severity of weed infestations within the area.

Cost of Phreatophyte Control

- Estimated total costs for removing 20% of phreatophytes from all reaches range from $870,700 for one-time removal only, to $45,524,846 for removal plus weed control, seeding, and shrub planting.

Recommendations

- Additional information will be needed to assess long-term trends in riparian forest spatial extent, dynamics of cottonwood regeneration, and successional trajectories for species composition within aging forest stands. A key question that remains from our survey work is how frequently cottonwood seedlings successfully recruit to the sapling stage within this system.

- Understanding both the historical trajectory of cottonwood recruitment, and the effects of the last three years of flood and high water on recruitment, would allow us to better predict the long-term trajectory of the forest. This study provides an important data point in time characterizing the riparian forest in the lower South Platte basin in 2015. It is recommended that this data be secured, and that the South Platte Roundtable determine a recurrence interval on the order of 3 to 5 years to update the data, allowing more accurate understanding of the state and trajectory of the riparian forest.

- Phreatophyte removal efforts — if pursued — should concentrate on the non-native phreatophytes in the system. Native species, such as cottonwood and willow, may be declining in abundance without intervention.

- Removal efforts — if pursued — need to include appropriate re-vegetation strategies that promote the maintenance of desirable native species, while preventing further expansion of noxious weed species.

Background

In 2014, the Colorado legislature passed SB14-195, directing the Colorado Water Conservation Board to study the effects of the September 2013 South Platte flood on phreatophyte spread and the feasibility of removing non-native phreatophytes from the South Platte River corridor.

The September 9-16, 2013 flood occurred due to an unusually heavy and prolonged rainfall event over a large area of the Colorado Front Range foothills, resulting in an exceptional flood event on the South Platte River. Record rainfall amounts were measured in several areas with the previous one-day state record of 11.08 inches of precipitation exceeded at Fort Carson, where 11.85 inches fell on September 12, 2013. The flood inundated large stretches of the floodplain from communities along the Front Range all the way to Nebraska, causing heavy damage, exceeding an estimated $2 billion in property loss, plus 10 fatalities. As the floodwaters reached the eastern plains along the river, widespread local flooding occurred as massive amounts of water moved through the system. Reconstructed estimated peak flood flows at Kersey in September 2013 were on the order of 55,000 cubic feet per second (cfs), while typical September flows at the Kersey gauge are in the neighborhood of 500 cfs. As a result, significant quantities of sediment, plants and debris were scoured and redistributed in the floodplain.

Following the September 2013 flood, there was concern that new sediment deposits, elevated groundwater levels, and altered stream banks would result in an increase the abundance of invasive non-native species, including woody phreatophytes and State of Colorado-listed noxious weeds. SB 14-195 directed the Colorado Water Conservation Board to: "*conduct at least the preliminary stages of a comprehensive study to evaluate the growth and identification of phreatophytes along the South Platte River in the aftermath of the September 2013 flood*". Additionally, the bill directs that: "*the Board shall prepare a Final Report, including its conclusions, and present it to the General Assembly no later than December 31, 2016*."

A total of four meetings were held with the South Platte BRT and/or their Phreatophyte Subcommittee to develop a two-phase plan of study and accompanying Scopes of Work. Phase 1 work was within the specialized expertise of CSU and also built on previous groundwater work by the CWI (HB12-1278 alluvial aquifer study). Phase 2 involved estimating non-beneficial consumptive use by phreatophytes, developing control strategies and cost estimates based on the inventory work done in Phase 1, and writing the final report required by SB-195. The Tamarisk Coalition, a non-profit entity based in Grand Junction, has unique capabilities and tools to assess cost and control strategies, and was contracted to develop these estimates.

Specific Concerns:

- Increased numbers of phreatophytes could non-beneficially consume more water via evapotranspiration of tributary groundwater.

- The presence of other, undesirable non-woody weed species may increase the cost and complexity of phreatophyte removal, due to a need for post-removal follow-up treatments.

Study Objectives:

1) Create a written review of the existing literature on the association between river hydrology, and native and non-native phreatophyte establishment and growth — with emphasis on issues particularly relevant to the South Platte River.

2) Determine the abundance and distribution of native and non-native woody phreatophyte species at twenty sites along the South Platte River, and establish the relationship between shallow ground water and phreatophyte presence and abundance.

3) Determine the frequency and severity of invasion by Colorado State-listed noxious weeds at these same sites.

4) For both phreatophytes and listed noxious weed species, determine the relationship between the changing landscape, and species incidence and abundance. Along with this, examine the effects of the September 2013 flood on species recruitment.

5) Link these data to GIS-based maps of the South Platte flood plain, and use these maps to predict the abundance of non-native phreatophytes and listed weeds along and within the river system.

6) Obtain data from existing groundwater monitoring wells from before and after the 2013 flood, and determine if there has been a measurable change in water table depth within the flood-affected region.

Results

Objective 1

Create a written review of the existing literature on the association between river hydrology and native and non-native phreatophyte establishment and growth, emphasizing issues of particular relevance to the South Platte River.

River hydrology and riparian trees: Literature review

Hydrology and recruitment

The dominant tree species here are highly dependent on river-related processes for seed dispersal, establishment, and survival. For long-term survival, they must be protected from perpetual flooding, complete burial by sediment, lethal scouring by water and ice, and lethal drought stress.

General effects of flooding and drought

In the short term (i.e., days to years), flooding can result in substantial mortality to riparian trees. In the long term (i.e., decades) flooding generally promotes rejuvenation of floodplain forest ecosystems, via its effects on recruitment of native cottonwoods and willows.

Similarly, drought can result in substantial mortality through declining water tables — but it can also allow for expansion into ground surfaces normally covered by floodwaters.

Native cottonwoods and willows

For cottonwoods and willows, seedlings are commonly established on bare, moist sediments left behind by river processes.

Reproduction methods For many riparian species, asexual vegetative or clonal reproduction is also important, and is linked to river hydrology and fluvial processes (Karrenberg et al. 2002, Rood et al. 2007). This is especially true for willows (*Salix* spp.), and for narrowleaf cottonwood, black cottonwood, and balsam poplar (species in the *Tacamahaca* taxonomic group of the genus *Populus*; Rood et al. 2007). For prairie cottonwoods (species in the *Aigeiros* taxonomic group of the genus *Populus*) such as Fremont cottonwood and plains cottonwood (the species present in the

South Platte River system in eastern Colorado), asexual reproduction can occur by shoot suckering, “flood training” where shoots sprout from buried stems, and by re-sprouting from cut stems (Rood et al. 2007). Further, many willows (including the non-native tree crack willow, *Salix fragilis*) can re-sprout from broken branch fragments, but this is not commonly observed in cottonwoods (Shafroth et al. 1994).

Time of propagation: Seeds for cottonwoods and some willows are dispersed at the time of, or immediately following, natural peak flows. Cottonwoods produce seeds during a short time period in spring or early summer, when snowmelt produces high flows in many western rivers. Seeds are viable for only a few weeks, and germinate quickly (24-48 hours, Stromberg 1993a).

The exact timing of seed release varies depending on individual tree characteristics, local conditions, and yearly weather.

Seedling characteristics

Initial seedling establishment of cottonwoods and willows typically occurs on “fluvial disturbance patches” — where moist sediment is free of competing vegetation and plant litter (Auble and Scott 1998).

Cottonwood seedlings are:

- intolerant of shade
- rarely established within intact herbaceous vegetation (Friedman et al. 1995, Katz et al. 2001), or beneath forest canopies (Johnson et al. 1976)

Both riparian cottonwood (Segelquist et al. 1993) and willow (Horton and Clark 2001) species are:

- intolerant of desiccation
- heavily dependent on moisture for survival

Therefore, each year, these trees typically establish themselves next to, or within, the active channel zone where areas are bare and moist (Stromberg 1993c, Friedman et al. 1997, Stromberg 1997, Galuska and Kolb 2002). However, seedlings established there are unlikely to survive.

SEEDLINGS

Cottonwoods and willows establish in bare, moist areas like this one.

However, their seedlings are unlikely to survive for the long-term.

Typical mortality rates

Most years, first-year cottonwood and willow seedlings have a high mortality.

- Seedlings established within the active channel zone are extremely vulnerable to removal by subsequent stream flows (Stromberg 1997, Auble and Scott 1998, Rood et al. 1998).

- Seedlings established at more elevated positions are vulnerable to summer drought stress and mortality (McBride and Strahan 1984).

- Mortality rates of close to 100% are commonly observed for cottonwood and willow seedlings established in the active channel zone, due to summer drought stress during their first growing season, or erosion during subsequent high flows (e.g., Sacchi and Price 1992, Stromberg 1997).

- In a pattern likely typical of seedling dynamics in most years, Sedgwick and Knopf (1989) found high mortality of first-year plains cottonwood seedlings on the South Platte River in 1984, a summer with average precipitation and discharge patterns.

Requirements for long-term survival

Survival and recruitment into older age classes requires protection from:

- perpetual flooding
- complete burial by sediment
- lethal scouring by water and ice
- lethal drought stress

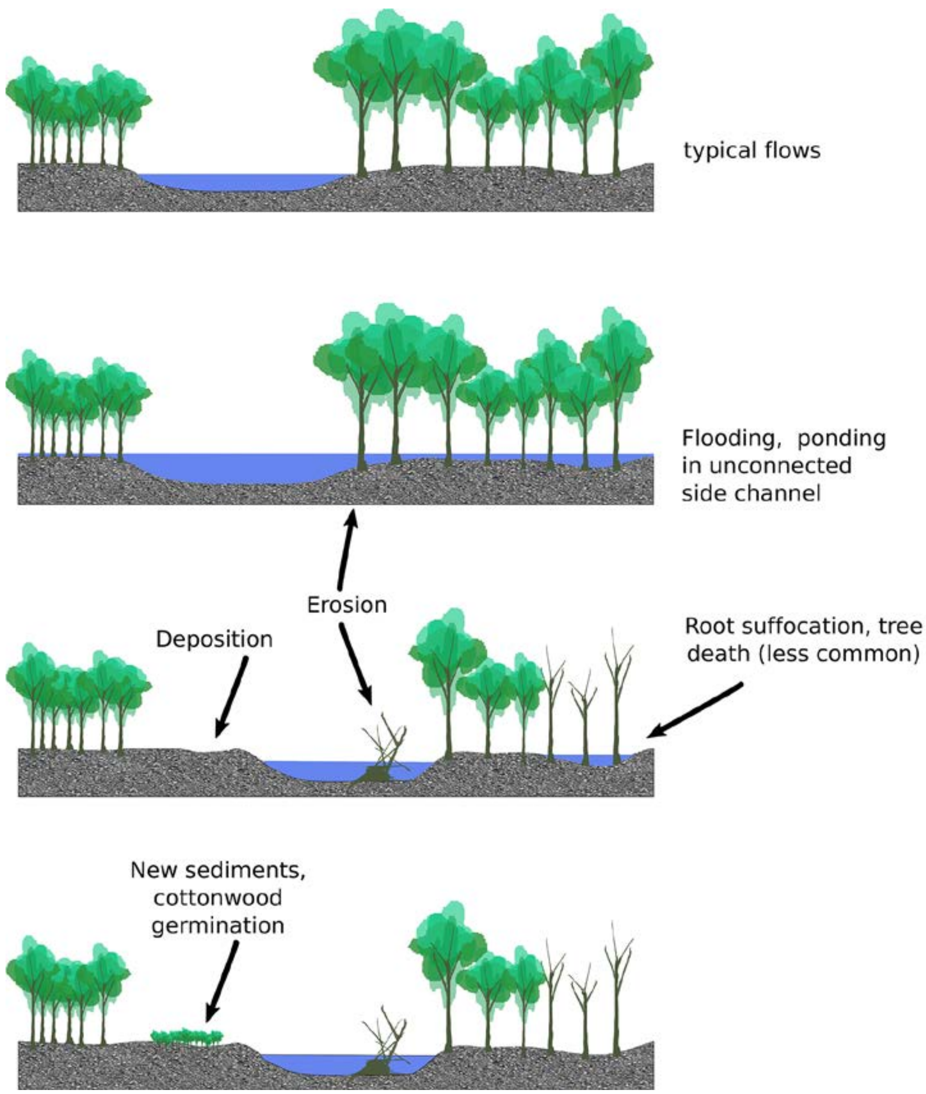

Figure 1

Cottonwood seedlings must also have access to groundwater. As riparian water tables recede following normal spring flooding, root growth must keep pace or the seedlings will with and die (Segelquist et al. 1993).

Optimal growth location

Mahoney and Rood (1998) reviewed the literature on cottonwood seedling establishment, and determined that successful recruitment occurred between approximately 60 and 150 cm above the river base flow elevation. Presumably, this allows for long enough root growth to reach water, while avoiding destruction through erosion.

Potential Outcomes

The long-term persistence of a riparian cottonwood forest on the South Platte River in eastern Colorado depends upon:

a) **fluvial processes** (i.e., sediment erosion and deposition) and
b) **hydrologic conditions** (i.e., flow dynamism and groundwater levels)

Because they are pioneer species, cottonwoods and willows require dynamic processes of flooding, erosion, and sediment deposits for seedling establishment. These processes must occur frequently enough to rejuvenate the forest as mature trees die. An imbalance of the processes could result in one of two long-term trajectories for the area's vegetation:

a) **Forest composition could shift to non-pioneer species** such as green ash, boxelder, Siberian elm, Russian olive and eastern juniper (Sedgwick and Knopf 1989, Johnson 1994).

b) **Mortality of cottonwoods could result in a shift to grassland conditions** (Figure 2, Friedman et al. 1997).

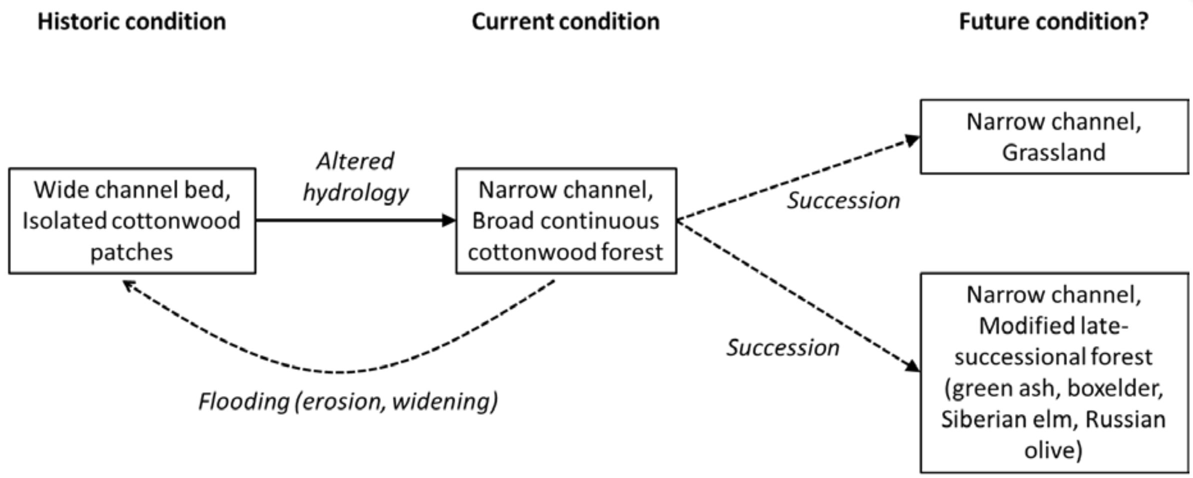

Figure 2. *Conceptual model of historic vegetation dynamics (solid arrow), and possible future conditions (dashed arrows), of the South Platte River riparian forest in eastern Colorado (modified from Friedman et al. 1997, Strange et al. 1999).*

Ecological succession could lead to grassland or a modified late-successional forest dominated by non-native species. Alternatively, flooding could widen the channel and lead to renewed cottonwood forest establishment. More research is needed to determine the trajectory of this forest.

Phreatophyte Evapotranspiration

Two previous studies developed estimations of phreatophyte evapotranspiration (ET) from groundwater in the S. Platte basin. South Platte DSS Task Memo 65 by David Groeneveld and Michael Prescott dated January 30, 2007 developed estimations of phreatophyte evapotranspiration (ET) from groundwater in the S. Platte basin for the baseline year of 2001. The HB12-1278 Groundwater study conducted by the Colorado Water Institute at CSU sought to validate the Groeneveld study and extend the timeline backward to 1990 and forward to 2001.

Both studies used Landsat data and a derivation of the Normalized Difference Vegetation Index (NDVI). Total annual estimated phreatophyte ET, including the tributaries to the South Platte River downstream from Denver, for 2001 was approximately 255,000 AF per year, within the riparian zones along both the river and the tributaries in the basin. The total annual phreatophyte ET estimated by Groeneveld for the riparian corridor along Water Districts 2, 1, and 64 was 123,686 AF for the year 2001.

By far, the largest proportion of phreatophyte ET occurs during the growing season along the mainstem of the South Platte in the floodplain.

The HB12-1278 study shows increases in phreatophyte ET from groundwater from 1990 to 2010 from 115,438 AF annually in 1990 to 156,601 AF annually in 2010, a 35% increase over the 20-year period.

Because the riparian corridor is constrained by development and agricultural fields for most of the river through Water Districts 2, 1, and 64, the majority of the increase in ET was due to increased density of the canopy within the existing riparian corridor.

SOUTH PLATTE TRENDS

The two study sites on the South Platte River in Colorado displayed trends of channel widening since the 1940's — along with loss of riparian forest.

Literature conclusions

Johnson (1994) focused primarily on sites in Nebraska, and concluded that the forest extent on the South Platte River system was overall in a dynamic steady state, with stabilized proportions of active channel, vs. vegetated floodplain area since the 1960s. However, the two study sites on the South Platte River in Colorado were different, instead displaying trends of channel widening since the 1940's — along with loss of riparian forest.

Similarly, Snyder and Miller (1991) found a slight increase in river channel width and loss of cottonwood forest area on the South Platte River in eastern Colorado between 1941 and 1979. These conclusions were based on analysis of aerial photographs.

Both Sedgwick and Knopf (1989) and Johnson (1994) cautioned that the cottonwood forest on the South Platte River was likely undergoing succession to less ecologically valuable species, and that the future riparian forest would be dominated by non-pioneer species.

Thus, these authors interpreted the twentieth century channel narrowing/cottonwood establishment event on the South Platte River as a historic occurrence that is not ongoing. However, Snyder and Miller (1991) were more optimistic about cottonwood recruitment on the South Platte

River, suggesting that it does still occur under the present hydrologic regime.

Further Research Requirements

Effective management of this forest requires an understanding of ongoing trends in forest area/extent and ecological succession. Although several studies addressed these questions in the past (i.e., Sedgwick and Knopf 1989, Snyder and Miller 1991, Johnson 1994), new efforts are needed to update these prior studies.

In particular, research is needed to assess long-term trends in:

- riparian forest spatial extent (i.e., loss and/or gain of forest area over time, and in association with specific flood events)
- dynamics of cottonwood regeneration
- successional trajectories of species composition within aging forest stands

This research will improve our understanding of the spatio-temporal dynamics of this riparian forest, and will provide an important context for management.

Objective 2

Determine the abundance and distribution of native and non-native woody phreatophyte species at twenty sites along the South Platte River, and establish the relationship between shallow ground water and phreatophyte presence and abundance.

Objective 3

Determine the frequency and severity of invasion by Colorado State-listed noxious weeds at these same sites.

Findings

Sites surveyed: 15 sites; 873 plots sized 10 x 20 m; a total of 435 acres — see Figure 3

Data collected: diameter at breast height, height, and canopy condition from 2182 trees

Definition:
Basal area (BA) — A common metric used to compare tree volume between sites, BA is a measure of the total cross sectional area occupied by trunks.

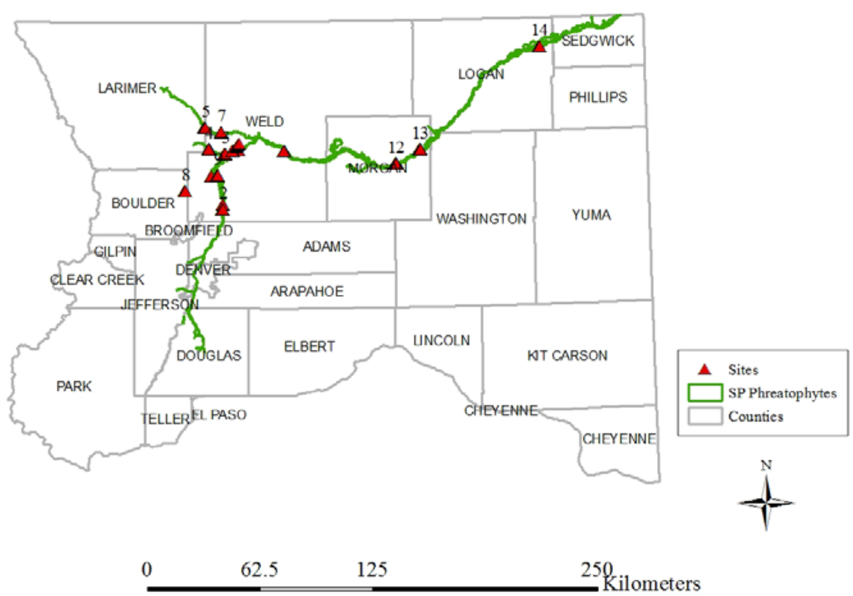

Figure 3. Study site locations in the S. Platte Basin.

Trees

Colorado Natives

As expected, plains cottonwood (*Populus deltoides*) is the dominant tree species in the South Platte floodplain, comprising more than 45% of the individuals recorded. Just over 80% of the total tree basal area for the study area is comprised of plains cottonwood, followed by peach leaf willow (*Salix amygdaloides*) at nearly 12% of the total basal area.

Colorado Non-natives

Species not native to Colorado comprise less 6% of basal area over all sites. The most common non-native tree species is Russian olive (*Elaeangus angustifolia*), which comprises 2.21 % of total basal area and 4.54 % of individuals encountered in the surveys.

Saplings

There were far fewer saplings within the study area than trees, with a combined total of 386 saplings over all species and all sites. Green ash was the most common species of sapling recorded, (131), followed by peach leaf willow (103).

Tamarix spp. was the third most common sapling recorded, with 44, all of which were on a single sandbar at site 11). We suspect that these saplings all originated from one or two large, buried *Tamarix* trees.

Although cottonwood is the most dominant tree species over all sites, we only recorded 43 sapling individuals. This is consistent with the idea that cottonwoods require a set of specific and relatively infrequent conditions for long-term survival.

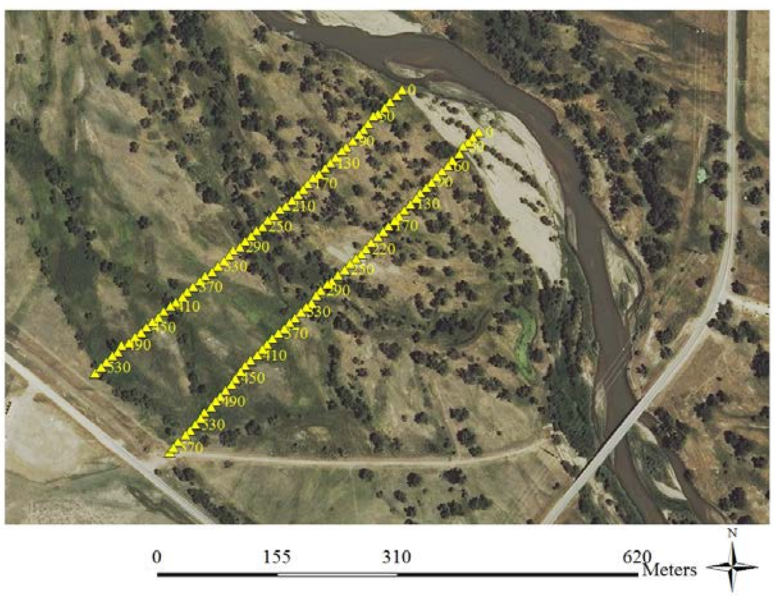

Figure 4. Example of transect sampling design from site 11. Yellow triangles are recorded GPS points taken every 10 m along transect.

Seedlings

Cottonwoods

Cottonwoods were by far the most common tree seedling encountered, with more than 100,000 over the entire survey area. (Table 1.)

- Highly variable numbers — ranging from 0 at site 1, to 32,936 at site 14.
- Variability likely results from the specific environmental requirements for cottonwood seed germination. Cottonwood seeds need bare, moist soil. Where these conditions occur, hundreds to thousands of seedlings may germinate per m^2 (see Literature Review).

Russian Olive

We found a total of 4 seedlings of Russian olive, a surprising result given that this species is considered invasive in Colorado and that it is common (though not abundant) in the study area.

Other

We found 275 and 32 seedlings for Siberian elm (*Ulmus pumilla*) and *Tamarix* spp., respectively.

Questions

One of the questions raised in the literature review, is to what degree cottonwood and willow are still reproducing within the study area.

With altered flow regimes and channel narrowing, it is possible that these pioneer species are in decline and are being replaced by other species, most notably green ash, Russian olive and Siberian elm.

Note: The single full growing season between the September 2013 flood and the summer 2015 data collection season is not a long enough period of time for a seedling to mature into a sapling. Thus, any seedlings germinated in summer 2014 or 2015 would be counted as seedlings in our data.

COTTONWOOD SURVIVAL

The number of cottonwood seedlings varied greatly from site to site.

Their possibility of survival cannot be predicted, however, given their relatively low survival rates as outlined in the Literature Review.

The number of Russian olive seedlings was surprisingly low.

It is possible that pioneer species are being replaced by green ash, Russian olive, and Siberian elm.

Table 1. Number of seedlings recorded for each tree species.

Reach	# plots	Area surveyed (ha)	Box elder	Russian olive	Green ash	Cottonwood	Peach leaf willow	Tamarix spp.	American elm	Siberian elm
1	46	9.2	0	0	1	0	0	0	0	0
2	24	4.8	0	0	4	5	3	0	0	4
3	67	13.4	0	3	0	328	1	29	0	2
4	48	9.6	0	0	0	17,777	90	3	0	0
5	47	9.4	55	0	5	1	35	0	0	71
6	47	9.4	0	0	0	25	12	0	0	0
7	59	11.8	0	0	3	19,961	72	0	0	0
8	48	9.6	0	0	4	6,388	1,029	0	0	125
9	65	13	0	1	0	23,560	58	0	0	1
10	63	12.7	39	0	98	39	17	0	0	4
11	112	22.4	0	0	18	153	0	0	0	0
12	46	9.3	0	0	33	1	7	0	0	3
13	61	12.2	1	0	3,226	350	26	0	5	0
14	84	16.86	0	0	1,125	32,936	0	0	0	0
15	56	11.2	0	0	18	63	28	0	3	65
Totals	873	174.86	95	4	4,535	101,586	1,378	32	8	275

Note: Seedling mortality is highly variable between species and year-to-year. Green ash, Russian olive and Siberian elm should have much lower seedling mortality rates than cottonwood or willow. It is difficult to predict forest succession based on seedlings counts; Saplings are a much better predictor of future forest composition.

Sapling Phreatophytes in the South Platte Flood Plain – Distribution of Counts

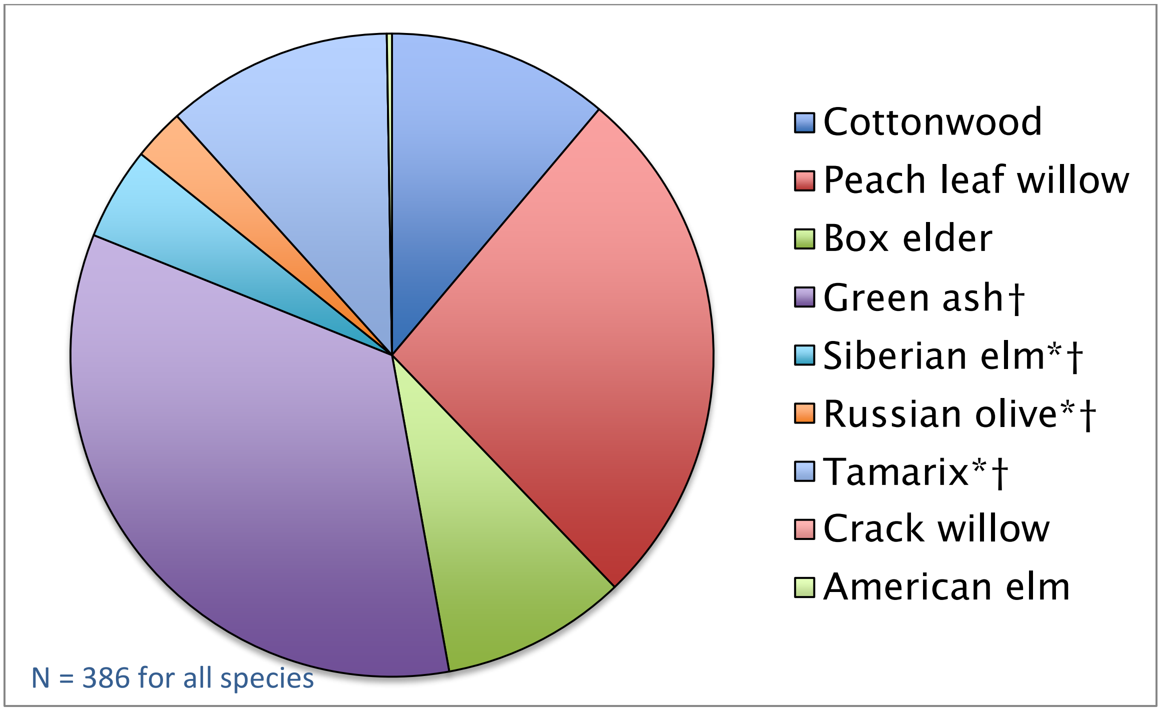

Figure 5

Note: Counts of saplings do not match mature basal area. Cottonwood is under-represented compared to the mature distribution. Green ash is over-represented.

**Not native to US. †Not native to Colorado*

Mature Phreatophytes in the South Platte Flood Plain – Basal Area

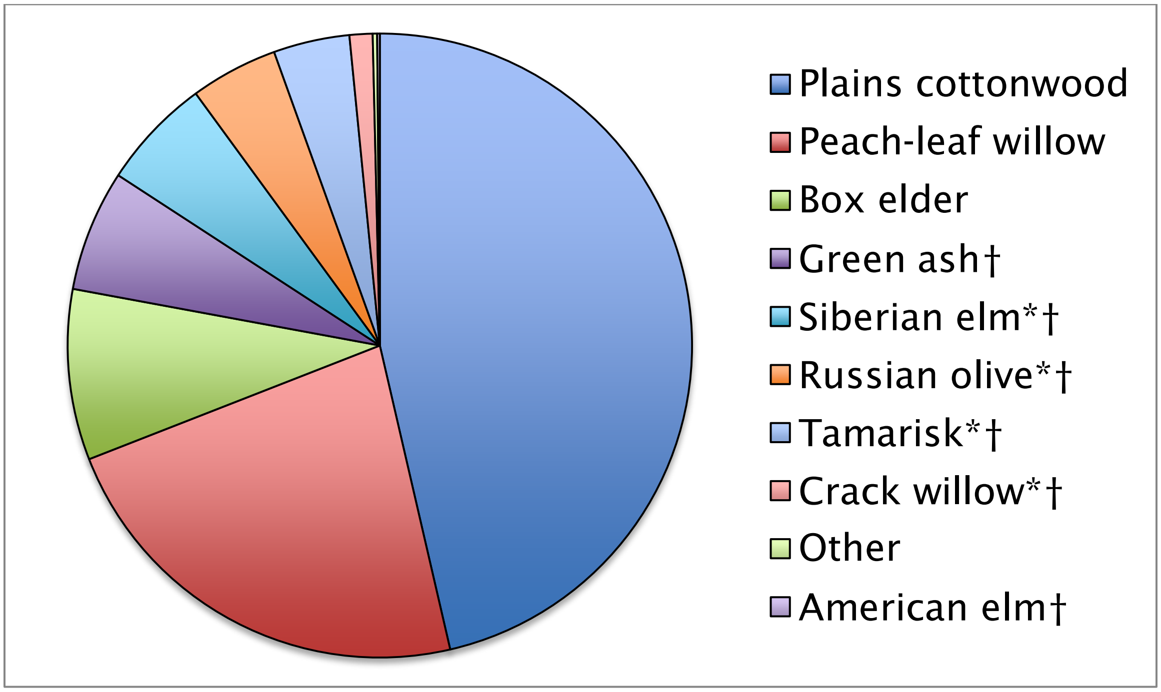

Figure 6

Note: Cottonwood and willow comprise greater than 90% of basal area in the system. Non-native to US – 4.65% of basal area in the system.

**Not native to US. †Not native to Colorado*

Weeds

State of Colorado-listed noxious weeds were common at all sites.

For example, nearly 30% of plots surveyed contained hoary cress (*Cardaria draba*), and almost 35% of plots contained downy brome (*Bromus tectorum*)

When all weed species are considered together, 90% of plots sampled contained one or more weed species.

Percent cover for each weed species presents a similar picture. Over all plots and all sites, listed weeds make up more than 20% of plant cover. Downy brome (10.42%) and hoary cress (4.35%) are the most abundant weed species we found.

Further Details

Trees

As expected, cottonwood and willow are the dominant tree species throughout the study area, comprising more than 90% of the basal area over all sites. Although these two native phreatophytes are the most abundant mature trees, the relative absence of saplings and abundance of seedlings for the two species confirms that they have specific requirements for recruitment.

In 2015, we found a large number of seedlings of these two species. The floods and high water of 2013, 2014, and 2015 likely created many bare, moist sites suitable for seedling germination.

Whether these seedlings will be able to survive the next few years and become newly recruited saplings is an open question, as cottonwood seedlings typically experience very low survival rates (see literature review above).

Contrary to expectations, non-native species make up a relatively small portion of the forest in the study area when compared to other western river systems (Nagler et al. 2010b). Additionally, there were few saplings and seedlings of these species. It seems unlikely at this point that the last few years of floods and high water have resulted in an outbreak of native or non-native tree species in the study area (Figures 5 and 6).

Weeds

State of Colorado-listed weeds are common throughout the study area and are present at all sites. The most common species, downy brome, is in Colorado list "C". Species on this list are of concern, but do not require management action to prevent their continued spread. Common mullein is also on list C.

One list-A species, purple loosestrife, was found at two different sites. These species are designated for eradication within the state.

All of the other weed species found are in Colorado list B. Species on this list must be managed in a way to prevent their continued spread.

Objective 4

For both phreatophytes and listed weed species, determine the relationship between river geomorphic surface and species incidence and abundance, and examine the effects of the September 2013 flood on species recruitment.

Objective 5

Link these data to GIS-based maps of the South Platte flood plain, and use these maps to predict the abundance of non-native phreatophytes and listed weeds along and within the river system.

Findings

In the interval between the October 2013 and July 2015, approximately 8.5% of the riparian forest died.

Visual examination of the output maps indicates that most of our estimated mortality is associated with the physical effects of the flood or from movement of the river channel. Less commonly, trees died when they were some distance away from the 2013 or 2015 channel. In most cases, these areas are next to back channels or other low spots in the floodplain.

- Tree mortality in the interval was lowest for the South Platte River, upriver from its confluence with the St. Vrain, equaling 4.68%.
- 5.55% of trees died on the South Platte between the St. Vrain and the Big Thompson, and 5.19% between the Big Thompson and the Poudre.
- Mortality was highest on the St. Vrain (10.84%), followed by the South Platte downstream from its confluence with the Poudre (9.51%).

Using Remote Sensing Data for South Platte Phreatophyte Assessment: Data and Method

Data Acquisition and Preparation

Remote sensing data of aerial imagery and LiDAR data are key elements in predicting the abundance of non-native phreatophytes and listed weeds along and within the river system. We used a combination of aerial imagery and LiDAR data to estimate phreatophyte species identity and tree mortality within the study area.

Aerial imagery was obtained from the National Agriculture Imagery Program (NAIP) (USDA FSA 2016). These images contain 4 bands of color information (red, green, blue and near infrared) and are produced with a 1 m ground resolution.

We acquired images for both summer 2013 (pre-flood) and summer 2015 (post-flood) and processed them using ArcGIS 10.1 (ESRI 2011).

- The approximately 100 images that cover the study area were combined into a single mosaic database.
- The four bands of color information allow us to measure the Normalized Difference Vegetation Index (NDVI) — a measure of how healthy vegetation is. NDVI values range from -1 (no vegetation) to +1 (healthy growing vegetation).
- Separate NDVI layers were generated for both 2013 and 2015.

About LiDAR Data

LiDAR data for the study area were acquired on October 25, 2013 and were obtained from the USGS National Geospatial Program. LiDAR remote sensing uses light pulses to measure surface elevation and texture. These data are acquired at approximately 60 cm intervals on the ground and can be processed into separate layers for:

- ground elevation (a Digital Elevation Model), and
- maximum elevation (for example the tops of vegetation — a Digital Surface Model)

From these layers, we can estimate vegetation height throughout the study area (a normalized Digital Surface Model)

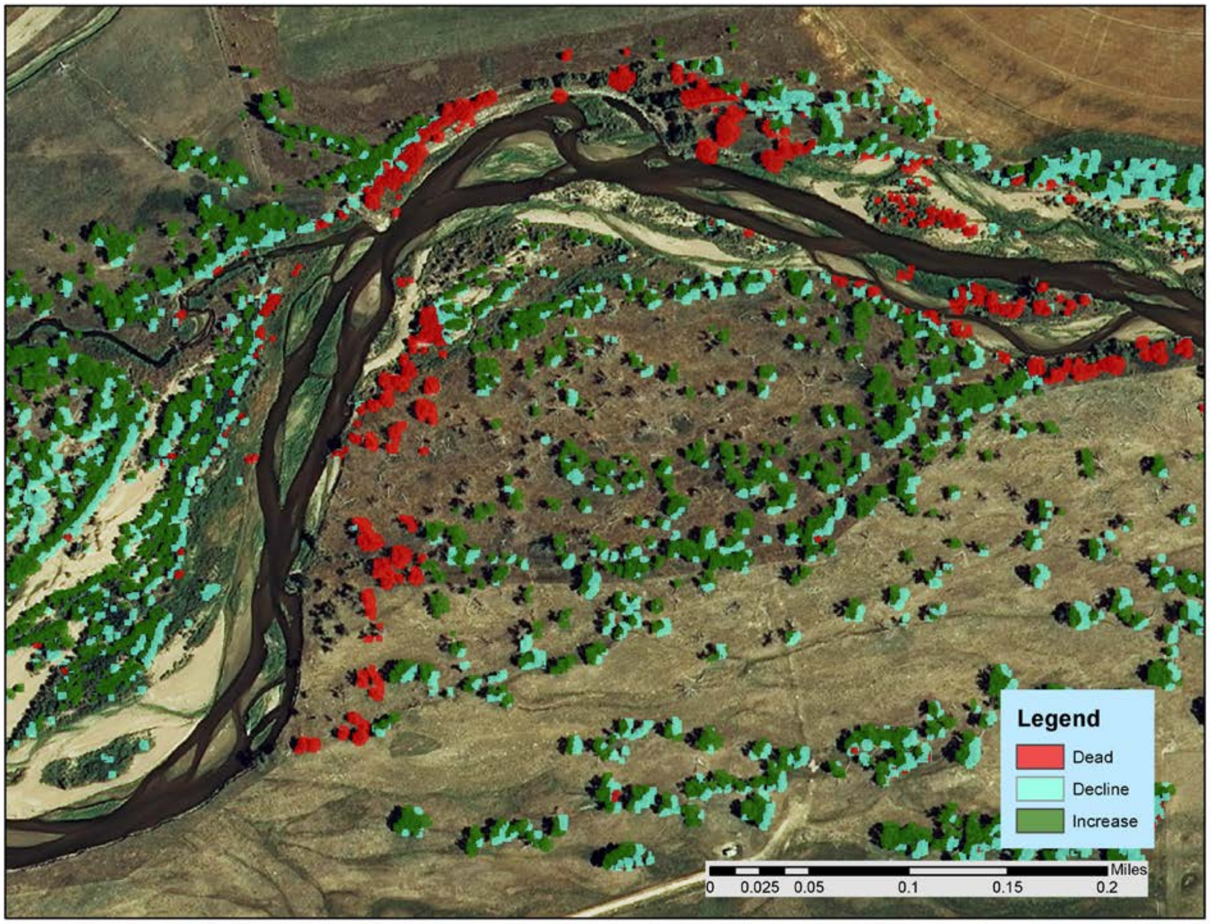

Figure 7a: Digital Surface Model (DSM).

Estimating Tree Mortality

We developed a model to predict changes in tree abundance and health using a combination of vegetation height data derived from the LiDAR dataset and vegetation health data from the 2013 and 2015 NDVI estimates.

To do this, we estimated for every portion of the study area with vegetation height greater than 2 m, the change in NDVI from summer 2013 (before the flood) to summer 2015 (after the 2013 flood and the high-flow years of 2014 and 2015).

Our process was to first select all portions of the study area with vegetation taller than 2 m, and 2013 NDVI > than 0.145. For these areas, we then calculated the difference in NDVI (d_NDVI) as NDVI 2015 – NDVI 2013. By examining d_NDVI values for plots with dead or live trees from our survey data and from summer 2013 and summer 2015 imagery, we classified areas with trees as:

d_NDVI < -0.35 = dead or removed,

-0.35 < d_NDVI < -0.1 = declined

and d_NDVI > 0.1 = increasing

These raster values were smoothed using a 5 m x 5 m majority filter, and classified into polygons for determination of the number of acres falling into each class.

Results

In the interval between the October 2013 and July 2015, approximately 8.5% of the riparian forest died (Table 9). Visual examination of the output maps indicates that most of our estimated mortality is associated with the physical effects of the flood or from movement of the river channel. Less commonly, trees died that were some distance away from the 2013 or 2015 channel. Figures 5a and 5b illustrate this.

In most cases these areas are next to back channels or other low spots in the floodplain. Tree mortality in the interval was lowest for the South Platte River, upriver from its confluence with the St. Vrain, equaling 4.68%. Meanwhile, 5.55% of trees died on the South Platte between the St. Vrain and the Big Thompson, and 5.19% between the Big Thompson and the Poudre.

Mortality was highest on the St. Vrain (10.84%), followed by the South Platte downstream from its confluence with the Poudre (9.51%).

These patterns are consistent with the pattern of flooding in 2013, with flooding occurring on the Poudre, Big Thompson, and St. Vrain, and moving into the main stem of the South Platte.

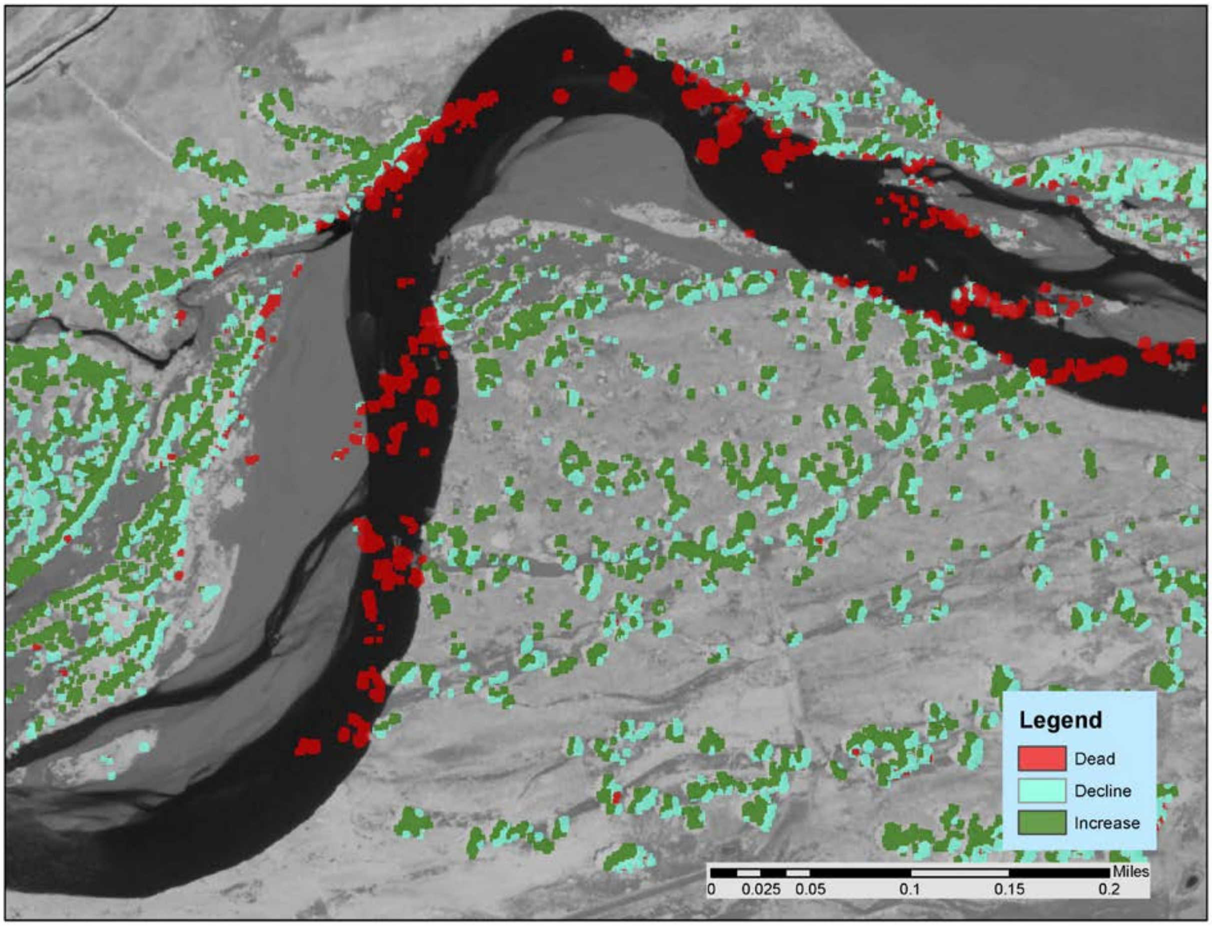

Figure 7b. Tree mortality estimated from LiDAR and remote imagery data. Background image is 2013 NAIP imagery.

Using Object-Based Image Analysis (OBIA) to Estimate Different Tree Species:

Object Based Image Analysis uses unsupervised classification to partition an image into areas with similar data values.

For this study, relevant data are:

- the 4 bands of color information from the 2015 NAIP imagery
- NDVI values from 2015, and
- nDSM values

The nDSM values were first filtered using ArcGIS's median and convolution filters using a 3x3 m range to minimize the effects of "spikes" in height data.

The image of the study area was then segmented into polygons with similar data values. This was performed using the software program eCognition (Trimble, 2016).

We then used an NDVI threshold of 0 to classify these polygons into vegetation and non-vegetation areas, and then an nDSM threshold of 2 m to classify vegetation into trees vs. other vegetation.

Finally, we compiled imagery, NDVI, and nDSM data from polygons that occurred on top of our field plots where we had identified trees to species. These data were then used in the R package *rpart*, a Decision Tree Classification program, to create a rule set that classifies all tree polygons into one of three classes: cottonwood, Russian olive, or other tree species.

Attempts to classify polygons into more specific classes than these three were unsuccessful due to the spectral similarity between many of the tree species.

Results:

Classifications across the entire study area:

- 62% of trees were classified as cottonwood
- 10% as Russian olive
- 28% as other

These values are higher than those estimated from the ground surveys. Basal area estimates (which correlate strongly with canopy area) were:

- 80% cottonwood
- 2% Russian olive
- 18% other

Objective 6

Obtain data from existing groundwater monitoring wells from before and after the 2013 flood and determine if there has been a measurable change in water table depth within the flood-affected region.

We obtained daily ground water measurements from 3 wells within the study area and compared water table elevation to River discharge as measured at the USGS Fort Morgan gauge.

- Well DSS38BLZ is located approximately 26 km downriver from the gauge. (Figure 8a)
- Wells DSS22KRY and DSS25KRY are located approximately 72 km upriver from the gauge. (Figures 8b and 8c)
- Wells DSS38BLZ and DSS22KRY are located adjacent to the river channel.
- DSS25KRY is located approximately 1 km south of the river.

For each well, we estimated the relationship between daily water table elevation and river discharge. This allowed us to further estimate the degree to which the water table depth within the flood plain changed as a result of the 2013 flood, using historical data from the Colorado Division of Water Resources HydroBase system for these wells and the Fort Morgan gauge.

Relationships were estimated for a 10-year period prior to the 2013 flood by regressing water table elevation on the square root of river discharge. We then used this relationship to predict the water table elevation as river discharge varied through time.

For wells DSS38BLZ and DSS22KRY, predicted water table elevation closely matches what was observed in the wells, indicating that ground water was not stored within the system following the flood. As river discharge increased, water table elevation increased. As river discharge decreased, water table elevation decreased contemporaneously and with no detectable time lag.

In contrast, well DSS25KRY, located 1 km south of the river, shows a different pattern. Water table elevation rapidly increased above predicted approximately 3 weeks after the flood and remained higher than predicted for the next 6 months. A possible explanation for this result is that this well is located in a pasture surrounded by a levee into the main stem of the South Platte.

The elevation of this leveed-off pasture is 2-3 feet lower than that of the pasture between it and the river. It is possible that the floodwaters breached this levee and pooled in the area, elevating water table for some months after the flood.

There are a limited number of monitoring wells located within the study area, making generalization from this one well difficult. However, pooling in one or several locations along the river would not permanently raise the water table within the system, and such effects are expected to have been localized and short term in duration.

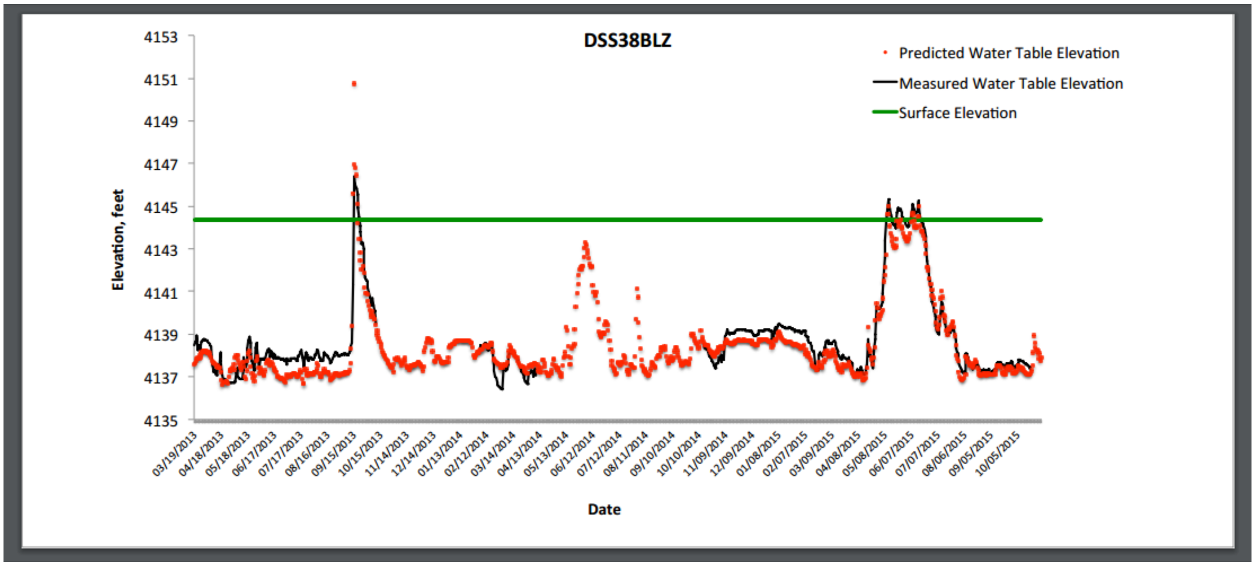

Figure 8a

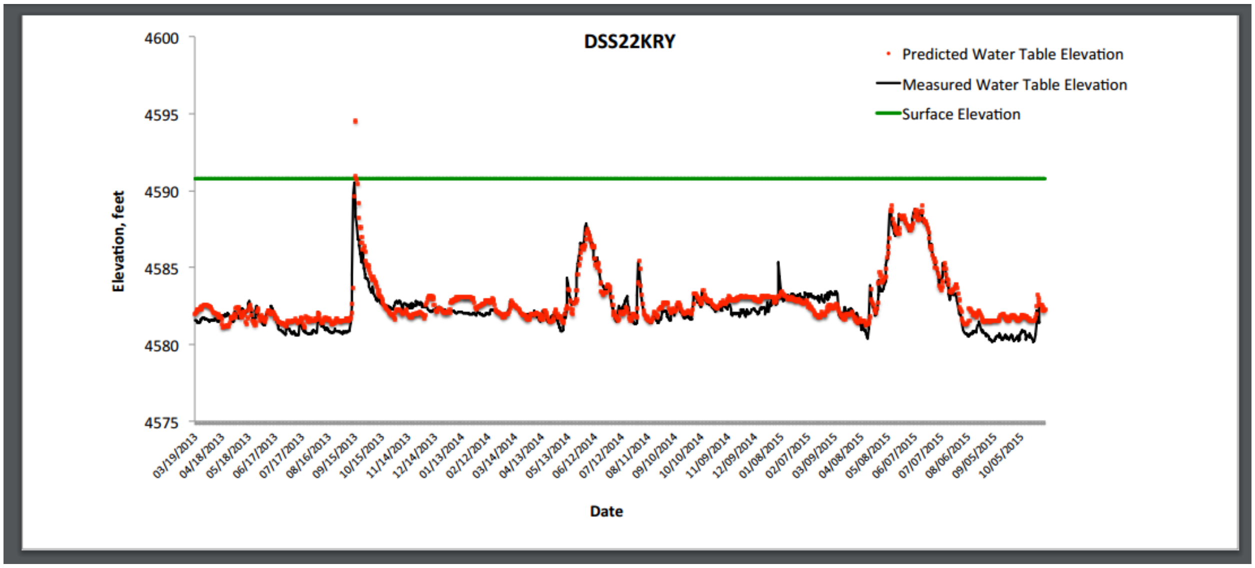

Figure 8b

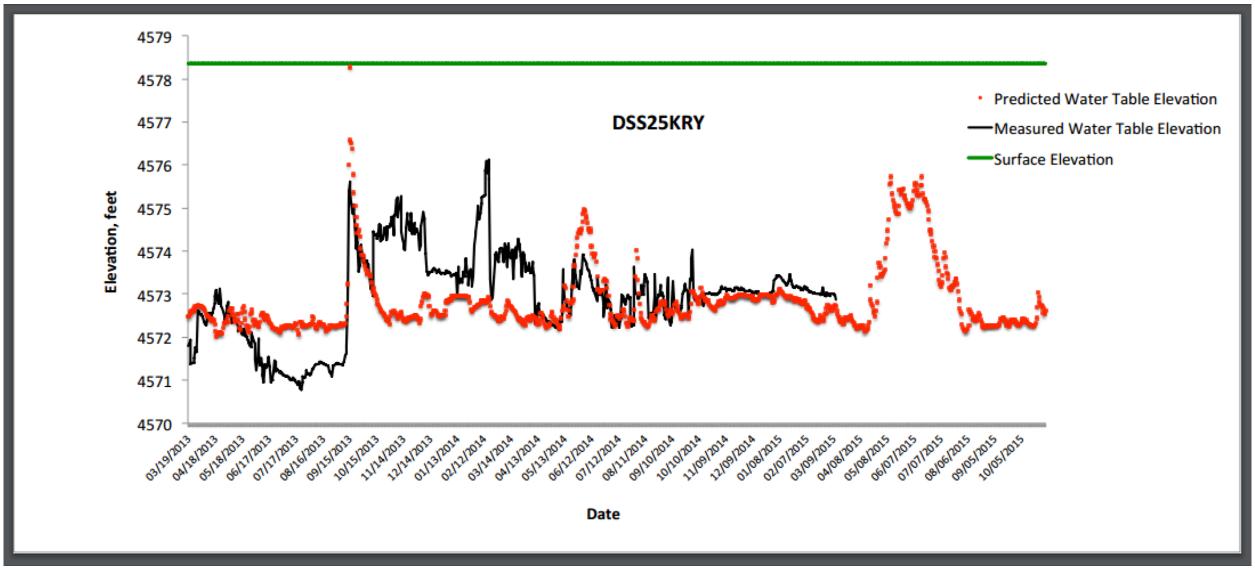

Figure 8c

Phreatophyte Envirotranspiration in the South Platte Basin

As there is no established crop coefficient developed for phreatophytes, it is difficult to precisely calculate ET. Nonetheless, previously reported ET estimates provide reasonable ballpark values, and validate the common understanding that these plants represent a significant nonbeneficial use of shallow groundwater in the basin.

The peer-reviewed scientific literature does not support the premise that simply removing these trees results in a one-to-one gain in river flows from salvaged water, as other biophysical processes are in play (Nagler, et al, 2010). Removal of phreatophyte vegetation may result in a rise in the water table near the river, along with greater bare soil evaporation.

While it is likely that some fraction of phreatophyte ET from groundwater can be salvaged following removal, riparian areas typically experience rapid regrowth of woody vegetation, unless control measures are continued indefinitely — which is rarely practical. In a review of potential water savings through phreatophyte control, Nagler, et al. (2010) report that it has yet to be conclusively demonstrated that the salvaged groundwater results in measurable increases in surface flows.

The 2013 flood caused the loss of approximately 8.5% of the mature trees in the South Platte River corridor. Thus, it is reasonable to assume that some temporary reduction of phreatophyte ET occurred as a result. However, it is not possible to assign any observed change in river gauge data to increased flow gain from salvaged ET, as small gauge changes are masked by flow variability, and fall within the margin of error of the river gauges.

Estimated Costs Related to Management of Invasive Phreatophytes

Objective

The Tamarisk Coalition (TC), in collaboration with Colorado State University, was tasked by Colorado Water Conservation Board (CWCB) to develop cost estimates for the restoration of riparian areas that have been affected by invasive phreatophytes and their associated secondary weed species in the South Platte Basin.

Methods

The Tamarisk Coalition (TC) developed a Cost Calculator to provide planners and managers with an estimate of expenses likely to be accrued during the management of invasive phreatophytes.

While initial phreatophyte removal work is often thought of as the main project expense, costs for secondary weed control (herbaceous noxious weeds that may establish as a secondary invasion once woody phreatophytes are removed), phreatophyte re-sprout treatment, biomass reduction, revegetation, monitoring, and maintenance must also be considered to ensure appropriate funding and staffing resources for successful long-term management.

The Cost Calculator uses average canopy cover and total site acreage to determine an approximate project cost based on site-specific recommendations, including:

- type of control

- method of biomass reduction
- specific amount of secondary weed control based on present densities
- amount and type of grass seeding
- amount and type of shrub and tree plantings

Control and biomass reduction costs were developed by TC, based on its local and regional experience with a variety of techniques and contractors.

Revegetation costs for seeding were based on current market prices, provided by Pawnee Buttes Seed, Greeley, Colorado, while shrub plantings were based on costs provided by Los Lunas Plant Materials Center, Los Lunas, New Mexico. A complete list of cost inputs is provided in the Cost Input tab on the attached Cost Calculator Excel document in the Appendix.

South Platte treatment scenarios

Based on the goals of this project, TC performed two analyses to determine approximate treatment costs by river reach:

1) TC examined the cost of removing 100% of the Russian olive present within each of the river reaches.

2) TC determined the cost of treating a total of 20% of all trees within each reach, including removal of 100% of the Russian olive (Table 1). In preplanning discussions, a 20% tree removal objective was selected to use as an example for costs.

A total of five different management scenarios were examined for both analyses, to provide a range of cost estimates for each.

Note: *In all scenarios, the recommended phreatophyte removal method was 90% mechanical removal, with 10% hand removal for areas difficult to access with equipment.*

Resulting Cost Estimates for Phreatophyte Control

Estimated total costs for removing 20% of phreatophytes from all reaches range from $870,700 for one-time removal only, to $45,524,846 for removal plus weed control, seeding, and shrub planting. Table 2 provides detailed estimates for the differing treatment scenarios.

Table 2: *Cost Estimates Based on Treatment Scenarios*

Treatment	Reach	Acres Russian Olive	90% Mechanical Treatment and 10% Hand Removal				
			Removal Only	Removal w/50% Weed Control	Removal w/25% Weed Control	Removal w/25% Weed Control & Seeding	Removal w/25% Weed Control & Seeding & Shrub Planting
100% RO removal	1	19	$39,992	$44,932	$42,462	$54,961	$184,636
	2	3	$6,314	$7,094	$6,704	$8,579	$29,054
	3	8	$16,839	$18,919	$17,879	$22,878	$77,478
	4	16	$33,677	$37,837	$35,757	$45,756	$154,956
	5	474	$997,689	$1,120,929	$1,059,309	$1,355,535	$4,590,585
	6	527	$1,109,245	$1,246,265	$1,177,755	$1,507,728	$5,104,503
	7	19	$39,992	$44,932	$42,462	$54,961	$184,636
	8	71	$149,443	$167,903	$158,673	$203,669	$688,244
	9	40	$84,193	$94,593	$89,393	$114,391	$387,391
	10	490	$1,031,367	$1,158,767	$1,095,067	$1,401,292	$4,745,542
	11	7	$14,734	$16,554	$15,644	$20,643	$68,418
TOTAL All REACHES			$3,523,485	$3,958,725	$3,741,105	$4,790,393	$16,215,443
AVERAGE ALL REACHES			$320,317	$359,884	$340,100	$435,490	$1,474,131

Table 2 Continued: *Cost Estimates Based on Treatment Scenarios*							
Treatment	Reach	Acres Total Trees	90% Mechanical Treatment and 10% Hand Removal				
			Removal Only	Removal w/50% Weed Control	Removal w/25% Weed Control	Removal w/25% Weed Control & Seeding	Removal w/25% Weed Control & Seeding & Shrub Planting
20% Total Tree Removal	1	1095	$594,777	$868,527	$731,652	$1,390,252	$2,827,439
	2	37	$20,097	$29,347	$24,722	$47,557	$96,120
	3	257	$139,596	$203,846	$171,721	$326,756	$664,069
	4	471	$255,835	$373,585	$314,710	$598,341	$1,216,529
	5	3897	$2,116,753	$3,091,003	$2,603,878	$4,946,235	$10,061,047
	6	3136	$1,771,533	$2,586,983	$2,179,213	$4,139,053	$8,419,693
	7	515	$279,735	$408,485	$344,110	$654,181	$1,330,118
	8	1326	$749,060	$1,093,820	$921,440	$1,750,122	$3,560,112
	9	616	$347,980	$508,140	$428,060	$813,028	$1,653,868
	10	5667	$3,201,300	$4,674,720	$3,938,010	$7,480,221	$15,215,676
	11	186	$101,031	$147,531	$124,281	$236,050	$480,175
TOTAL All REACHES			$9,577,697	$13,985,987	$11,781,797	22,381,796	$45,524,846
AVERAGE ALL REACHES			$870,700	$1,271,453	$1,071,072	$2,034,709	$4,138,622

For detail on the literature review, study methodology and results of the cost estimates and Objectives 1-6, please see the full report with appendices online at http://cwi.colostate.edu/.

Appendices

Appendix 1. **South Platte Phreatophyte Literature Review and Survey**

Appendix 2. **Senate Bill 14-195 Cost Estimate Summary**

Appendix 3. **Riparian Cost Calculator**

Appendix 4. **Senate Bill 14-195**

Appendix 1

South Platte Phreatophyte Survey

Andrew Norton[1], Gabrielle Katz[2], Ahmed Eldeiry[1], Reagan Waskom[3], Tom Holtzer[1]

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Background

In 2014, the Colorado State legislature appropriated funds to study the effects of the 2013 South Platte flood on phreatophytes, and the feasibility of removing non-native phreatophytes from the South Platte River.

Following the September 2013 floods, there has been concern that new sediment deposits and altered stream banks will increase the abundance of non-native species, including woody phreatophytes and State of Colorado listed noxious weeds.

An increase in phreatophyte abundance has the potential to consume more groundwater via evapotranspiration. Phreatophytes are deep-rooted plants that access a substantial portion of their water needs from ground water sources. The presence of other, undesirable weed species has the potential to increase the cost and complexity of phreatophyte removal, by necessitating post-removal follow up treatments.

Our specific objectives were:

1) Create a written review of the existing literature on the association between river hydrology and native and non-native phreatophyte establishment and growth, emphasizing issues of particular relevance to the South Platte River.

2) Determine the abundance and distribution of native and non-native woody phreatophyte species at twenty sites along the South Platte River,

and establish the relationship between shallow ground water and phreatophyte presence and abundance.

3) Determine the frequency and severity of invasion by Colorado State listed noxious weeds at these same sites.

4) For both phreatophytes and listed weed species, determine the relationship between river geomorphic surface and species incidence and abundance, and examine the effects of the September 2013 flood on species recruitment.

5) Link these data to GIS-based maps of the South Platte flood plain, and use these maps to predict the abundance of non-native phreatophytes and listed weeds along and within the river system.

6) Obtain data from existing groundwater monitoring wells from before and after the 2013 flood and determine if there has been a measurable change in water table depth within the flood-affected region.

This report is divided into 3 sections: A literature review of the ecology and hydrology of riparian forests; Field survey methods and results; and Using remote sensing data to predict forest attributes.

Objective 1: Create a written review of the existing literature on the association between river hydrology and native and non-native phreatophyte establishment and growth, emphasizing issues of particular relevance to the South Platte River.

River hydrology and riparian trees: Literature review

1) Abstract

This literature review describes the role of hydrology in influencing reproduction and survival of the dominant tree species of the South Platte River riparian forest, and the role of river dynamics in shaping riparian forest patterns in space and time. East of the foothills, the South Platte River supports a broad riparian forest dominated by plains cottonwood, with peachleaf willow also abundant at some sites. Non-native tamarisk and Russian olive are present in the system, generally occurring infrequently and at low abundances.

Cottonwood and willow are native, riparian pioneer species whose ecology is strongly linked to fluvial (river-related) disturbance processes and hydrology. Seed dispersal coincides with annual natural stream peak flows. Seedling establishment typically occurs on areas of moist sediment exhumed or deposited by floodwaters. For seedlings to survive and recruit into older age classes, they must be protected from perpetual flooding, complete burial by sediment, lethal scouring by water and ice, and lethal drought stress. Protected establishment sites are most commonly found outside of the active channel area, but must occur at low enough elevations for seedling roots to maintain access to groundwater.

Both floods and droughts affect riparian forests. In the short term (i.e., days to years), flooding can result in substantial mortality to riparian trees. In the long term (i.e., decades) flooding generally promotes rejuvenation of floodplain forest ecosystems, via its effects on recruitment of native cottonwoods and willows. Cottonwoods and willows are not drought tolerant, and require access to riparian groundwater for long term survival. Drought can result in substantial mortality to riparian trees by causing declines in riparian water tables. On the other hand, drought can also allow riparian forest establishment on fluvial surfaces normally scoured by floodwaters, resulting in forest expansion during periods of low flow.

The influence of river hydrology on riparian forest spatial patterns and temporal dynamics differs according to river type. On braided rivers, such as the South Platte River east of the foothills, the primary mode of riparian forest establishment is channel narrowing. This process occurs when annual stream flows are lower than that required to re-work the channel bed sediments, allowing vegetation to establish on the formerly wide channel bed. Forest establishment by this process is episodic, occurring over several decades and producing uneven-aged tree stands with variable spatial patterns.

The broad, spatially continuous cottonwood forest on the South Platte River in eastern Colorado became established between 1900 and ~1930, as the wide river channel became narrower in response to anthropogenic hydrologic

alterations. Prior to this, the river east of the foothills had a wide, braided form, with multiple, shifting channels and many sand bars and islands. Riparian vegetation was characterized by a mosaic of grasslands, marshes, and isolated woodland patches. Beginning in the 1880's flow was progressively stabilized and augmented by dams, sub-surface irrigation return flows and trans-basin diversions, raising riparian water tables in some areas. Cottonwood and willow established on the former channel bed. Today, the main pulse of forest expansion appears to have stopped as the area available for colonization has been reduced.

The long term persistence of a riparian cottonwood forest on the South Platte River in eastern Colorado depends upon fluvial processes and hydrologic conditions that allow for both seedling establishment and long term survival. In the absence of appropriate levels of fluvial disturbance, vegetation dynamics might follow two possible trajectories – forest succession could result in a shift in forest composition to non-pioneer species, or mortality of cottonwoods could result in a shift to grassland conditions. Additional research is needed to assess long term trends in riparian forest spatial extent, dynamics of cottonwood regeneration, and successional trajectories of species composition within aging forest stands. This research will improve our understanding of the spatio-temporal dynamics of this riparian forest, and will provide an important context for management.

2) Introduction

Floodplain ecosystems are among the most dynamic on earth, experiencing the ecological disturbances typical of uplands (e.g., fire, insect outbreaks, windthrow, browsing) as well as those of the river system itself (e.g., erosion, sedimentation, inundation; Johnson 1994, Rood et al. 2007). However, in most cases the river flow regime, the pattern of discharge variability through time, is considered to be the 'master variable' that shapes river and riparian ecosystems (Poff et al. 1997). For example, high flows rejuvenate aquatic biological communities, create or improve in-channel habitat, and increase aquatic diversity and productivity (Poff et al. 1997). Further, high flows connect floodplain environments to the river channel, enhancing wetland and riparian habitats that sustain high biodiversity. In low elevation riparian ecosystems of arid and semi-arid western North America, vegetation patterns result from the interaction of plant adaptations and life history traits with fluvial (river-related) hydrologic and geomorphic processes. Thus, riparian forest patterns strongly reflect current hydrologic conditions, as well as past patterns of streamflow (e.g., past floods).

East of the foothills, the South Platte River currently supports a broad riparian forest dominated by plains cottonwood (*Populus deltoides*), with peachleaf willow (*Salix amygdaloides*) also abundant at some sites (Sedgwick and Knopf 1989, Johnson 1994). The cottonwood and willow species are native, riparian pioneer species whose ecology is strongly linked to fluvial disturbance processes and river hydrology. The non-native tamarisk (*Tamarix* spp.) is another riparian pioneer species, infrequently present at low abundance in the South Platte River system. Additional tree species present at low abundances in the South Platte River floodplain include green ash (*Fraxinus pennsylvanica*), boxelder (*Acer negundo*), Siberian elm (*Ulmus pumila*), and Russian olive (*Elaeagnus angustifolia*). These species are later successional species, whose reproduction is not strongly tied to fluvial disturbance processes. Of these non-pioneer species, Russian olive and Siberian elm are non-native in North America; green ash is native in eastern North America; and boxelder is native in the South Platte River system. There likely would be more Russian olive and tamarisk in the South Platte system, except that both species have been the subjects of control measures. Tamarisk, in particular, has been aggressively controlled on all Colorado State Wildlife Areas in eastern Colorado (Cory Chick, personal communication to G. Katz, June 9, 2015). Russian olive and tamarisk were removed from most properties in Weld County on the Cache la Poudre River in 2010, and Saint Vrain Creek in 2014, with removal projects currently (2016/2017) underway on the Big Thompson River and South Platte River mainstem (Tina Booton, personal communication to G. Katz, June 23, 2016). The South Platte River riparian forest is a valued natural resource, providing important wildlife habitat, water quality enhancement, and recreation opportunities (Strange et al. 1999).

This literature review focuses on cottonwoods and willows, the dominant woody riparian species of the South Platte River downstream of Denver, and the lower sections of key tributaries. Cottonwoods and willows are generally considered to be near-obligate or obligate phreatophytes, species that utilize groundwater sources for their water needs (Rood et al. 2003). This literature review will also consider tamarisk and Russian olive, since these non-native species are present in the South Platte River system and potentially are of management concern. Tamarisk is usually considered to be a facultative phreatophyte, meaning that it can use both soil water and groundwater for transpiration (Glenn and Nagler 2005). Russian olive is also a facultative phreatophyte, since it readily establishes and survives utilizing soil water (Katz and Shafroth 2003, Reynolds and Cooper 2010).

The purpose of this literature review is to describe the role of hydrology in influencing the reproduction and survival of the dominant riparian tree species of low elevation rivers in arid and semi-arid western North America (i.e., primarily cottonwoods and willows, secondarily tamarisk and Russian olive), and the role of river dynamics in shaping riparian forest patterns in space and time. The literature review emphasizes processes and dynamics of particular relevance to the South Platte River system in Colorado downstream of Denver, Colorado (the project study area).

The hydrology of the South Platte River today differs significantly from historic conditions (Nadler and Schumm 1981, Johnson 1994, Strange et al. 1999, Waskom 2013). Prior to water development, the South Platte River experienced an annual hydrograph dominated by mountain snowmelt, with high flows typically occurring in May and June, and low flows occurring in late summer. There was substantial inter-annual variability in flow, resulting from climate fluctuations. In addition, late summer thunderstorms occasionally produced large floods in tributaries that affected flow in the mainstem (e.g., West Bijou and Kiowa Creeks, Friedman and Lee 2002). Water development in the South Platte Basin began in the 1840's, and the system now includes >18,500 diversion points, as well as considerable water inputs from trans-basin diversions and return flows from irrigation groundwater (Strange et al. 1999, Waskom 2013). One key effect of water management has been the stabilization of South Platte River streamflow (i.e., reduced seasonal flow variation) and augmentation of the alluvial aquifer by seepage from the vast network of irrigation ditches, canals and reservoirs (Waskom 2013). However, there is still substantial inter-annual variation in streamflow; for example, annual flow at Julesburg, Colorado ranged from 30,355 acre feet to 2,130,245 acre feet between 1925 and 2012 (Waskom 2013). Large floods still occasionally occur in the river, such as occurred in September, 2013. Thus, the South Platte River is a highly modified system that nonetheless experiences substantial hydrologic variability relevant to the structure and functioning of riparian ecosystems.

3) Hydrology and recruitment

For the dominant woody plant species typical of low elevation western US riparian ecosystems (e.g., cottonwoods, willows, and tamarisk), regeneration is strongly linked to river hydrology and fluvial processes. In general, these dominant trees are 'pioneer species' whose reproduction depends on fluvial disturbance to creates sites for seedling establishment. In contrast, the reproductive ecology of later successional species (e.g., Russian olive, Siberian elm, boxelder and green ash) is less linked to river processes, and recruitment can occur in the absence of flooding or physical disturbance. In this context, *establishment* refers to the process of plant establishment in a new location, usually by seed but sometimes by vegetative means (Rood et al. 2007). *Survival* refers to the persistence of the seedling (or vegetative propagule) through subsequent growing seasons, typically at least three years (Rood et al. 2007). *Recruitment*, prospective membership in the future adult population, results from both establishment and survival (Rood et al. 2007). Thus, recruitment of riparian tree species is affected by river dynamics and hydrologic conditions that affect both initial seedling establishment and longer term tree survival.

4) Native cottonwoods and willows

The reproductive ecology of cottonwoods and willows is strongly linked to river hydrology, with seedling establishment commonly occurring on bare, moist sediments deposited or exhumed by dynamic river processes. In this section, we focus on sexual reproduction by seed and its links to hydrology. However, for many riparian species asexual vegetative or clonal reproduction also can be an important mode of regeneration linked to river hydrology and fluvial processes (Karrenberg et al. 2002, Rood et al. 2007). This is especially true for willows (*Salix* spp.), and for narrowleaf cottonwood, black cottonwood, and balsam poplar (species in the *Tacamahaca* taxonomic group of the genus *Populus*; Rood et al. 2007). For prairie cottonwoods (species in the *Aigeiros* taxonomic group of the genus *Populus*) such as Fremont cottonwood and plains cottonwood (the species present in the South Platte River system in eastern Colorado), asexual reproduction can occur by shoot suckering, 'flood training' where shoots sprout from buried stems, and 'coppice regrowth' or re-sprouting from cut stems (Rood et al. 2007). Further, many willows (including the non-native tree crack willow, *Salix fragilis*) can re-sprout from broken branch fragments, but this is not commonly observed in cottonwoods (Shafroth et al. 1994).

Seed dispersal of cottonwoods and some willows coincides with, or immediately follows, natural stream peak flows. Cottonwoods produce seeds during a short time period in spring or early summer, when snowmelt produces high flows in many western rivers. Seeds remain viable for only a few weeks, and germinate rapidly (24-48 hours, Stromberg 1993a). In the eastern plains of Colorado, cottonwood peak seed release tends to occur in June, though this varies depending on individual tree characteristics, local conditions, and yearly weather. For example, Friedman et al. (1995) documented peak seed release of plains cottonwood on Boulder Creek, Boulder County to occur during the first two weeks of June, while peak seed release of peachleaf willow occurred during the last two weeks of May (Friedman et al. 1995). Elsewhere in Colorado, peak cottonwood seed release can occur later, e.g., in late June or early July for Fremont cottonwood on the Green and Yampa Rivers in northern Colorado (Cooper et al. 1999). Sedgewick and Knopf (1989) reported plains cottonwood seed release on the South Platte River, Logan County from mid-June to mid-August in 1984. Johnson (1994) reported seed release of plains cottonwood on the North Platte and Platte Rivers in Nebraska to occur for <2 months (mid-May to early July), with the peak in mid-June.

Initial seedling establishment of cottonwoods and willows typically occurs on 'fluvial disturbance patches', areas of moist sediment free of competing vegetation and plant litter (Auble and Scott 1998). Cottonwood seedlings are intolerant of shade, and rarely establish within intact herbaceous vegetation (Friedman et al. 1995, Katz et al. 2001), or beneath forest canopies (Johnson et al. 1976). Seedlings of riparian cottonwood (Segelquist et al. 1993) and willow (Horton and Clark 2001) species are also intolerant of desiccation, relying on constantly available moisture for survival. Because of these constraints, in any given year cottonwood and willow seedlings usually become established adjacent to, or within, the active channel zone where bare moist substrate is available for colonization (Stromberg 1993c, Friedman et al. 1997, Stromberg 1997, Galuska and Kolb 2002). However, seedlings established in this active channel zone are unlikely to survive.

In most years, mortality rates of first-year cottonwood and willow seedlings are high, often resulting in no survival of a given cohort. Seedlings established within the active channel zone are extremely vulnerable to removal by subsequent stream flows (Stromberg 1997, Auble and Scott 1998, Rood et al. 1998). However, seedlings established at more elevated positions are vulnerable to summer drought stress and mortality (McBride and Strahan 1984). Mortality rates of close to 100% are commonly observed for cottonwood and willow seedlings established in the active channel zone, due to summer drought stress during their first growing season, or erosion during subsequent high flows (e.g., Sacchi and Price 1992, Stromberg 1997). In a pattern likely typical of seedling dynamics in most years, Sedgwick and Knopf (1989) found high mortality of first-year plains cottonwood seedlings on the South Platte River in 1984, a summer with average precipitation and discharge patterns; of 100 0.1-m^2 micro-plots containing seedlings in late June, 67 contained live seedlings in mid-July, 8 contained live seedlings in mid-August, and 3 contained live seedlings by mid-September, representing a 97% decrease in frequency. Mean seedling densities declined from $189 \pm 32/m^2$ to $1.4 \pm 1.2/m^2$ during this same period, representing a decrease of 99%.

In order for seedling establishment to lead to longer term survival and recruitment into older age classes, cottonwood and willow seedlings must be protected from perpetual flooding, complete burial by sediment, lethal scouring by water and ice, and lethal drought stress. Long-term seedling survival occurs on bare patches characterized by both adequate moisture and protection from lethal levels of physical disturbance (Auble and Scott 1998, Mahoney and Rood 1998, Rood et al. 1998). Such protected sites may occur in localized geomorphic situations such as the downstream ends of islands (Scott et al. 1997), but are more commonly found outside of the active channel area. Regardless of establishment location, successful recruitment of cottonwood seedlings depends on the ability of seedlings to access groundwater. As riparian water tables recede following normal spring flooding, root growth must keep pace or the seedlings will desiccate and die (Segelquist et al. 1993). Mahoney and Rood (1998) reviewed the literature on cottonwood seedling establishment and determined that successful recruitment occurred from approximately 60 to 150 cm above river base flow elevation. Presumably, the lower elevation limit is determined by erosional processes, while the upper limit results from the combination of seedling root elongation potential and the depth of the capillary fringe above the riparian water table.

a) Tamarisk

The reproductive ecology of tamarisk is somewhat similar to that of cottonwoods and willows. Like native cottonwood and willow species, tamarisk produces large numbers of very small wind- and water-dispersed seeds (Brock 1994). The seeds are short lived, and lose germinability after a few weeks (Warren and Turner 1975). Optimal germination sites for tamarisk are moist, fine silt deposits (Brock 1994). Seedling establishment typically occurs on bare moist surfaces, such as along the high water line following flood events (Glenn and Nagler 2005).

However, there are several aspects of tamarisk reproductive ecology that differ importantly from that of native cottonwoods and willows. In contrast to the limited seed dispersal periods of native cottonwood and willow species, tamarisk seeds are dispersed throughout the spring and summer (Warren and Turner 1975, Brock 1994). Thus, tamarisk is able to establish on fluvial disturbance patches created later in the summer than can native species, allowing it to flourish on rivers with altered flow regimes (Glenn and Nagler 2005). For example, regeneration of native species was limited due to the unusual timing of high flows on the lower Colorado River in the summer of 1983. Tamarisk, in contrast, was able to take advantage of summertime germination opportunities (Ohmart et al. 1989). In addition, tamarisk seedlings have faster root elongation rates and greater rooting depths than native cottonwoods and willows, enabling them to survive better where water conditions are less favorable, e.g., at higher elevations above the water table (Hultine and Bush 2011). Thus, although its reproduction is tied to fluvial disturbance, tamarisk establishment occurs in a broader range of micro-environments than cottonwoods and willows, e.g., on higher terrace surfaces (Hultine and Bush 2011).

b) Russian olive

The reproductive ecology of Russian olive is not strongly tied to river hydrology. Thus, it differs substantially from the reproductive ecology of native cottonwoods and willows, and the non-native tamarisk. In contrast to those riparian pioneer species, Russian olive produces large fruits that ripen in late summer or fall, and are dispersed by birds and mammals, as well as by gravity and water. After dispersal, Russian olive seeds can survive in the soil, forming a soil seed bank (Brock 2003). Seeds are dormant when they ripen and are dispersed, requiring a period of over-winter cold stratification for germination to occur (Guilbault et al. 2012). Russian olive seeding establishment occurs under a variety of environmental conditions. Experimental studies indicate that seedlings are tolerant of a broad range of moisture conditions -- Russian olive seedling performance is not reduced under conditions optimal for cottonwood recruitment (Shafroth et al., 1995), and Russian olive seedlings grow and survive better than cottonwood and tamarisk seedlings over a variety of moisture conditions, including high and low water availability (Reynolds & Cooper, 2010). Experimental studies have also demonstrated that Russian olive seedlings are more shade tolerant than seedlings of co-occurring woody riparian species -- Russian olive seedlings can establish within undisturbed herbaceous vegetation (Katz et al. 2001), and have higher survival than both cottonwood and tamarisk seedlings under almost all combinations of shade and moisture (Reynolds & Cooper 2010). Consistent with these experimental studies, many field studies have documented Russian olive seedlings and adults growing in the understories of riparian gallery forests, as well as in open meadow habitats (e.g., Katz et al. 2005, DeCant 2008, Reynolds and Cooper 2010).

c) Impacts of hydrology on mature riparian forests

The survival and performance of adult riparian trees depends on the balance between flooding and drought, among other factors. Stromberg and Patten (1992) observed both drought-induced and flood-induced mortality of adult black cottonwood (*Populus trichocarpa)* on two streams in the eastern Sierra Nevada, California. They argued that these effects can be compounded, such that trees physiologically weakened by prolonged drought stress become more susceptible to flood-induced mortality. In this section we describe the role of hydrology in influencing long term survival of established riparian trees, including cottonwood, willow, tamarisk and Russian olive.

d) Flooding

In the short term (i.e., days to years), flooding can result in substantial mortality to riparian trees. However, in the long term (i.e., decades) flooding generally promotes rejuvenation and renewal of floodplain forest ecosystems, via its effects on recruitment of native cottonwoods and willows (see above). The short term deleterious effects of flooding on riparian trees will depend on the magnitude and duration of the flood event, the spatial pattern of forest exposure to flood impacts, as well as the flood/inundation tolerance adaptations of each species. For example, Dixon et al. (2015) assessed the effects of a large flood on riparian forests on the Missouri River in 2011. They found that the flood resulted in higher mortality rates of all tree species in young forest patches compared to older patches, and preferential mortality of non-pioneer species (i.e., Russian olive and redcedar), particularly in older forest patches where cottonwood tended to survive.

> Direct physical damage by moving flood waters can result in mortality of adult riparian trees of all species. Moving flood waters may carry debris and ice which can severely damage trees, and in the extreme, the hydraulic force of flood waters can completely remove established trees. For example, a large flood on Plum Creek, Colorado in 1965 sheared off or uprooted half of the adult bottomland cottonwood and willow trees (Friedman et al. 1996). Rood et al. (2007) argued that in northern latitudes the breakup of winter river ice, followed by its transport downstream and subsequent local jamming, damming, breakage and surge, can be the most extreme physical disturbance in riparian ecosystems. Large blocks of ice carried by flood waters can wound and shear trees, and can also scrape and mobilize sediments (Rood et al. 2007).

Floods also carry and deposit sediment, and the resulting sediment burial can damage or kill established riparian trees. Kui and Stella (2016) reviewed a number of experimental studies assessing the effects of sediment burial on riparian species. Most studies have evaluated the effects of sediment burial on small plants rather than adult trees, indicating that young cottonwood, willow, and tamarisk (i.e., seedlings and cuttings) can generally survive partial burial, with rates of survival up to 100% in some cases. However, on the Bill Williams River, Arizona first-year tamarisk seedlings were less tolerant of flood induced scour and sediment burial than native willow seedlings (Wilcox and Shafroth 2013). In contrast to the marked ability of most riparian species to survive partial burial, complete burial results in high mortality of cottonwood and tamarisk seedlings, but not boxelder (Kui and Stella 2016). Because cottonwoods exhibit high survival rates following partial burial (e.g., >20 cm stem length exposed, Kui and Stella 2016), it is likely that sediment deposition alone does not result in high mortality rates for larger, older individuals such as mature trees. Indeed, sedimentation may benefit adult trees by providing nutrient inputs to the floodplain environment.

In addition to the physical forces associated with moving flood water, prolonged inundation can also damage or kill adult riparian trees. The primary effect of inundation, from the point of view of plants, is usually an immediate reduction in soil aeration (Kozlowski et al. 1991). Additional effects include changes in microbial communities and processes, changes in soil redox potential and pH, and presence of phytotoxic compounds in waterlogged soils (Kozlowski et al. 1991). Cottonwood and willow adults are fairly well adapted to flooding, possessing several physiological adaptations to cope with inundation. These include the development of adventitious roots, which enhance water and nutrient uptake under saturated conditions and enhance rhizosphere aeration, and the production of hypertrophied lenticels, which facilitate stem aeration and the release of toxins (Kozlowski et al. 1991, Amlin and Rood 2001).

Despite these adaptations, adult cottonwoods cannot survive permanent inundation.

For example, many Fremont cottonwoods were killed by long periods of inundation (~12 months) experienced on the lower Colorado River downstream of Davis Dam in 1980's (Ohmart et al. 1988). Further, adult black cottonwoods flooded by a small reservoir in Alberta, Canada died within two years of inundation (Amlin and Rood 2003). In contrast to cottonwoods, some willow species can survive prolonged flooding; shrub willows *(Salix bebbiana* and *Salix discolor*) survived at least five years of inundation by beaver damming on Midvale Creek, Montana, while co-occurring black cottonwoods died (Amilin and Rood 2003). Similar to native cottonwoods and willows, tamarisk is fairly tolerant of prolonged, but not permanent, inundation. For example, tamarisk was observed to survive 80-90 days of inundation on the shore of the San Carlos reservoir, Arizona (Warren and Turner 1975). Russian olive appears to be less tolerant of inundation than native cottonwoods and willows; Russian olive exhibited high (~80-90%) mortality following a large flood on the Missouri River in 2011, while co-occurring plains cottonwood mortality was much lower (~30%, Dixon et al. 2015).

e) Drought

Native cottonwoods and willows are not drought tolerant, and require access to riparian groundwater for long term survival. Adult cottonwoods avoid drought stress by maintaining water uptake through deep roots that utilize groundwater sources (Bush et al. 1992). This reliance on alluvial groundwater generally limits the occurrence of adult trees to streamside banks or floodplain elevations up to 3-4 m above the base stage of the river in late summer (Stromberg et al. 1996). Alluvial groundwater declines can cause stress and/or mortality of adult cottonwood trees, if roots cannot maintain contact with deepening groundwater sources. Such groundwater declines can occur naturally during climatic drought, or in response to river damming and dewatering. Drought stress can cause a variety of physiological responses in riparian cottonwoods, including reduced photosynthesis, reduced growth, early leaf senescence, branch sacrifice, crown die-back, and mortality (reviewed in Rood et al. 2003). Both Rood et al. (2003) and Glenn and Nagler (2005) reviewed many studies that documented loss (mortality) of adult cottonwoods and willows during climatic drought or anthropogenic stream dewatering on a variety of rivers in western North America, e.g., Virgin River, Utah; Big Lost River, Montana; Saint Mary River, Alberta, Canada.

Tamarisk appears to be more drought tolerant than native cottonwoods and willows. Hultine and Bush (2011) reviewed literature indicating that tamarisk is much more resistant to xylem cavitation than native cottonwoods and willows, maintaining shoot hydraulic conductivity at much more negative xylem pressure. Drought tolerance is a key factor that has enabled tamarisk to become a dominant riparian species in the southwestern US, enabling it to establish and persist in habitats that are not suitable for most other riparian species (Hultine and Bush 2011), and where periodic natural drought and/or anthropogenic groundwater decline result in mortality of native riparian tree species (Glenn and Nagler 2005). Where riparian areas are characterized by high salinity levels, tamarisk is also better able to survive than native riparian trees. Thus, tamarisk commonly spreads into disturbed, dry and saline floodplain areas (Glenn and Nagler 2005).

Russian olive is also more drought tolerant than native cottonwood and willow species, and appears to be at least as drought tolerant as the non-native tamarisk (Katz & Shafroth, 2003). Field observations suggest that Russian olive can establish on higher and drier geomorphic surfaces compared to cottonwood in the Great Plains (Katz, Friedman, & Beatty, 2005), and compared to both cottonwood and tamarisk in the Colorado Plateau (Reynolds & Cooper, 2010). Indeed, isotopic analysis of water sources indicated that Russian olive established and survived for at least 15 years on terraces on Chinle Creek, Arizona where precipitation derived soil water was the only water source, not groundwater (Reynolds & Cooper, 2010). Hultine and Bush (2011) provide data demonstrating that Russian olive operated at a broader range of leaf water potential than Fremont cottonwood at a site near Salt Lake City, Utah, indicating greater tolerance of dry conditions. However, Russian olive does experience oxidative injury to leaf cell membranes under severe drought conditions, and is not a truly xeric species (Gong, et al., 2006).

f) Fluvial processes and forest patterns

The influence of river hydrology on riparian forest patterns is strongly conditioned by geomorphic context, with different processes operating on braided, meandering and bedrock streams (Scott et al. 1996, Scott et al. 1997). On meandering rivers with fine sediment, moderate flows cause the migration of river bends -- progressively eroding banks on the outsides of bends, and progressively depositing sediment (point bars) on the insides of bends. Point bars provide seedling establishment sites that become increasingly protected from flooding as the river migrates farther away and as sediment deposition builds up the bar.

Thus on meandering rivers, natural flow variability results in cottonwood establishment at relatively frequent intervals, corresponding to discharges typical of the 1-in-3 or 1-in-5 year floods (Rood et al. 2007). This process yields a riparian forest comprised of narrow, arc-shaped bands of even-aged trees. In contrast, on bedrock streams where rivers are constrained in narrow valleys, sediment deposition and scouring by infrequent large floods are the most important processes creating recruitment sites for pioneer species. This process produces narrow linear bands of even-aged trees (Scott et al. 1997).

On braided rivers, of which the South Platte River is a prime example, the primary mode of riparian forest establishment is channel narrowing. Braided rivers are naturally wide and shallow, with a coarse sediment load; stream flow is distributed among multiple, shifting channels separated by transient sand or cobble bars within the active channel zone. The process of channel narrowing depends upon the occurrence of one or more years of stream flows lower than that required to re-work the channel bed sediments, thus allowing vegetation to establish on the formerly wide channel bed. Thus, on braided rivers, cottonwood establishment tends to be associated with periods of low flow (Johnson 1994, Friedman et al. 1996). This vegetation in turn promotes sediment deposition and resists erosion, stabilizing a narrower channel configuration. In the Great Plains physiographic region in Colorado, riparian forest establishment associated with channel narrowing has been documented to occur after flood-induced channel widening (e.g., on Plum Creek, Friedman et al. 1996; on the Arikaree and South Fork Republican Rivers, Katz et al. 2005; and on Bijou and Kiowa Creeks, tributaries of the South Platte River, Friedman and Lee 2002), downstream of dams (e.g., on the Arkansas River, Friedman et al. 1998), and in response to land use and water management changes (e.g., the South Platte River, Nadler and Schumm 1981). Forest establishment by this process can occur over several decades, producing uneven-aged tree stands with variable spatial patterns. This mode of forest regeneration is highly episodic and infrequent on unregulated rivers of the western Great Plains, with flood induced channel widening (the precursor to narrowing) possibly exceeding the lifespan of the cottonwoods and willows that comprise the riparian forest (Friedman et al. 1996, Friedman and Lee 2002).

g) South Platte riparian studies

The broad, spatially continuous cottonwood forest on the South Platte River in eastern Colorado became established between 1900 and ~1930, as the wide river channel became narrower in response to anthropogenic hydrologic alterations (Nadler and Schumm 1981, Johnson 1994). Prior to this episode of narrowing, the South Platte River east of the foothills had a wide, braided form, with multiple, shifting channels and many sand bars and islands. The historic annual flow regime of the South Platte River was dominated by spring snowmelt from the Rocky Mountains, with low flows occurring in late summer. The combination of high spring flows that reworked channel bed sediments and eroded seedlings, and low late summer flows that created drought conditions, limited the extent of forest vegetation in the riparian zone. Thus, pre-development riparian vegetation was characterized by a mosaic of grasslands, marshes, and isolated woodland patches (Johnson 1994). However, beginning in the 1880's the flow of the South Platte River was progressively stabilized and augmented by dams, sub-surface irrigation return flows and trans-basin diversions, raising riparian water tables in some areas (Nadler and Schumm 1981).

These hydrologic changes allowed cottonwood and willow to establish on the former channel bed. By 1937, ~90% of the formerly active channel area on the South Platte River in eastern Colorado was vegetated (Johnson 1994). This vegetation, in turn, stabilized channel morphology and further promoted the narrowing of the river to its present day single thread, more sinuous form. Today, the main pulse of forest expansion appears to have stopped as the area available for colonization has been reduced.

The long-term persistence of a riparian cottonwood forest on the South Platte River in eastern Colorado depends upon fluvial processes (i.e., sediment erosion and deposition) and hydrologic conditions (i.e., flow dynamism and groundwater levels). As described above, because cottonwoods and willows are pioneer species, a steady state forest over the long term requires dynamic processes of flooding, erosion and sediment deposition to create suitable seedling establishment sites. These processes can be episodic, but must occur frequently enough to rejuvenate the forest as mature cottonwoods senesce and die. Alternatively, in the absence of appropriate levels of fluvial disturbance, vegetation dynamics might follow two possible trajectories – (1) forest succession could result in a shift in forest composition to non-pioneer species such as green ash, boxelder, Siberian elm, Russian olive and eastern juniper (Sedgwick and Knopf 1989, Johnson 1994), or (2) mortality of cottonwoods could result in a shift to grassland conditions (Figure 1, Friedman et al. 1997). Johnson (1994) concluded that the forest extent on the South Platte River system overall was in a dynamic steady state, focusing mostly on sites in Nebraska that showed stabilized proportions of active channel vs. vegetated floodplain area since the 1960's.

However, the two study sites on the South Platte River in Colorado exhibited a contrasting trend to those downstream: the Colorado sites showed trends of channel widening (increased active channel area) since the 1940's, and loss of riparian forest. Similarly, Snyder and Miller (1991) found a slight increase in river channel width and loss of cottonwood forest area on the South Platte River in eastern Colorado between 1941 and 1979, based on aerial photograph analysis. Both Sedgwick and Knopf (1989) and Johnson (1994) cautioned that the cottonwood forest on the South Platte River was likely undergoing succession to less ecologically valuable species, and that the future riparian forest would be dominated by non-pioneer species.

Thus, these authors interpreted the twentieth century channel narrowing/cottonwood establishment event on the South Platte River as a historic occurrence that is not ongoing. However, Snyder and Miller (1991) were more optimistic about cottonwood recruitment on the South Platte River, suggesting that it does still occur under the present hydrologic regime. More research is needed to determine the trajectory of this forest.

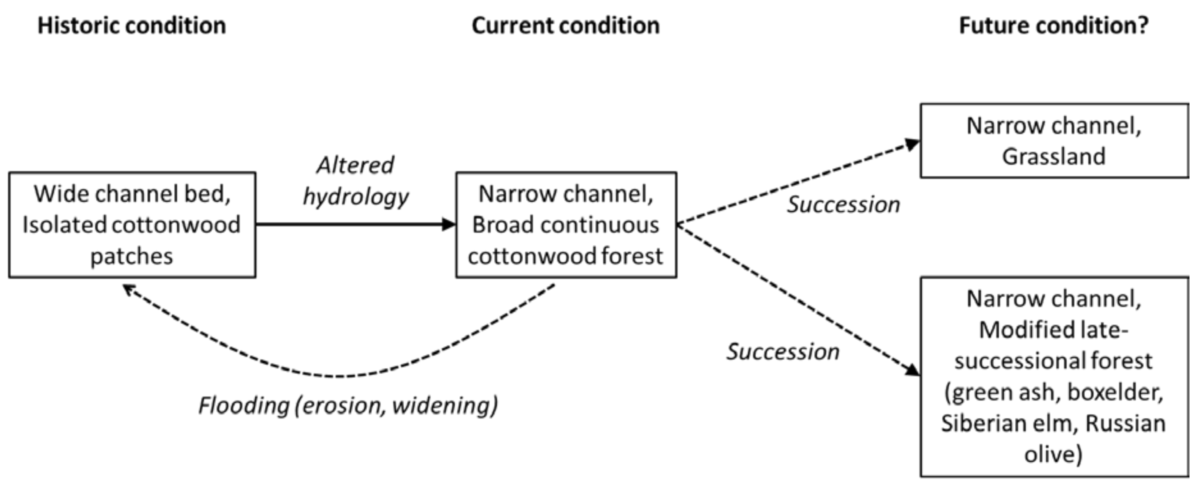

Figure 1. Conceptual model of historic vegetation dynamics (solid arrow), and possible future conditions (dashed arrows), of the South Platte River riparian forest in eastern Colorado (modified from Friedman et al. 1997, Strange et al. 1999). Ecological succession could lead to grassland or a modified late-successional forest dominated by non-native species. Alternatively, flooding could widen the channel and lead to renewed cottonwood forest establishment.

h) Questions/Research Needs

Understanding the long-term dynamics of the South Platte River riparian forest is critical to the management of this valuable natural resource. The riparian forest on the South Platte River provides important wildlife habitat, water quality enhancement, and recreation opportunities (Strange et al. 1999). On the other hand, evapotranspiration from this forest has been mentioned as a concern in the context of water resources management (Waskom 2013). Nagler et al. (2010) review the current status of studies examining the potential for water salvage following phreatophyte removal and discuss the challenges to achieving water savings even if evapotranspiration is reduced. Effective management of this forest requires an understanding of ongoing trends in forest area/extent and ecological succession. Although several studies addressed these questions in the past (i.e., Sedgwick and Knopf 1989, Snyder and Miller 1991, Johnson 1994), new efforts are needed to update these prior studies. In particular, research is needed to assess long term trends in riparian forest spatial extent (i.e., loss and/or gain of forest area over time, and in association with specific flood events), dynamics of cottonwood regeneration, and successional trajectories of species composition within aging forest stands. This research will improve our understanding of the spatio-temporal dynamics of this riparian forest, and will provide an important context for management.

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Objective 2: Determine the abundance and distribution of native and non-native woody phreatophyte species at twenty sites along the South Platte River, and establish the relationship between shallow ground water and phreatophyte presence and abundance.

Objective 3: Determine the frequency and severity of invasion by Colorado State listed noxious weeds at these same sites.

Data Collection and Field Survey Results

Methods

We collected tree, shrub, and noxious weed presence and abundance data from 873 10 x 20 meter plots over 15 sites. Sites were selected to be representative of the study area and were distributed to along the South Platte and its tributaries. Within each site, 2 – 4 transects were selected at random and extended perpendicular to the river extending to the edge of the current floodplain. In most areas the historic floodplain has been constrained by human activities such as the construction of levees and roads. Within 10 m x 20 m plots located continuously along each transect we collected data on tree abundance and condition, weed presence and weed abundance. The sampling design and site locations are provided in Figures 2 – 4 and Table 1.

For each tree within each transect, we recorded diameter at breast height (dbh), the percent of the tree canopy estimated to be alive, and tree height. Height was measured with a laser range finder or a telescoping measuring rod. Trees were defined as individuals with dbh ≥ 2 cm. For tree saplings (individuals of tree species ≥1 m tall, but <2 cm dbh) and shrubs, we recorded basal diameter classes (<1 cm, 1 – 3 cm, >3 cm) and abundance. At many locations there were hundreds to thousands of shrub stems present within each 10 x 20 m belt. In these cases we subsampled several representative 1 x 1 m areas and estimated total abundance by size class for an entire 10 x 20 m plot. Tree seedlings (individuals of tree species < 1 m tall) were counted separately in basal diameter size classes as above. When more than 50 seedlings occurred within a

20 x 20 m plot we estimated their number using the same methods as for saplings and shrubs.

We estimated the abundance of any State of Colorado listed weed species by collecting point data every two meters along the transects. At each point, all listed weeds that touched a vertical measuring rod were recorded a present. In addition, presence / absence of listed weeds was recorded in a 10 m x 10 m plot every 10 m along each transect. GPS coordinates were recorded every 10 m along the transects using a Trimble GeoXM and post-processed in TerraSync.

Results

We surveyed 873 10 x 20 m plots over 15 sites, for a total of 435 acres surveyed. Over all of these sites we collected dbh, height and canopy condition data from 2182 trees.

Trees- As expected, plains cottonwood (*Populus deltoides*) is the dominant tree species in the South Platte floodplain, comprising more than 45% of the individuals recorded. Basal area (BA) is a common metric used to compare tree volume between sites, and is a measure of the total cross sectional area occupied by trunks. Just over 80% of the total tree basal area for the study area is comprised of plains cottonwood, followed in abundance by peach leaf willow (*Salix amygdaloides*) at nearly 12% of the total basal area. Species not native to Colorado comprise less 6% of basal area over all sites. The most common non-native tree species is Russian olive (*Elaeangus angustifolia*), which comprises 2.21 % of total basal area and 4.54 % of individuals encountered in the surveys. Tree data are summarized for each site in Tables 2 and 3.

Shrubs - Table 4 summarizes the shrub data collected. Coyote willow (*Salix exigua*) was the dominant shrub species found, with approximately 83% of all stems recorded being from this species. Snowberry (*Symphoricarpos occidentalis*) was the next most abundant shrub species, with just over 14% of the total stems.

Saplings - There were far fewer saplings within the study area than trees, with combined total of 386 saplings over all species over all sites. In contrast to mature trees, green ash was the most common species of sapling recorded, (131), followed by peach leaf willow (103). *Tamarix spp.* was the third most common sapling recorded, with 44, all of which were on a single sandbar at site 11 (Table 5). We suspect that these saplings all originated from one or two large, buried *Tamarix* trees. Although cottonwood is the most dominant tree species over all sites, we only recorded 43 sapling individuals, consistent with the idea that cottonwood recruitment requires aset of specific and relatively infrequent conditions in order for recruitment to occur.

Seedlings – Cottonwood seedlings were by far the most common tree seedling encountered, with more than 100,000 found over the entire survey area (Table 6). The number of cottonwood seedlings recorded was highly variable – ranging from 0 (site 1) to 32,936 at site 14. This variability likely results from the specific environmental requirements for cottonwood seed germination. Cottonwood seeds need bare, moist soil. Where these conditions occur, hundreds to thousands of seedling may germinate per m^2 (see literature review, above). We found a total of 4 seedlings of Russian olive, a surprising result given that this species is considered invasive in Colorado and that it is common (though not abundant) in the study area. We found 275 and 32 seedlings for Siberian elm (*Ulmus pumilla*) and *Tamarix* spp., respectively.

One of the questions raised in the literature review, above, is to what degree cottonwood and willow are still reproducing within the study area. With altered flow regimes and channel narrowing it is possible that these pioneer species are in decline and are being replaced by other species, most notably green ash, Russian olive and Siberian elm. Figures 4a – f illustrate the size-class distribution of saplings and trees for the most common tree species in the area. Note that the single full growing season between the September 2013 flood and the summer 2015 data collection season is not a long enough period of time for a seedling to mature into a sapling. Thus, any seedlings germinated in summer 2014 or 2015 (post-2013 flood) would be counted as seedlings in our data.

If a species recruits at a constant rate, we would expect to see a monotonic decline in frequency of size classes for the species. Species with pronounced pulses of recruitment might exhibit a more 'bumpy' size-class histogram. Species that are no longer recruiting at a rate that will maintain population size will have a distribution with fewer smaller (=younger) size classes than larger (=older) size classes.

Cottonwood shows some evidence for this latter pattern, with a peak in the size class distribution at moderate dbh. However, it appears to be a recent phenomenon as only the two smallest size classes (0 – 5 cm and 5 – 10 cm) are affected. Thus it is possible that fewer smaller trees is simply the result of several years without flow patterns sufficient for seedling persistence. Siberian elm shows a similar pattern as well. In contrast, Russian olive and green ash do not have this pattern, and appear to have been recruiting at a constant or perhaps increasing rate through time. These data are size classes, which should correlate with tree age. However, the relationship between diameter and age differs for different tree species. Data on how diameter at breast height relates to tree age for each species would be very useful, but is beyond the scope of this project.

Weeds – State of Colorado listed noxious weeds were common at all sites. For example, nearly 30% of 10 x 10 m plots surveyed contained hoary cress (*Cardaria draba*), and almost 35% of plots contained downy brome (*Bromus tectorum*) (Table 7). When all weed species are considered together, 90% of plots sampled contained one or more weed species. Percent cover for each weed species presents a similar picture. Over all plots and all sites, listed weeds make up more than 20% of plant cover (Table 8). Downy brome (10.42%) and hoary cress (4.35%) are the most abundant weed species we found.

Discussion

a) Trees

As expected, cottonwood and willow are the dominant tree species throughout the study area, comprising more than 90% of the basal area over all sites. Although these two native phreatophytes are the most abundant mature trees, the relative absence of saplings and abundance of seedlings for the two species confirms that they have specific requirements for recruitment. In 2015 we found a large number of seedlings of these two species. The floods and high water of 2013, 2014 and 2015 likely created many bare, moist sites suitable for seedling germination. Whether these seedlings will be able to survive the next few years and become newly recruited saplings is an open question, as cottonwood seedlings typically experience very low survival rates (see literature review above). Contrary to expectations, non-native species make up a relatively small portion of the forest in the study area when compared to other western river systems (Nagler et al. 2010b). Additionally, there were few saplings and seedlings of these species. It seems unlikely at this point that the last few years of floods and high water have resulted in an outbreak of native or non-native tree species in the study area.

b) Weeds

State of Colorado listed weeds are common throughout the study area and are present at all sites. The most common species, downy brome, is in Colorado list “C”. Species on this list are of concern, but do not require management action to prevent their continued spread. Common mullein is also on list C. One list A species, purple loosestrife, was found at two different sites. These species are designated for eradication within the state. All of the other weed species found are in Colorado list B. Species on this list must be managed in a way to prevent their continued spread.

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Objective 4. For both phreatophytes and listed weed species, determine the relationship between river geomorphic surface and species incidence and abundance, and examine the effects of the September 2013 flood on species recruitment.

Objective 5. Link these data to GIS-based maps of the South Platte flood plain, and use these maps to predict the abundance of non-native phreatophytes and listed weeds along and within the river system.Using Remote Sensing Data for South Platte Phreatophyte Assessment

Data Acquisition and Preparation

Remote sensing data of aerial imagery and LiDAR data are key elements in predicting the abundance of non-native phreatophytes and listed weeds along and within the river system. We used a combination of aerial imagery and LiDAR data to estimate phreatophyte species identity and tree mortality within the study area.

Aerial imagery was obtained from the National Agriculture Imagery Program (NAIP) (USDA FSA 2016). These images contain 4 bands of color information (red, green, blue and near infrared) and are produced with a 1 m ground resolution. Images for both summer 2013 (pre flood) and summer 2015 (post flood) were acquired and processed in ArcGIS 10.1 (ESRI 2011). The approximately 100 images that cover the study area were first combined into a single mosaic database.

The four bands of color information allow us to measure the Normalized Difference Vegetation Index (NDVI), which is used as a measure of how healthy vegetation is. Separate NDVI layers were generated for both 2013 and 2015.

LiDAR data for the study area were acquired on October 25 2013 and were obtained from USGS National Geospatial Program. LiDAR remote sensing uses light pulses to measure surface elevation and texture. These data are acquired at approximately 60 cm intervals on the ground and can be processed into separate layers for ground elevation, (a Digital Elevation Model), and maximum elevation (for example the tops of vegetation – a Digital Surface Model). From these layers we can estimate vegetation height throughout the study area (a normalized Digital Surface Model)

LiDAR data were processed using ArcGIS 10.1's LAS Dataset tools to create 1 m horizontal resolution DEM, DSM and nDSM for the entire study area. Sample images of these layers are presented in Figures 6 a-d.

Estimating tree mortality

Methods

We developed a model to predict changes in tree abundance and health using a combination of vegetation height data derived from the LiDAR dataset and vegetation health data from the 2013 and 2015 NDVI estimates. To do this, we estimated for every portion of the study area with vegetation height greater than 2 m. the change in NDVI from summer 2013 (before the flood) to summer 2015 (after the 2013 flood and the high flow years of 2014 and 2015). Our process was to first select all portions of the study area with vegetation taller than 2 m and 2013 NDVI > than 0.145. For these areas, we then calculated the difference in NDVI (d_NDVI) as NDVI 2015 – NDVI 2013. By examining d_NDVI values for plots with dead or live trees from our survey data and from summer 2013 and summer 2015 imagery, we classified areas with trees as:

d_NDVI < -0.35 = dead or removed,

-0.35 < d_NDVI < -0.1 = declined

and d_NDVI > 0.1 = increasing

These raster values were smoothed using a 5 m x 5 m majority filter and classified into polygons for determination of the number of acres falling into each class. See figure 7 for images demonstrating this output.

Results

In the interval between the October 2013 and July 2015, approximately 8.5% of the riparian forest died (Table 9). Visual examination of the output maps indicates that most of our estimated mortality is associated with the physical effects of the flood or from movement of the river channel. Less commonly, trees died that were some distance away from the 2013 or 2015 channel.

Figures 5a and 5b illustrate this. In most cases these areas are next to back channels or other low spots in the floodplain. Tree mortality in the interval was lowest for the South Platte River upriver from its confluence with the St. Vrain, equaling 4.68%. 5.55% of trees died on the South Platte between the St. Vrain and the Big Thompson and 5.19% between the Big Thompson and the Poudre. Mortality was highest on the St. Vrain (10.84%), followed by the South Platte downstream from its confluence with the Poudre (9.51%). These patterns are consistent with the pattern of flooding in 2013, with flooding occurring on the Poudre, Big Thompson and St. Vrain and moving into the main stem of the South Platte.

Discussion

It is difficult to unequivocally correlate our estimates of change in forest state to ground observations of tree mortality during the interval given the data we are able to collect. An ideal data set for this analysis would have ground observations of tree size and canopy condition in 2013 and again for the same locations in 2015. We do not have pre-flood ground data, and must rely on LiDAR just after the flood and aerial imagery data from just before the flood to estimate the scope and condition of the pre-flood riparian forest.

Below are sources of error in our estimates of change in forest condition, and our estimates of how these might alter our conclusions on change in forest extent and status pre- 2013 flood and post 2014 & 2015 high flow years:

1) Vegetation height data were generated from LiDAR data that were collected several weeks after the 2013 flood. Vegetation that was immediately uprooted by the 2013 flood and carried away are not included in our estimates. The effect of this is we are **underestimating** the magnitude of tree removal.

2) If a tree died or is removed, the difference in NDVI depends not only on how green the tree was in 2013 but also on what vegetation, if any, has replaced that tree. For example, for areas that were trees in 2013 and are now bare ground or active river, change in NDVI is very large. Bare ground and water have very low NDVI values. If a tree dies and there is now grass growing where the tree used to be, NDVI change is much smaller, as grass has an NDVI greater than bare ground, but still less than an actively growing tree. This leads us to **underestimate** the decline in riparian forest extent 2013 – 2015 in areas where trees died from standing water but where grasses and forbs were able to survive this or re-colonized the area between spring 2014 and spring 2015.

3) Variation in the spectral quality of NAIP images between years and for locations within years make it difficult to conclude that a small decline in NDVI represents a real change in vegetation quality or quantity, and is not simply a result of sampling noise. This requires us to use a more

stringent cut-off for vegetation decline (tree death) instead measures of canopy decline and die-back. This **underestimates** the reduction in riparian forest.

4) The riparian forest could also have grown in response to the 2013 flood and 2014 and 2015 high water. Phreatophyte recruits (seedlings) that have established since the floods are too small to be picked up by our remote sensing data (but see the survey data above). Remote sensing measurements of change in canopy volume are not possible without more recent LiDAR data. Even with more recent LiDAR data it would be difficult to separate change in forest extent or volume that is due to the flood from changes that occur every year as trees grow and reproduce. These act to **overestimate** the effect of the flood on forest decline.

Using Object Based Image Analysis (OBIA) to Estimate Different Tree Species

Object Based Image Analysis uses unsupervised classification to partition an image into areas with similar data values. For this study, relevant data are the 4 bands of color information in from the 2015 NAIP imagery, NDVI values from 2015 and nDSM values. OBIA is a computational intensive process. To speed up the process we divided the study area in 11 reaches, each reach delimited by a river gauge. These reaches are illustrated in figure 8.

nDSM values were first filtered using ArcGIS's median and convolution filters with a 3m x 3 m pixel size to minimize the effects of "spikes" in height data. The image of the study area was then segmented into polygons with similar data values using the software program eCognition (Trimble 2016).

We then used a NDVI threshold of 0 to classify these polygons into vegetation – non-vegetation areas and then an nDSM threshold of 2 m to classify vegetation into trees vs. other vegetation.

Finally, we compiled imagery, NDVI and nDSM data from polygons that occurred on top of our field plots where we had identified trees to species. These data were then used in a Decision Tree Classification program to create a rule set that classifies all tree polygons into one of three classes: Cottonwood, Russian olive, or Other tree species. Attempts to classify polygons into more specific classes than these three were unsuccessful due to the spectral similarity between many of the tree species.

Results

Over the entire study area, 62% of trees were classified as Cottonwood, 10% as Russian olive and 28% as other. These values are higher than those estimated from the ground surveys: basal area estimates (which correlate strongly with canopy area) were 80%, 2% and 18% for these same species groups. Estimated classification accuracies for the segmentation process were 82%, 78% and 61% for these Cottonwood, Russian olive and other, respectively. Classification errors will result in overestimates for rare classes and underestimates of more common classes. For example, if 9% of Cottonwood trees are, on average, misclassified as Russian olive, a large section of forest that truly contains only Cottonwood would be expected to be classified as containing 9% Russian olive, 82% Cottonwood and 9% other. Table 9 provides estimated acres of trees for 11 sections of the study area.

Using Regression Techniques to Estimate the Basal Area (BA)

The collected field data were regressed on the acquired LiDAR data in order to develop a BA map for the whole study area. The following are the steps of estimating the BA:

- The DBH data are measured for each tree in the plot samples (20 * 20 meter).
- The BA is calculated for each of the individual plots.
- The corresponding plots are extracted from the LIDAR data using Fusion software (USFS RSAC 2016).
- A matrix was developed from the measured BA area from the field data and the extracted LiDAR data.
- LiDAR data used included canopy height variables such as: min., max, mean, mode, stdev, CV, different percentiles from 1 to 99, and canopy density variables such as: 1st cover above mean, 1st cover above mode, 1st cover above 2 meters, all cover above mean, all cover above mode, all cover above 2 meters.

Three different models are tested to select the best of them in order to estimate the BA area. Linear regression model:

1) Ordinary Least Squares (OLS) using stepwise regression and model selection based on Akaike Information Criteria.

2) Multivariate Adaptave Regression (MARS), which is a non-linear. It is a nonparametric regression method that models multiple nonlinearities in data using hinge functions (functions with a kink in them).

3) Decision tree (Random forest). It is an ensemble learning method for regression, that operate by constructing a multitude of decision trees at training time and outputting the class that is the mean prediction (regression) of the individual trees. Random forests correct for decision trees' habit of over-fitting to their training set. It grows a forest of many trees, each tree is a little different (slightly different data, different choice of predictors); and then combines the trees to get predictions for new data.

Figure 11 shows the predicted and observed values of the basal area using the different models: Linear regression, non-linear regression, and random forest. Since the results of the linear and non-linear are close to each other, only linear and random forest models will be analyzed.

Figure 12 shows that there is no trend in the residuals for the linear model. The red line is close to the dashed line, which means that the mean of the residuals are close to zero. This means that the performance of the model is good. Table 10 provides estimates for the linear model that predicts basal area.

Figure 13 shows an example of the different trees that can be used to construct the random forest model. The random forest model combines the advantages of tree, which was mentioned earlier as well as the advantages of the Radom Forest itself. The main advantages of the Random Forest model is that it is a built-in estimates of accuracy, which means there is no need for validation. Some other advantages are: it has an automatic variable selection, variable importance, and handles wide data.

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Objective 6. Obtain data from existing groundwater monitoring wells from before and after the 2013 flood and determine if there has been a measurable change in water table depth within the flood-affected region.

We obtained daily ground water measurements from 3 wells within the study area and compared water table elevation to River discharge as measured at the USGS Fort Morgan gauge. Well DSS38BLZ is located approximately 26 km downriver from the gauge. Wells DSS22KRY and DSS25KRY are located approximately 72 km upriver from the gauge. Wells DSS38BLZ and DSS22KRY are located adjacent to the river channel. DSS25KRY is located approximately 1 km south of the river.

We estimated the degree to which the water table depth within the flood plain changed as a result of the 2013 flood by estimating for each well the relationship between daily water table elevation and river discharge. Historical data from the Colorado Division of Water Resources HydroBase system for these wells and the Fort Morgan gauge was used to estimate these relationships for a 10-year period prior to the 2013 flood by regressing water table elevation on the square root of river discharge. We then used this relationship to predict the water table elevation as river discharge varied through time.

Figures 9 a-c plot measured vs. predicted water table elevation for the three wells for 5 months prior to and 24 months after the 2013 flood. For wells DSS38BLZ and DSS22KRY, predicted water table elevation closely matches what was observed in the wells, indicating that ground water was not stored within the system following the flood. As river discharge increased, water table elevation increased. As river discharge decreased, water table elevation decreased contemporaneously and with no detectable time lag.

In contrast, well DSS25KRY, located 1 km south of the river, shows a different pattern. Water table elevation rapidly increased above predicted approximately 3 weeks after the flood and remained higher than predicted for the next 6 months. A possible explanation for this result is that this well is located in a pasture surrounded by a levee (Figures 10 a, b). The elevation of this leveed-off pasture is 2 – 3 feet lower than that of the pasture between it and the river. It is possible that the floodwaters breached this levee and pooled in the area, elevating water table for some months after the flood. There are a limited number of monitoring wells located within the study area, making generalization from this one well difficult. However, pooling in one or several locations along the river would not permanently raise the water table within the system, and such effects are expected to have been localized and short term in duration.

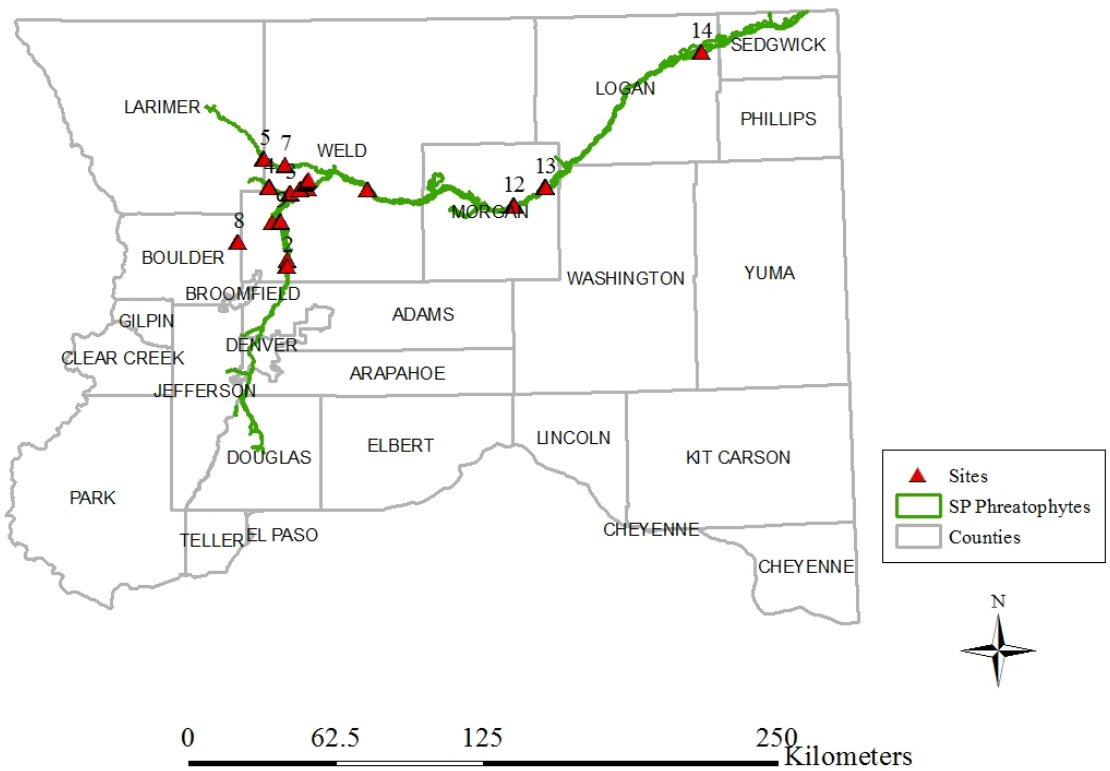


Figure 2. Site locations.

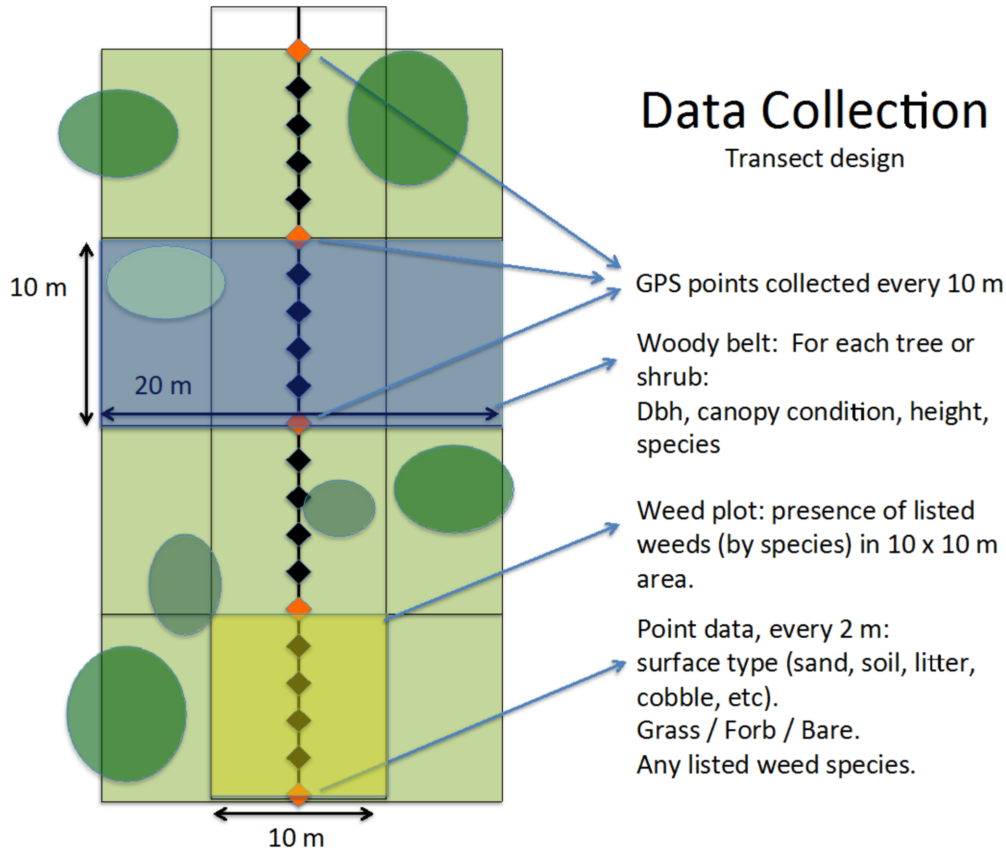


Figure 3. Transect sampling design. Transects are oriented perpendicular to the river at each site. Along the transects all tree and shrub species are measured within 10 x 20 m belts. Weed incidences is recorded every 2 m (point data) and within each 10 x 10 m block (incidence data). GPS coordinates are recorded every 10 m

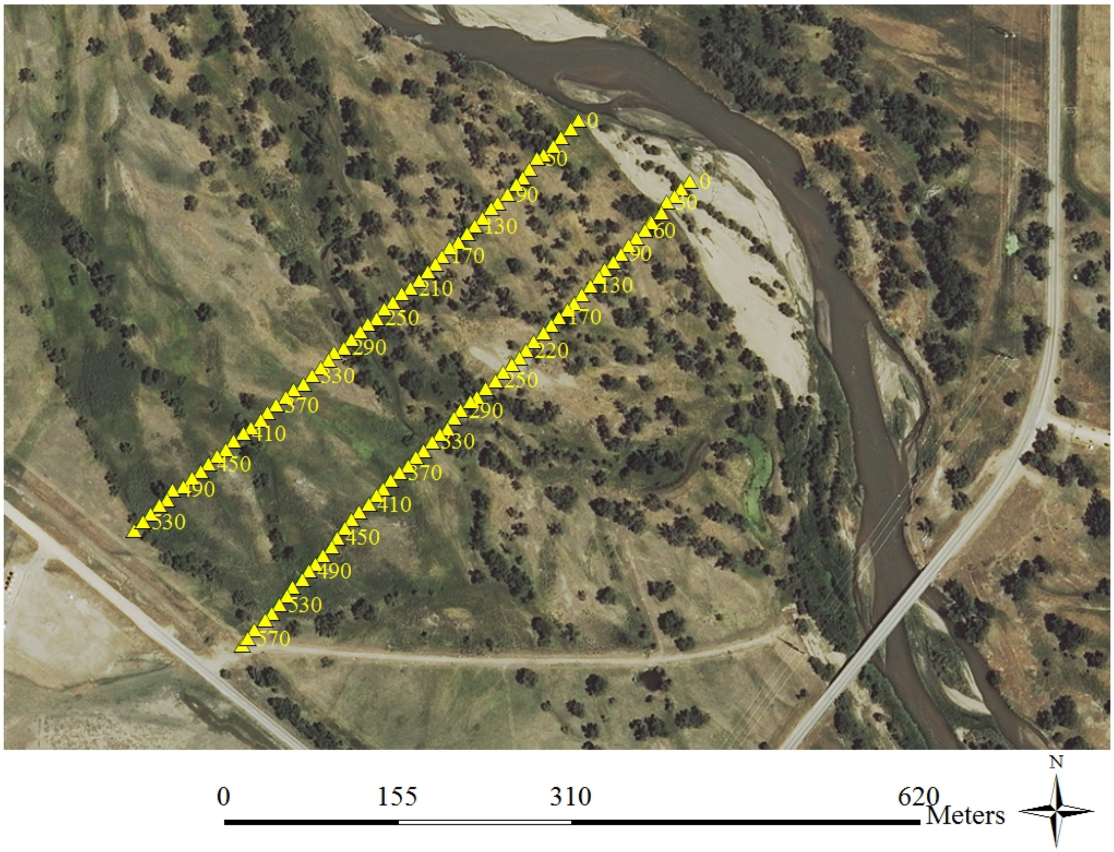
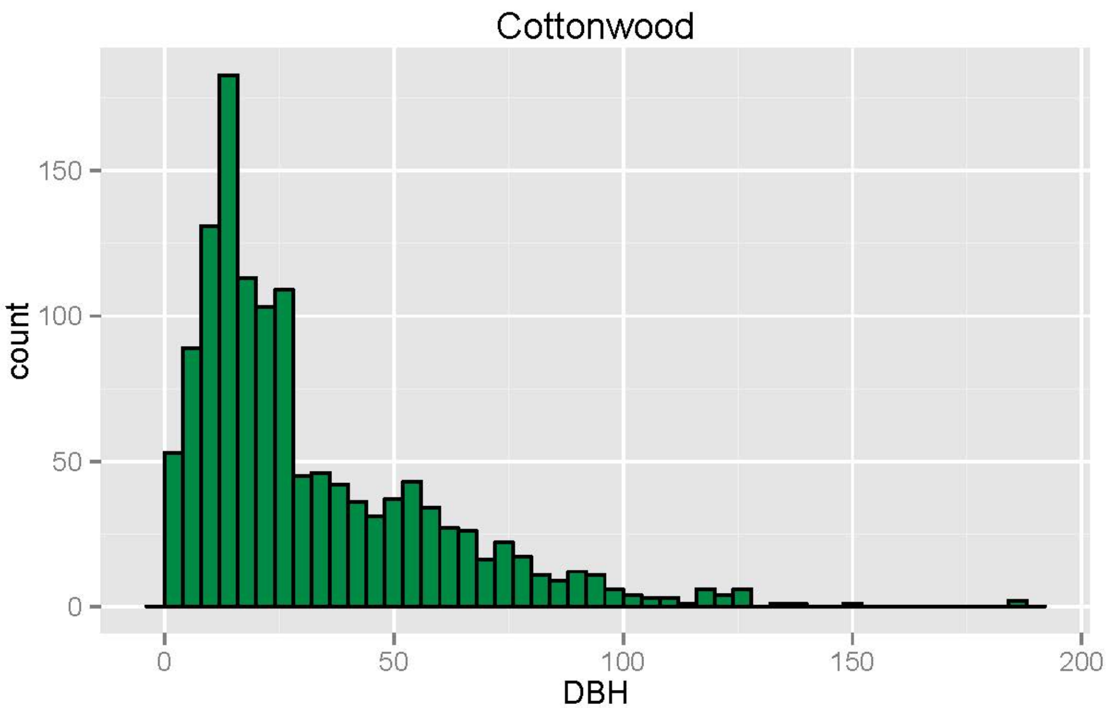
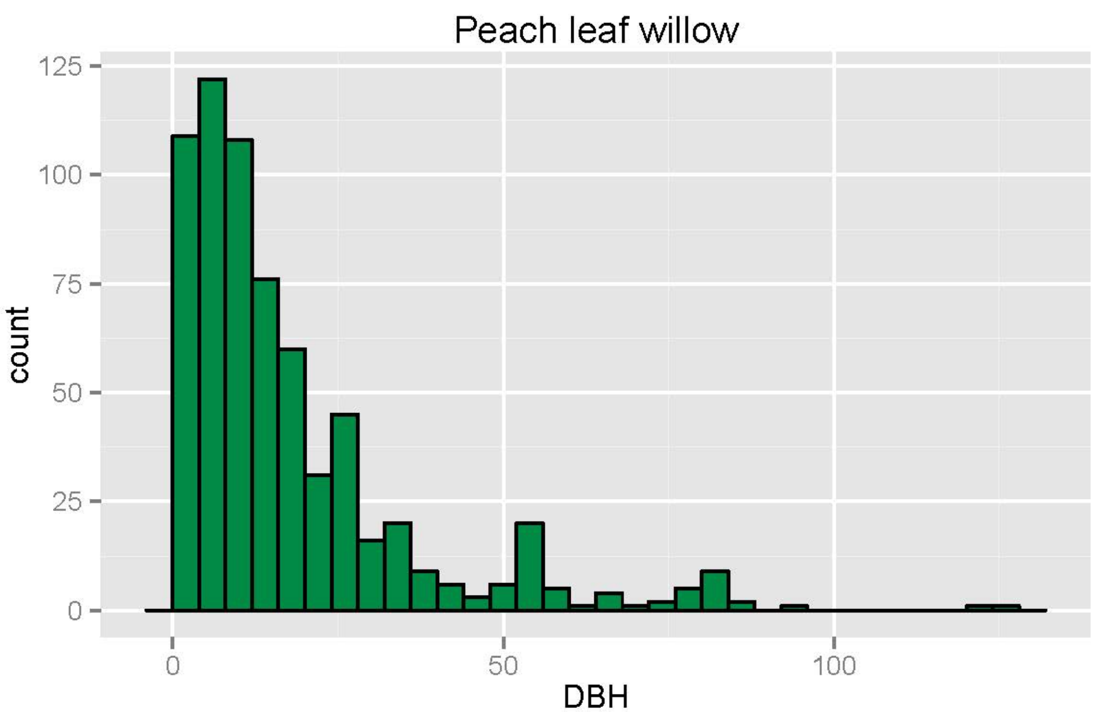
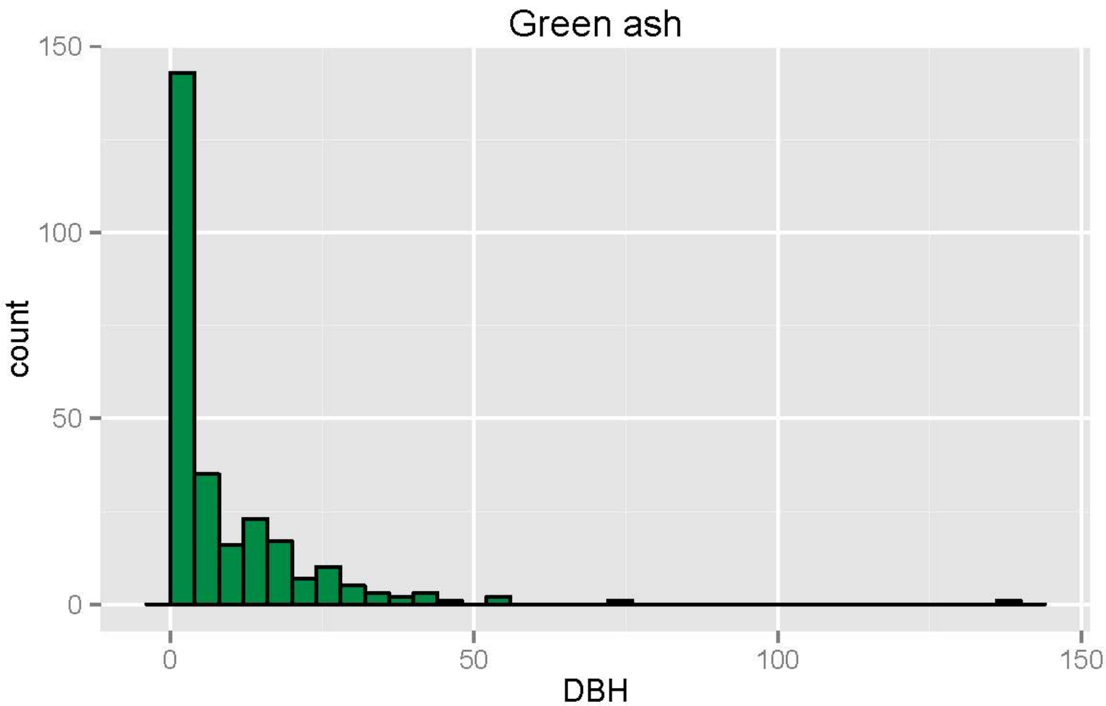


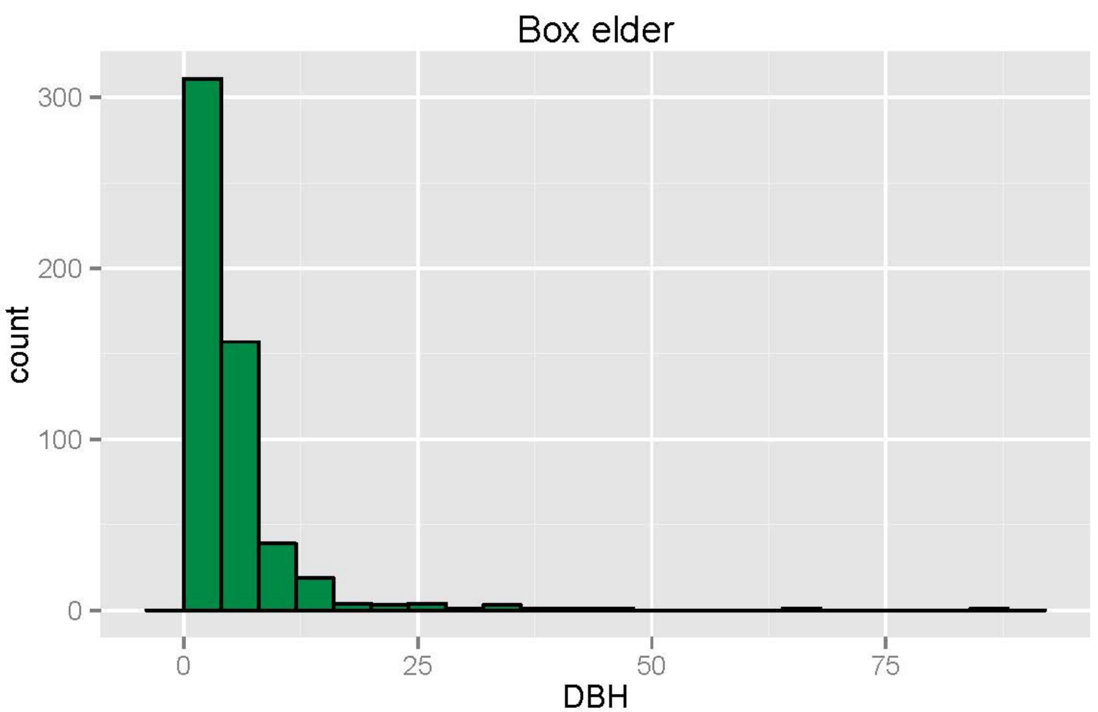
Figure 4: Example of transect sampling design from site 11. Yellow triangles are recorded GPS points taken every 10 m along transect.


Cottonwood
150
100
50
0
count
0
50
100
150
200
DBH

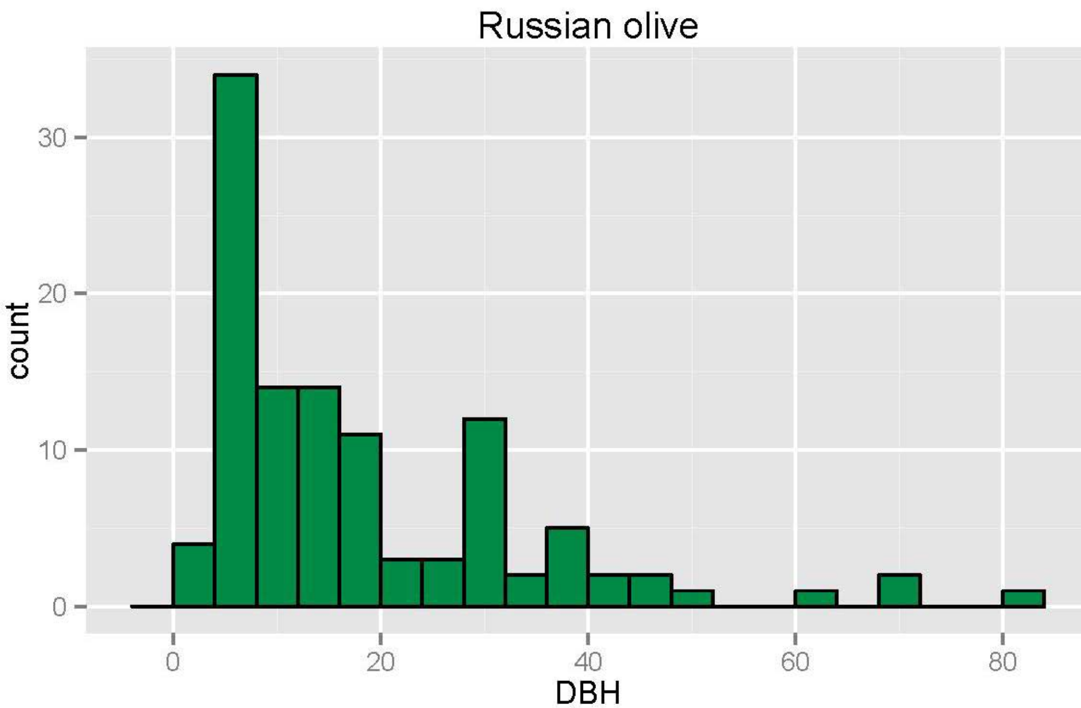

Peach leaf willow
125
100
75
50
25
0
count
0
50
100
DBH



Green ash
150
100
50
0
count
0
50
100
150
DBH



Box elder
300
200
100
0
count
0
25
50
75
DBH



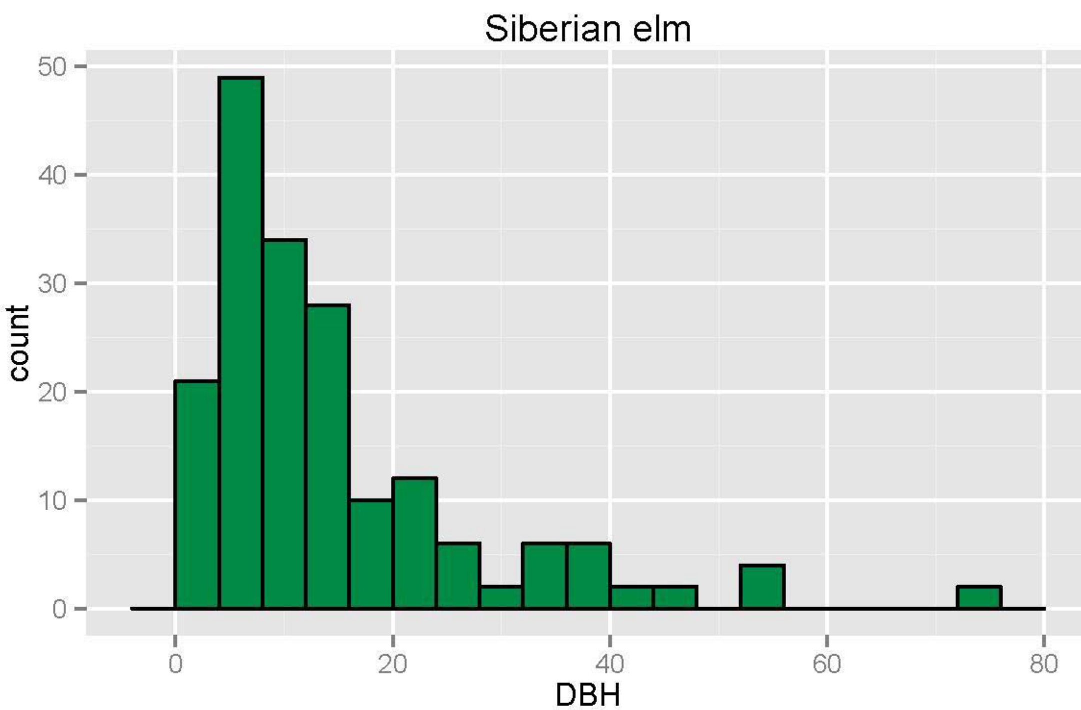


Figure 5 a-f: Size distributions for trees in the study area. DBH = diameter at breast height (cm). Counts include both saplings and mature trees.

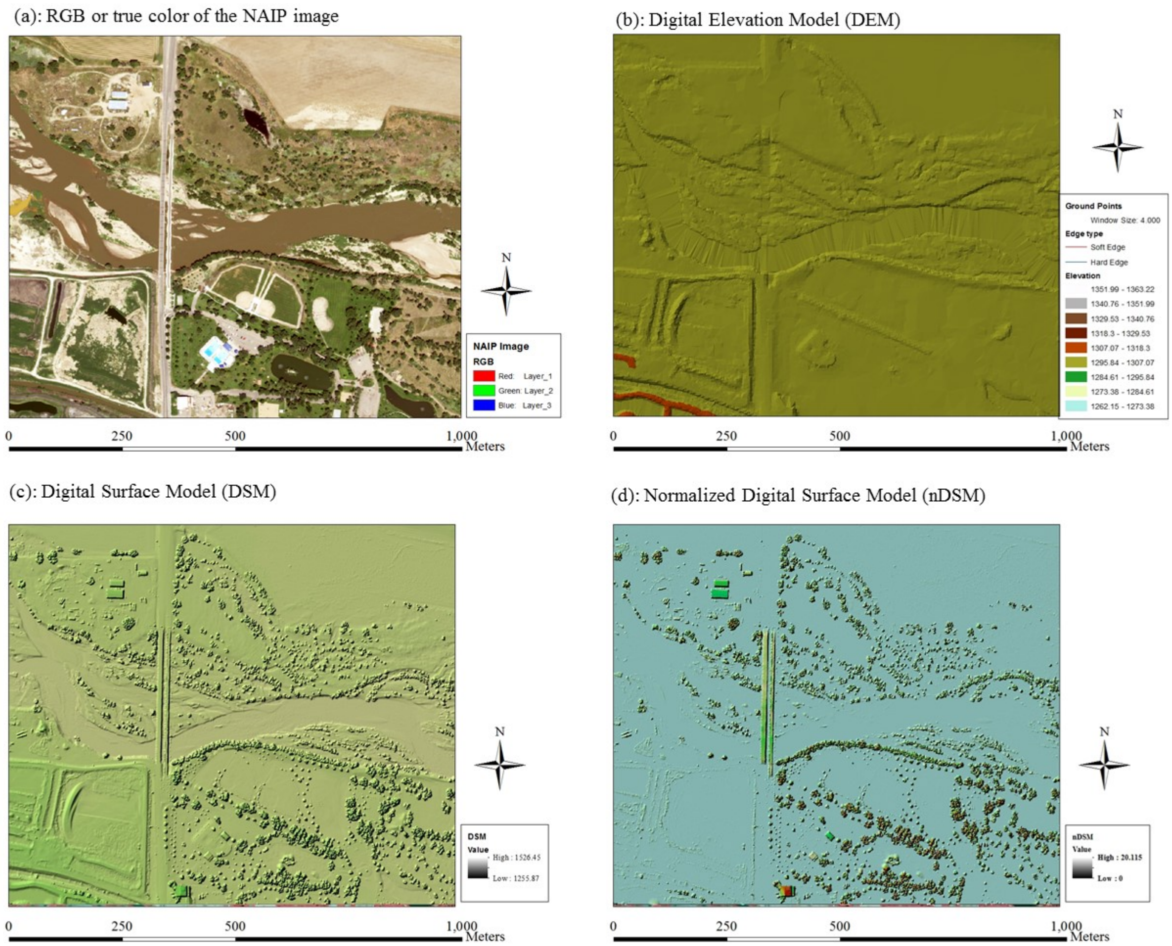


Figure 6a-d: Different Surfaces Generated from LiDAR Datasets.

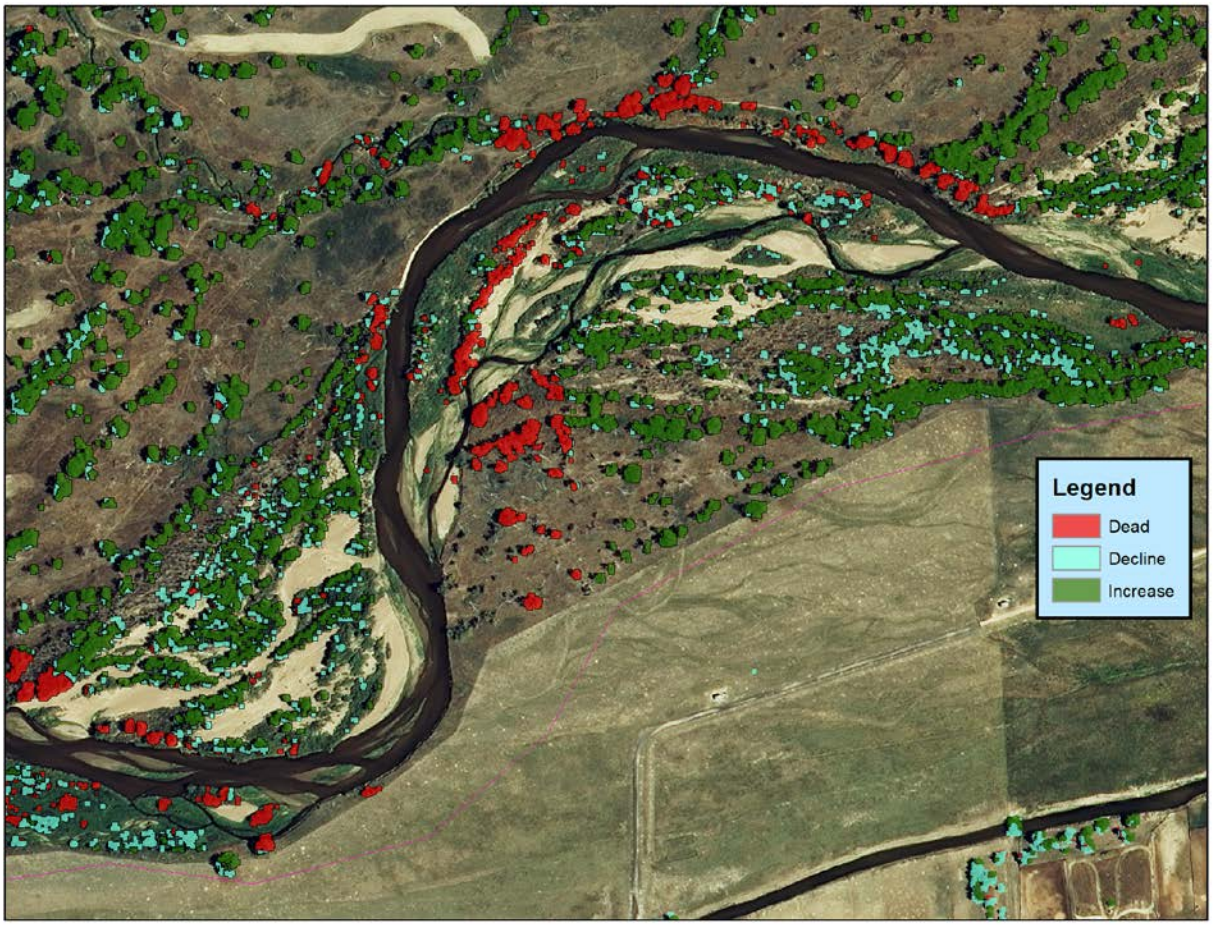


Figure 7a. Tree mortality estimated from LiDAR and remote imagery data. Background image is 2013 NAIP imagery.

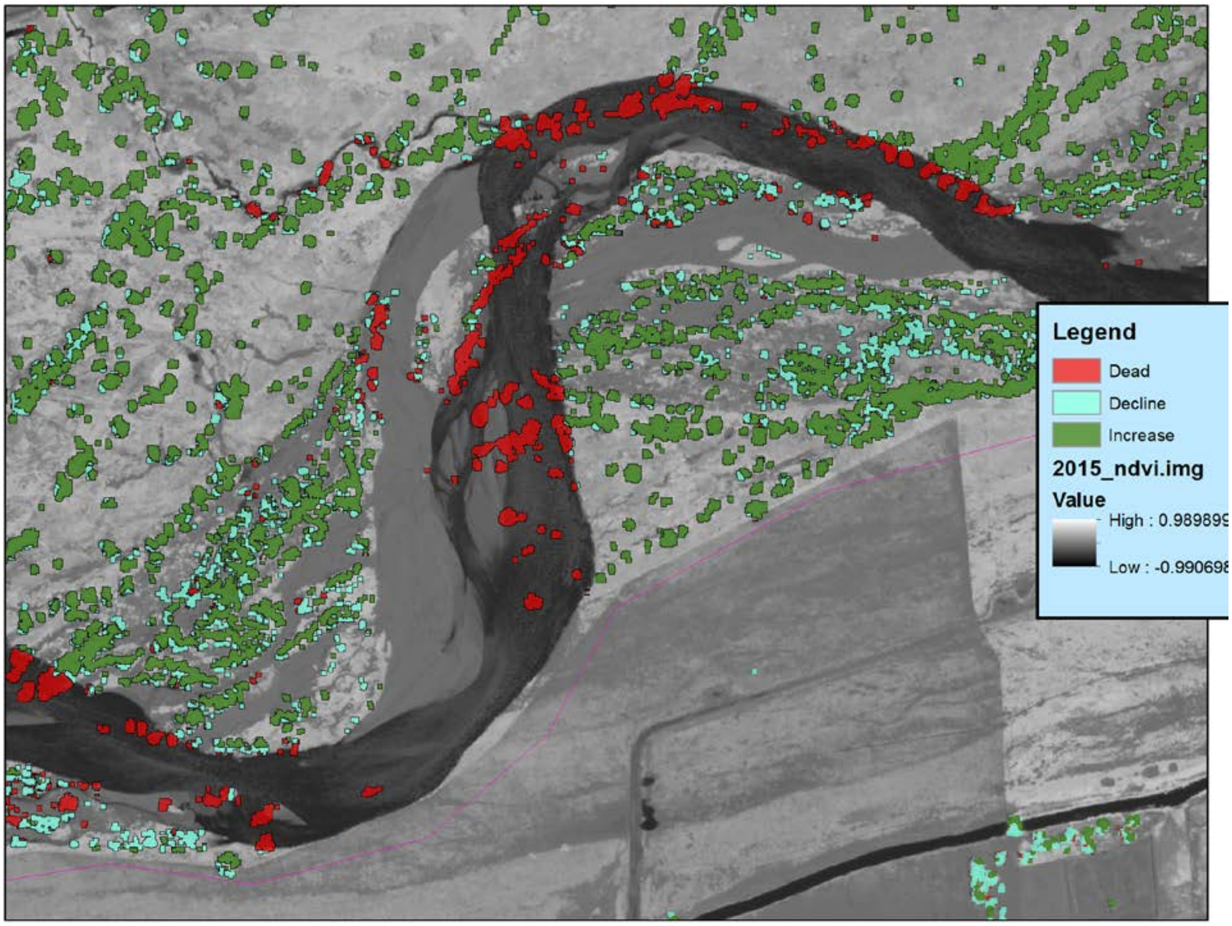


Figure 7b. This is the same portion of the study area as in 5a, but with 2015 NDVI as the base image. Note how the position of the river (dark pixels in this image) has changed relative to the 2013 image in 7a.

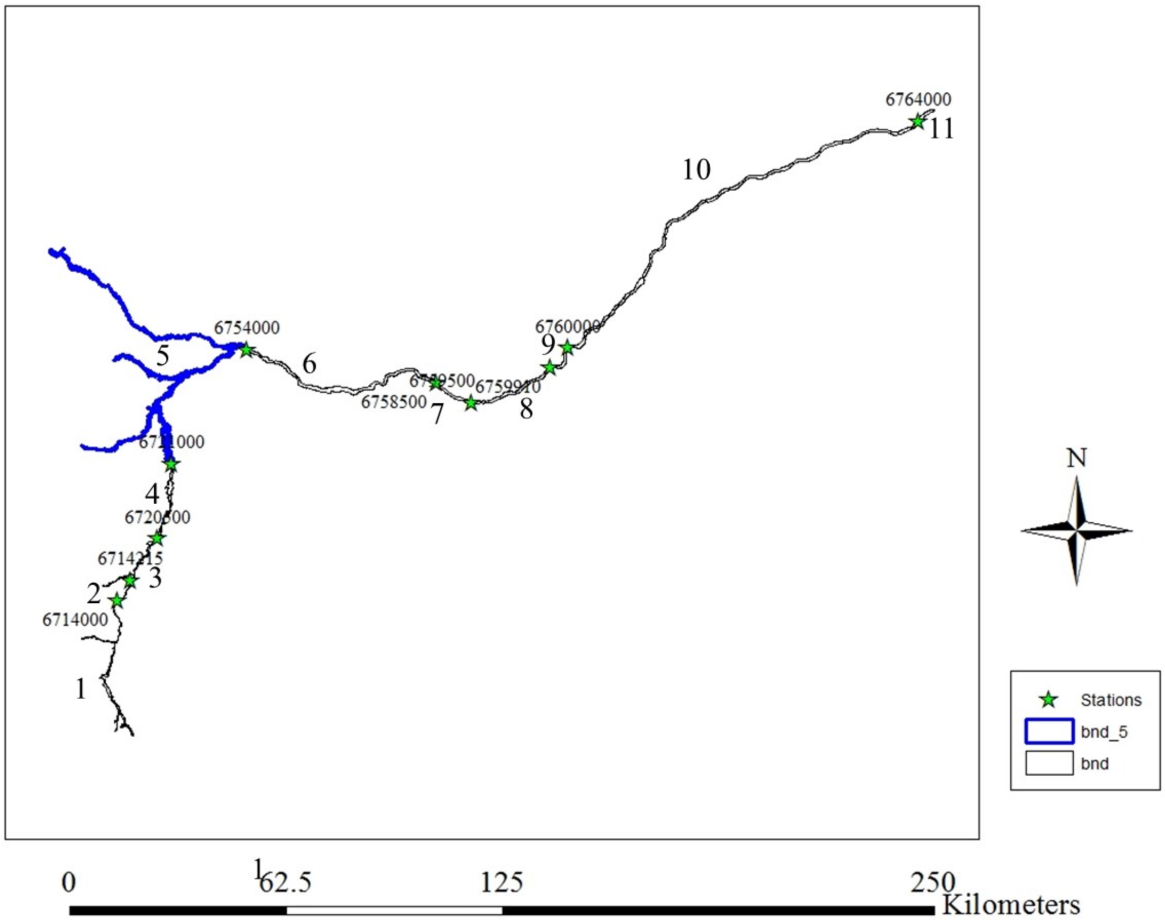
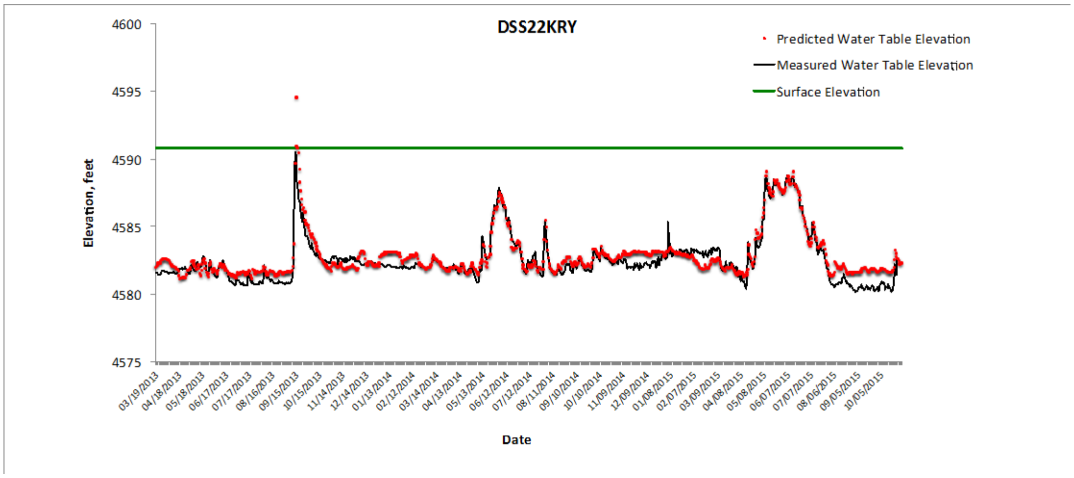
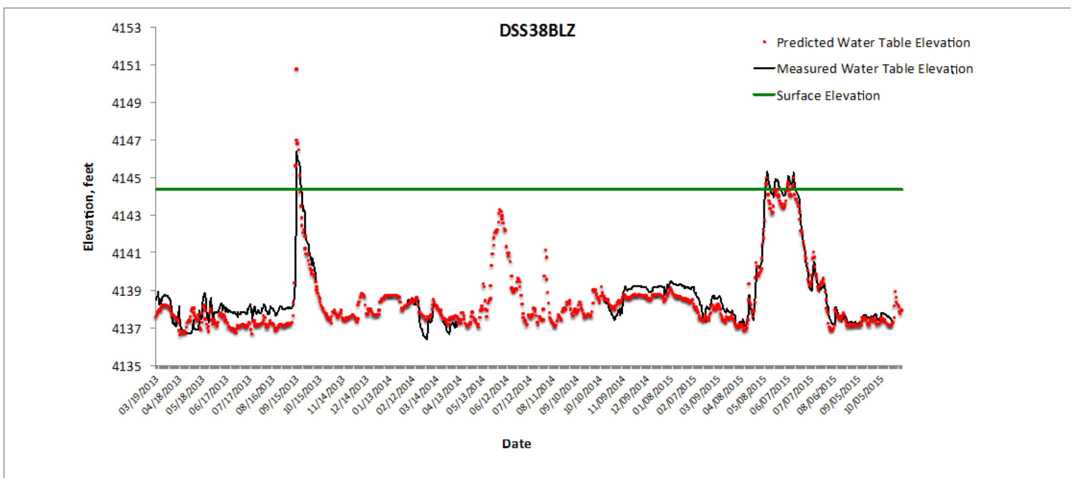
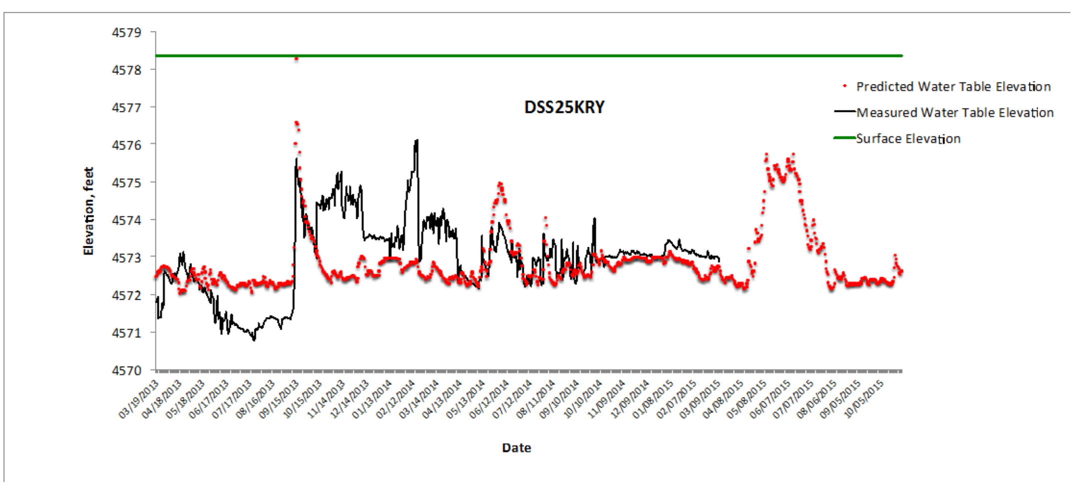


Figure 8. Reaches used for tree species classification.







Figures 9 a-c. Predicted water table elevation based on river discharge at the Fort Morgan gauge (red points) and measured water table elevation (black lines) for three wells along the South Platte River.

Figure 10. Well DSS25KRY

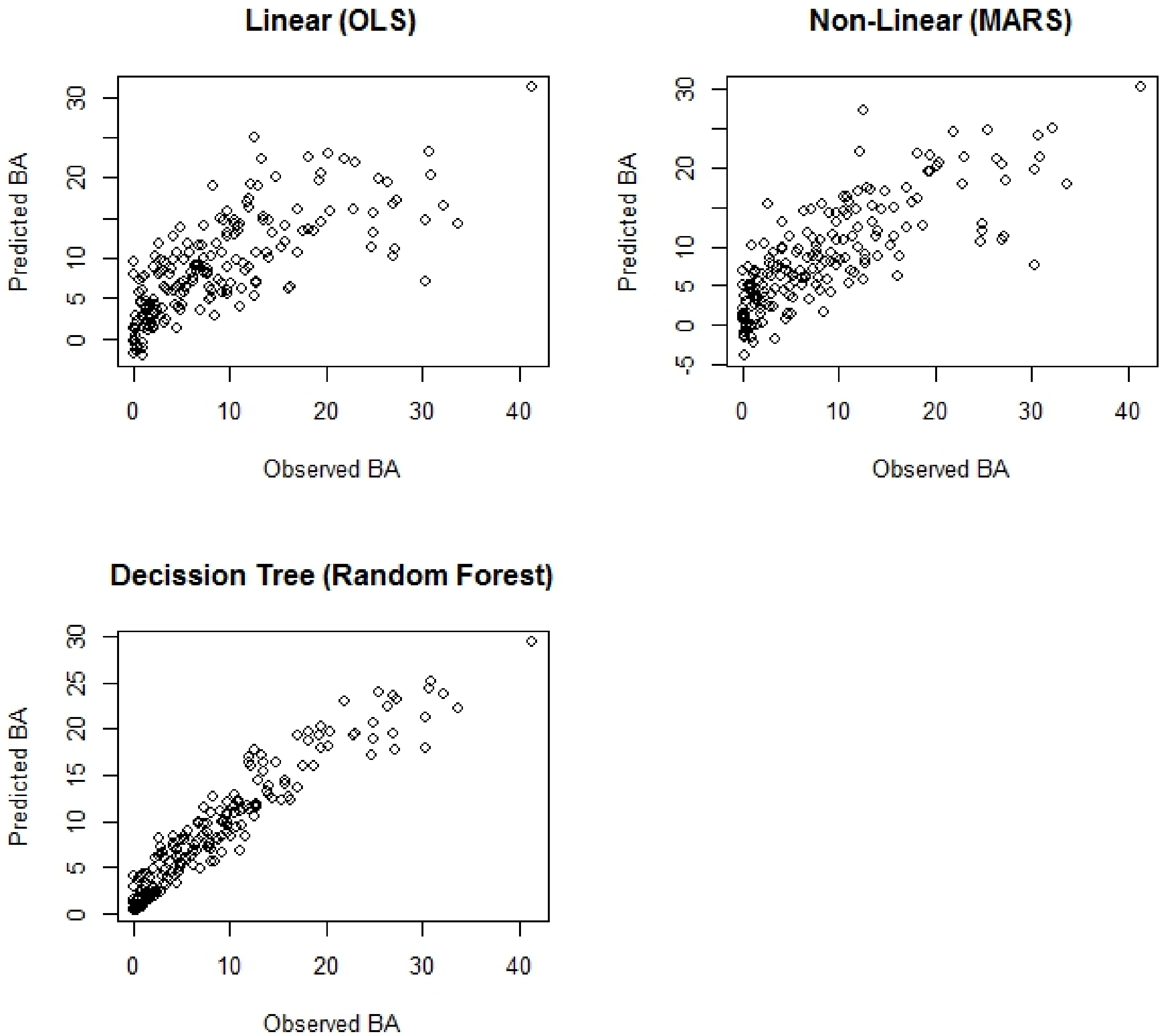


Figure 11: Predicted and Observed values used three different regression models

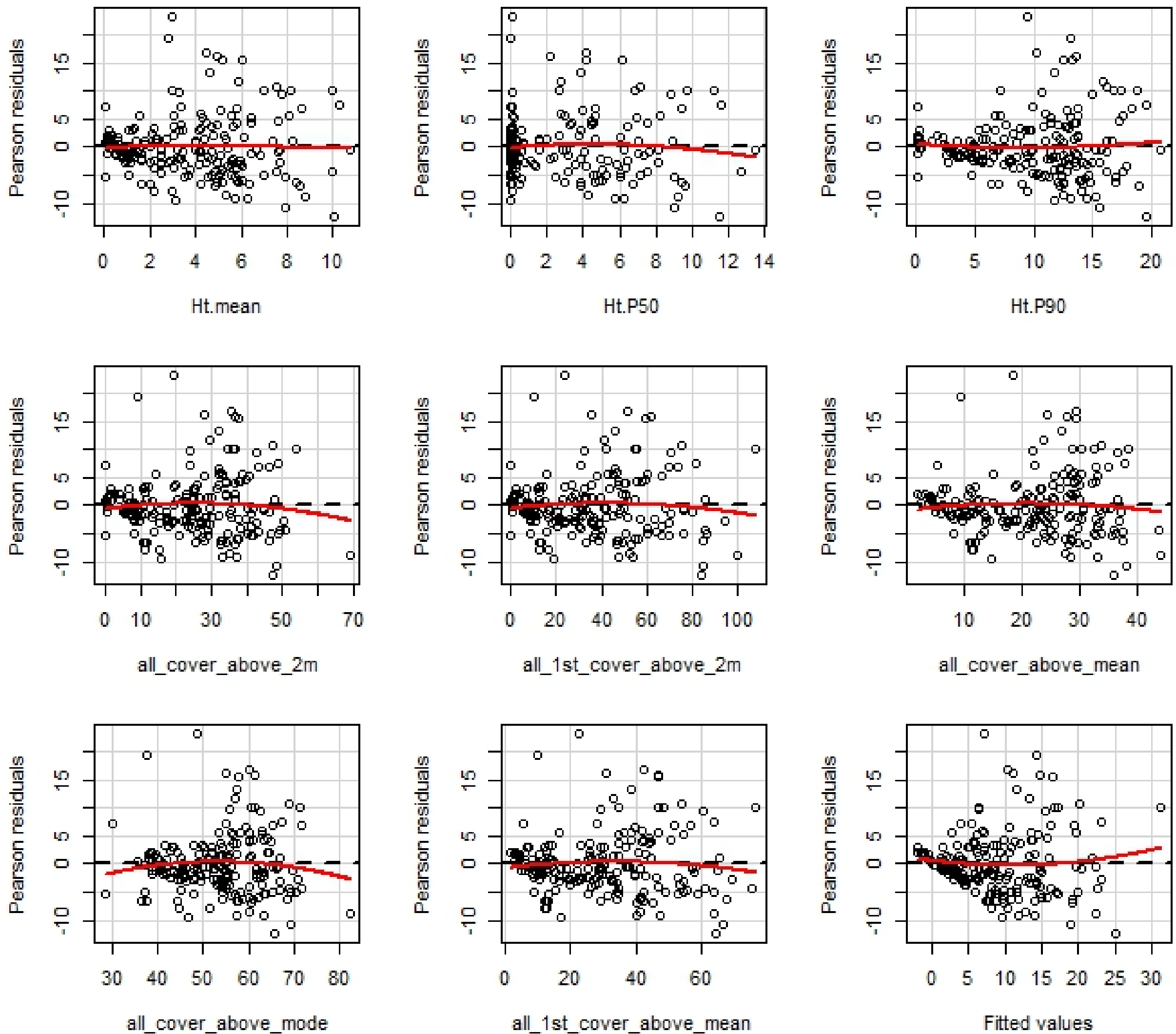


Figure 12: The residuals from the linear model

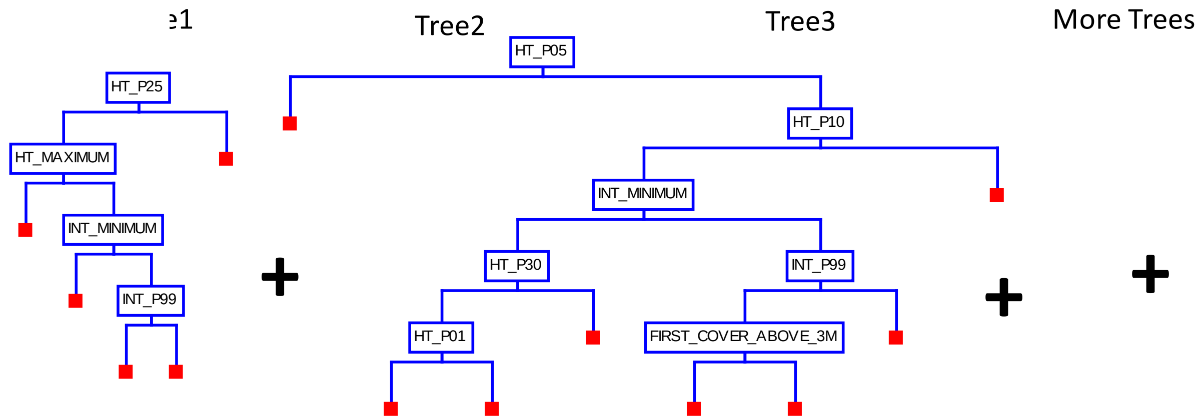


Figure 13: Example of different trees used for Random Forest Regression.

Table 1: Site locations

Site	Name	River	County	Coordinates, UTM NAD83	
1	Pearson Park, City of Fort Lupton	South Platte	Weld	4437111	515286
2	City of Thornton	South Platte	Weld	4434481	514779
3	Daniels	Big Thompson	Weld	4465379	516258
4	Rite-A-Way	Big Thomspon	Weld	4467974	507422
5	Frank SWA	Cache la Poudre	Weld	4480175	504927
6	Houston	Saint Vrain	Weld	4453036	508746
7	Marietta	Cache la Poudre	Weld	4477109	514003
8	Keyes, Boulder County Open Space	Saint Vrain	Boulder	4444687	493924
9	Jensen	South Platte	Weld	4453547	512103
10	Evans/Sylvester	South Platte	Weld	4467184	523845
11	70 Ranch	South Platte	Weld	4467055	549544
12	Jean K Tool SWA	South Platte	Morgan	4460198	611073
13	Cottonwood SWA	South Platte	Morgan	4468199	624617
14	Tamarack SWA (east)	South Platte	Logan	4525388	690554
15	Sorin/Allely	South Platte	Weld	4467164	520715

Site	# plots	Hectare surveyed	American elm†	Box elder	Crack willow*†	Green ash†	Peach-leaf willow	Plains cottonwood	Russian olive*†	Siberian elm*†	Tamarisk *†	Other	Total	Total Non-native
1	46	9.2	0	0	0	0.20	1.38	10.83	1.57	0.07	0	0	14.05	1.84
2	24	4.8	0	0.26	0.52	0	0.08	2.87	0	0.12	0	0	3.86	0.13
3	67	13.4	0	0.08	0	0	0.72	16.21	0.93	0.26	0	0	18.19	1.19
4	48	9.6	0	0	0	0	2.52	4.87	0.66	0.01	0.01	0.02	8.09	0.68
5	47	9.4	0.01	1.75	0	0.02	2.84	12.87	0.02	0.74	0	0	18.24	0.79
6	47	9.4	0	0	0	0	0.83	10.81	0	0	0	0	11.64	0
7	59	11.8	0	0.19	0	0	3.71	12.35	0	0	0	0	16.25	0
8	48	9.6	0	0	1.46	0	1.05	2.49	0	0.75	0	0	5.76	0.75
9	65	13	0	0	0	0	2.26	8.84	0.02	0.14	0	0	11.25	0.16
10	63	12.7	0	0.24	0	0	0.94	21.44	0.62	0.20	0.01	0	23.45	0.83
11	112	22.4	0	0	0	0.58	1.57	14.30	0	0	0.04	0	16.49	0.62
12	46	9.3	0	0.07	0	0.27	0.61	12.80	0.21	0.14	0	0.02	14.12	0.62
13	61	12.2	0.02	0.20	0	1.63	0.05	8.11	0.33	0.19	0	0	10.53	2.17
14	84	16.86	0	0.09	0	0.82	2.16	15.55	0.12	0	0	0.05	18.79	0.94
15	56	11.2	0	0.03	0	0.60	3.68	15.73	0	0.69	0	0	20.74	1.29
Total	**873**	**174.86**	**0.03**	**2.91**	**1.98**	**4.12**	**24.41**	**170.07**	**4.48**	**3.31**	**0.07**	**0.09**	**211.46**	**12**
Percent of total, by species			**0.01**	**1.38**	**0.94**	**1.95**	**11.54**	**80.43**	**2.12**	**1.56**	**0.03**	**0.04**	**100.00**	**5.68**

Table 2. Summary of tree basal area (m^2) by species for each site. *Not native to North America †Not native to Colorado. Non-native column includes all species not native to Colorado.

Site	# plots	Hectare surveyed	American elm†	Box elder	Crack willow	Green ash†	Peach-leaf willow	Plains cottonwood	Russian olive*†	Siberian elm*†	Tamarisk *†	Other	Total	Total Non-native
1	46	9.2	0	0	0	6	5	71	16	5	0	0	103	27
2	24	4.8	0	2	17	3	9	36	0	2	0	0	69	5
3	67	13.4	0	1	0	0	6	30	47	5	2	0	91	54
4	48	9.6	0	0	0	0	67	24	3	2	1	1	98	6
5	47	9.4	2	67	0	8	55	38	1	66	0	0	237	77
6	47	9.4	0	0	0	0	43	32	0	0	0	0	75	0
7	59	11.8	0	2	0	0	41	15	0	0	0	0	58	0
8	48	9.6	0	0	9	0	25	19	0	26	0	0	79	26
9	65	13	0	0	0	0	35	21	2	4	0	0	62	6
10	63	12.7	0	104	0	0	49	81	12	2	3	0	251	17
11	112	22.4	0	0	0	9	25	63	0	0	76	0	173	85
12	46	9.3	0	2	0	3	45	342	10	4	4	3	413	21
13	61	12.2	1	7	0	63	3	18	5	3	0	0	100	72
14	84	16.86	0	1	0	35	55	159	3	0	0	1	254	38
15	56	11.2	0	7	0	10	32	63	0	7	0	0	119	17
Total	**873**	**174.86**	**3**	**193**	**26**	**137**	**495**	**1012**	**99**	**126**	**86**	**5**	**2182**	**451**
Percent of total, by species			**0.14**	**8.85**	**1.19**	**6.28**	**22.69**	**46.38**	**4.54**	**5.77**	**3.94**	**0.23**	**100.00**	**20.67**

Table 3. Summary of number of individuals by site. *Not native to North America †Not native to Colorado. Non-native column includes all species not native to Colorado.

Site	# plots	Hectare surveyed	Japanese honeysuckle*	Golden currant	*Rosa* species	Sweetbriar rose	Wood's rose	Coyote willow	Snowberry	Total
1	46	9.2	2	13	0	0	86	228	2,856	3,185
2	24	4.8	0	314	0	0	0	10,728	483	11,524
3	67	13.4	34	0	0	0	0	0	40	74
4	48	9.6	0	0	0	0	0	241	0	241
5	47	9.4	1	0	1,545	0	0	705	0	2,253
6	47	9.4	0	0	0	0	0	7,238	0	7,238
7	59	11.8	0	25	0	155	0	8,946	2,005	11,131
8	48	9.6	0	7	0	0	0	4,247	4	4,258
9	65	13	0	0	0	0	6	2,334	0	2,340
10	63	12.7	0	88	0	175	87	13,028	74	13,452
11	112	22.4	0	0	109	1,339	5,566	100,626	26,010	133,655
12	46	9.3	0	247	0	0	10	17,189	2,746	20,192
13	61	12.2	0	97	37	8	45	36,593	4,251	41,034
14	84	16.86	0	0	0	19	15	50,078	2,910	53,023
15	56	11.2	0	20	0	98	76	331	1,845	2,370
Total	**873**	**174.86**	**37**	**811**	**1,691**	**1,794**	**5,891**	**252,509**	**43,223**	**305,968**
Percent of total, by species			**0.01**	**0.26**	**0.55**	**0.59**	**1.93**	**82.53**	**14.13**	**100.00**

Table 4. Summary of shrubs recorded at 15 sites along the study area. Numbers are number of stems recorded per site.
*Not native to North America.

Site	# plots	Hectare surveyed	American elm†	Box elder	Crack willow	Green ash†	Peach-leaf willow	Plains cottonwood	Russian olive*†	Siberian elm*†	Tamarisk*†
1	46	9.2	0	0	0	0	0	0	0	0	0
2	24	4.8	0	0	0	1	8	4	0	1	0
3	67	13.4	0	0	0	0	0	0	0	0	0
4	48	9.6	0	0	0	0	1	0	0	0	0
5	47	9.4	0	0	0	0	0	0	0	0	0
6	47	9.4	0	0	0	0	9	0	0	0	0
7	59	11.8	0	0	0	0	2	0	0	0	0
8	48	9.6	0	0	0	0	1	9	0	2	0
9	65	13	0	0	0	0	14	0	0	1	0
10	63	12.7	0	30	0	1	18	10	9	0	0
11	112	22.4	0	2	0	0	0	1	0	0	44
12	46	9.3	0	1	0	0	10	4	1	0	0
13	61	12.2	0	0	0	96	0	6	0	0	0
14	84	16.86	0	2	0	33	7	4	0	0	0
15	56	11.2	1	1	0	0	33	5	0	14	0
Total	**873**	**174.86**	1	36	0	131	103	43	10	18	44
Percent of total, by species			0.26	9.33	0.00	33.94	26.68	11.14	2.59	4.66	**11.4**

Table 5. Summary of number of saplings by site. *Not native to North America †Not native to Colorado. Non-native column includes all species not native to Colorado.

	# plots	Hectare surveyed	Box elder	Russian olive	Green ash	Cottonwood	Peach leaf willow	Tamarix sp.	American elm	Siberian elm
1	46	9.2	0	0	1	0	0	0	0	0
2	24	4.8	0	0	4	5	3	0	0	4
3	67	13.4	0	3	0	328	1	29	0	2
4	48	9.6	0	0	0	17,777	90	3	0	0
5	47	9.4	55	0	5	1	35	0	0	71
6	47	9.4	0	0	0	25	12	0	0	0
7	59	11.8	0	0	3	19,961	72	0	0	0
8	48	9.6	0	0	4	6,388	1,029	0	0	125
9	65	13	0	1	0	23,560	58	0	0	1
10	63	12.7	39	0	98	39	17	0	0	4
11	112	22.4	0	0	18	153	0	0	0	0
12	46	9.3	0	0	33	1	7	0	0	3
13	61	12.2	1	0	3,226	350	26	0	5	0
14	84	16.86	0	0	1,125	32,936	0	0	0	0
15	56	11.2	0	0	18	63	28	0	3	65
Total	**873**	**174.86**	95	4	4,535	101,586	1,378	32	8	275

Table 6. Number of seedlings recorded for each tree species.

Site	Sampled plots	*Cardaria draba*	*Bromus tectorum*	*Cirsium arvense*	*Lepidium latifolia*	*Convolvulus arvensis*	*Onopordum acanthium*	*Verbasum thapsus*	*Carduus nutans*	*Euphorbia esula*	*Dipsacus fullonum*
1	40	67.5	25.0	20.0	45.0	17.5	2.5	7.5	10.0	0.0	0.0
2	24	45.8	66.7	12.5	20.8	20.8	54.2	0.0	0.0	75.0	0.0
3	39	66.7	71.8	2.6	15.4	28.2	17.9	7.7	25.6	0.0	0.0
4	62	45.2	32.3	8.1	8.1	22.6	0.0	14.5	19.4	0.0	1.6
5	49	8.2	0.0	36.7	0.0	20.4	0.0	2.0	0.0	51.0	4.1
6	57	40.4	56.1	1.8	45.6	40.4	0.0	3.5	17.5	0.0	0.0
7	43	0.0	0.0	18.6	11.6	81.4	0.0	0.0	0.0	65.1	0.0
8	50	50.0	72.0	26.0	22.0	12.0	12.0	22.0	28.0	0.0	18.0
9	65	15.4	3.1	15.4	53.8	1.5	0.0	1.5	0.0	24.6	0.0
10	21	33.3	57.1	4.8	23.8	9.5	28.6	0.0	28.6	47.6	9.5
15	25	42.9	0.9	23.2	20.5	6.3	0.0	0.0	1.8	25.0	0.0
11	112	19.1	51.1	10.6	14.9	0.0	0.0	14.9	8.5	17.0	0.0
12	47	0.0	1.6	54.1	0.0	8.2	0.0	8.2	0.0	16.4	0.0
13	61	1.2	0.0	8.2	0.0	0.0	0.0	0.0	0.0	8.2	0.0
14	85	8.0	84.0	4.0	20.0	8.0	56.0	12.0	32.0	48.0	0.0
Sum		**29.6**	**34.8**	**16.4**	**20.1**	**18.5**	**11.4**	**6.3**	**11.4**	**25.2**	**2.2**

Table 7: Proportion of plots with listed weed species present.

Site	Sampled plots	*Cynoglossum officinale*	*Acroptilon repens*	*Dipsacus laciniatus*	*Lythrum salicaria*	*Linaria dalmatica*	*Linaria vulgaris*	*Verbascum blattaria*	*Centaure a diffusa*	*Elaeagnus angustifolia*	Any listed weed
1	40	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	5.0	100.0
2	24	0.0	0.0	16.7	0.0	0.0	0.0	0.	20.8	0.0	83.3
3	39	20.5	0.0	0.0	0.0	0.0	0.0	2.	7.7	7.7	100.0
4	62	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	1.6	93.5
5	49	2.0	8.2	0.0	0.0	0.0	0.0	0.	0.0	0.0	91.8
6	57	0.0	5.3	0.0	0.0	0.0	0.0	1.	0.0	0.0	93.0
7	43	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	0.0	97.7
8	50	0.0	0.0	0.0	4.0	4.0	6.0	0.	2.0	0.0	98.0
9	65	0.0	0.0	12.3	9.2	0.0	0.0	0.	0.0	0.0	86.2
10	21	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	0.0	100.0
15	25	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	0.0	70.5
11	112	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	0.0	91.5
12	47	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	1.6	86.9
13	61	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	1.2	57.6
14	85	0.0	0.0	0.0	0.0	0.0	0.0	0.	0.0	0.0	100.0
Sum		**1.5**	**0.9**	**1.9**	**0.9**	**0.3**	**0.4**	**0.**	**2.0**	**1.1**	**90.0**

Table 7 (continued). Proportion of plots with listed weed present.

Fate of trees: 2013 flood to summer 2015	Acres: Still Alive	Acres: Died in interval	Percent dead
River			
Poudre	2414.40	137.61	5.39
Big Thompson	405.58	31.16	7.13
St. Vrain	402.56	48.97	10.84
South Platte upriver from the St. Vrain	778.58	38.24	4.68
South Platte between St. Vrain and Big Thompson	446.50	26.21	5.55
South Platte between the Big Thompson and the Poudre	477.27	26.11	5.19
South Platte East of Poudre	12217.52	1284.71	9.51

Table 8: Tree mortality 2013 – 2105.

Reach #	Reach Area	Vegetation	Trees	Russian olive	Cottonwood	Others	Non-vegetation
4	1648	252	257	8	175	74	1138
5	3350	400	471	16	354	101	2479
6	18544	3449	3897	474	2574	849	11198
7	13422	3002	3136	527	1997	611	7284
8	1941	413	515	19	330	165	1013
9	4995	1100	1326	71	807	448	2570
10	3350	394	616	40	439	137	2339
11	23906	5858	5667	490	3166	2011	12381
Total	71156	14868	15885	1645	9842	4396	40402

Table 9: Results (in acres) for vegetation and tree species classification.

Table 10: parameters of the linear regression model

Coeff	Estimae	Std. error	t value	P vale
Intercept	16.5743	6.3979	2.591	0.01034
Ht_P90	0.8008	0.1626	4.925	1.85e-06
all_cover_above_2m	-1.5964	0.6690	-2.386	0.01802
all_1st_cover_above_2m	1.6313	0.5114	3.19	0.00167
all_cover_above_mean	2.142	0.9044	2.368	0.01888
all_cover_above_mode	-0.4795	0.1647	-2.911	0.00404
all_1st_cover_above_mean	-1.7897	0.6929	-2.583	0.01056

Appendix 2

Senate Bill 14-195
Cost Estimate Summary

PREPARED BY TAMARISK COALITION
OCTOBER 13, 2016

BACKGROUND

Tamarisk Coalition (TC), in collaboration with Colorado State University (CSU), was tasked by Colorado Water Conservation Board (CWCB) to develop cost estimates for the restoration of riparian areas impacted by invasive phreatophytes and their associated secondary weed species in the South Platte Basin. This work, which was completed under Purchase Order PDAA7000 with the State of Colorado – Department of Natural Resources, was predicated by the passage of Senate Bill 14-195 (SB195) which appropriated funds to: 1) study the effects of the 2013 flood on phreatophytes and 2) develop a cost analysis for the removal of unwanted phreatophytes along the South Platte River.

To address the first objective, CSU surveyed 20 sites along the South Platte River for native and non-native phreatophytes and Colorado State-listed noxious weed species. These data were then used by CSU to generate a GIS-based map to predict the probability of native and non-native phreatophytes presence and abundance along the entire length of the river in the study area. The GIS-based phreatophyte data was developed by river reach, for a total of 11 reaches. CSU is also currently utilizing the additional noxious weed species site data collected to generate predictions of noxious weed presence along the river in the study area. A complete report on these data is being prepared by CSU.

Utilizing CSU's GIS-based phreatophyte data, TC employed a "Cost Calculator" to determine approximate restoration costs for control and restoration work associated with the treatment of invasive phreatophytes. TC examined the cost of: 1) controlling 100% of all Russian olive (*Elaeagnus angustifolia*) infestations on each river reach, and 2) selectively thinning 20% of all trees from each river reach, including and prioritizing 100% of all Russian olive present. The methodologies and results from this work are described below.

METHODS

TC developed a Cost Calculator to provide planners and managers with an estimate of expenses likely to be accrued during the management of invasive phreatophytes (example provided as Appendix A with working Excel version attached). While initial phreatophyte removal work is often thought of as the main project expense, costs for secondary weed control (herbaceous noxious weeds that may establish as a secondary invasion once woody phreatophytes are removed), phreatophyte resprout treatment, biomass reduction, revegetation, monitoring, and maintenance must also be considered to ensure appropriate funding and staffing resources for successful long-term management.

The Cost Calculator utilizes average canopy cover and total site acreage to determine an approximate project cost based on site specific recommendations, including: type of control, method of biomass reduction, specific amount of secondary weed control based on present densities, amount and type of grass seeding, and amount and type of shrub and tree plantings. Control and biomass reduction costs were developed by TC based on its local and regional experience with a variety of techniques and contractors. Revegetation costs for seeding were based on current market prices, provided by Pawnee Buttes Seed, Greeley, Colorado, while shrub plantings were based on costs provided by Los Lunas Plant Materials Center, Los Lunas, New Mexico. A complete list of cost inputs is provided in the Cost Input tab on the attached Cost Calculator Excel document.

Please refer to *Methods for Tamarisk Control, Biomass Reduction and Revegetation* (Tamarisk Coalition 2016) for additional information on various removal and restoration techniques, including the applicability of each methodology.

COST CALCULATOR USAGE

The following list defines the assumptions, appropriate uses, and limitations of TC's Cost Calculator. While every effort was made to ensure accuracy and relevancy of the tool, given the nature of resource management, it is impossible to account for all possible variables one may encounter while planning and/or implementing a project.

- Control costs are for actual on-the-ground work; they do not include any pre-planning or site visit costs. Control costs reflect average contractor charges to manage and perform the work; they include contractor profit.
- Remote settings may incur additional costs not reflected in these estimates for mobilization, demobilization, employee housing/per diem, and time to access remote sites (e.g., backpacking, horseback, or rafting into a site).
- Site-specific conditions that may add costs, such as grazing exclusion, traffic control and permitting, are not included in these estimates.
- Equipment is assumed to be appropriately sized to meet the conditions encountered (e.g., for mechanical mulching equipment horsepower and cutting head size are appropriate for density and/or trunk diameter).
- Each area that experiences control will require post-control monitoring and assessment to determine the degree to which revegetation will be required. Adaptive management is thus a key ingredient to successful restoration efforts.
- Herbaceous secondary weed management costs were based on the costs to treat Russian knapweed (*Acroptilon repens*), which can be a common secondary weed associated with phreatophyte removal. Cost estimates include three seasons of herbicide application to reduce Russian knapweed and any other major secondary weed infestation to less than 15% cover.

- The use of mechanical equipment, because of mobilization and demobilization costs, generally requires more sizable and contiguous infestations to warrant their use.

- The use of a combination of techniques for any one site will provide the best results for the least cost and should be chosen based on professional judgment.

- Other factors that may impact costs are land management desires such as using a site for training, education, and/or research - all of which can increase costs. Also, some landowners may restrict the use of vehicular access across their property to access public land; thus, adding to the overall costs.

SOUTH PLATTE TREATMENT SCENARIOS

Based on the goals of this project, TC performed two analyses to determine approximate treatment costs by river reach. In the first analysis, TC examined the cost of removing 100% of the Russian olive present within each of the river reaches. In the second analysis, TC determined the cost of treating a total of 20% of all trees within each reach, including removal of 100% of the Russian olive (Table 1). In preplanning discussions a 20% tree removal objective was selected to use as an example for costs.

Since the total percentage of Russian olive did not exceed 20% along any of the reaches, the 20% removal target can include selective thinning of other trees, including invasives such as tamarisk (*Tamarix* spp.) and Siberian elm (*Ulmus pumila*), and, in some instances, native phreatophytes that may be potentially considered too dense for site management objectives.

As the data provided by CSU grouped all trees, aside from Russian olive and cottonwood (*Populus* spp.), the 20% total tree removal target did not differentiate between other invasives and native phreatophytes. Furthermore, as the Cost Calculator was originally developed to determine costs for invasive tamarisk and Russian olive removal, not natives, the calculations for 20% total tree removal were solely based on treatment costs for Russian olive. While this does not change the cost for removal, it may slightly increase revegetation costs.

A total of five different management scenarios were examined for both analyses to provide a range of cost estimates for each reach (Table 1). In all scenarios, the recommended phreatophyte removal method was 90% mechanical removal, with 10% hand removal for areas difficult to access with equipment. Additional treatment and revegetation methods were then added on to this base cost, as described in the table.

Table 1: Cost Estimate Scenarios

	Scenarios					
Analysis	**1**	**2**	**3**	**4**	**5**	**Maintenance**
	Phreatophytes - 90% Mechanical Removal with 10% Hand Removal					
#1 – 100% Russian olive removal (RO)	Removal only	w/50% Weed Control	w/25% Weed Control	w/25% Weed Control & Seeding	w/25% Weed Control & Seeding & Shrub Planting	Resprout control & revegetation 30%

#2 – 20% Total tree removal, including RO	Removal only	w/50% Weed Control	w/25% Weed Control	w/25% Weed Control & Seeding	w/25% Weed Control & Seeding & Shrub Planting	Resprout control & revegetation 25%

ASSUMPTIONS & CONSIDERATIONS FOR SOUTH PLATTE TREATMENT SITES:

While the Cost Calculator can return myriad permutations, TC standardized the variables used for each analysis based on the assumptions and considerations outlined below. For those interested in more fine-tuned estimates, the complete Cost Calculator is provided for use by interested parties; all variables can be altered based on specific site needs.

- Access & Treatment Recommendations
  - Access to the various river reaches will not be an impediment (e.g. sites are not remote or located in difficult terrain), nor will the site contain large areas that are difficult to navigate with equipment.
  - Due to the assumed ease of access, phreatophyte mechanical control is suggested as the primary control methodology (90%), with limited hand control (10%)
- Canopy Cover
  - For 100% Russian olive removal, canopy cover for Russian olive was listed at 100%, based on the number of impacted acres across the reach (e.g. if Russian olive was present on 10 acres, the average canopy cover was listed at 100% and the total site was entered at 10 acres).
  - For 20% total tree removal, canopy cover was listed at 20% and the total number of impacted acres was based on the “trees” acreage provided by CSU (e.g. if the total number of acres listed as trees for the reach was 100, 20% was used as the average canopy cover and the total site was listed at 100 acres).
    - Tree canopy cover was stated as Russian olive in the Cost Calculator to ensure consistency
  - While tamarisk canopy cover is listed as a data input option in the Cost Calculator, it was not utilized for any computation due to the vegetation data being grouped.
- Secondary Noxious Weeds
  - As State-listed noxious weed species were present within each of the river reaches examined, treatment of these species was included for various scenarios.

- Site specific data were not used in the calculations due to the limitations of the Cost Calculator; rather, the scenarios were run at 0%, 25%, and 50% for percent area infested with secondary weeds.

- Maintenance Costs
  - Costs for phreatophyte resprout control and revegetation establishment were included.
    - For 100% Russian olive control, maintenance costs were determined at 30%
    - For 20% tree control, maintenance costs were determined at 25%

- Revegetation
  - Some sites, especially those with a high percentage of invasives, may require additional seeding and/or planting of shrubs to reach site objectives.
    - The number of shrubs recommended for planting in the Cost Calculator were based on replacing each Russian olive removed (assuming approximately 90 Russian olive per acre) with two riparian shrubs or one upland shrub to provide superior cover, habitat, and food resources.
    - In order to account for plant survival, an 85% success rate was utilized.
  - Tree plantings were not recommended based on the expressed desire by some managers to reduce the amount of phreatophytes, invasive or native, currently present in these reaches post-flood.
  - A suite of South Platte specific species for seeding was developed by Pawnee Butte Seeds in Greeley, Colorado (see Appendix B).
    - While Pawnee Buttes provided costs for both drill and broadcast seeding, all costs were determined in the Cost Calculator using the broadcast rates.
      - Half of the site was estimated using an upland grass mix, while the other half was estimated using a riparian grass mix.
  - CWCB recently developed an Access database that should be of use in planning for revegetation needs. A link is provided on CWCB's website.

RESULTS

The following table provides the cost estimate for the scenarios described above. For 100% Russian olive removal, costs range from an average of $320,317 for removal only to $1,474,131 for removal with weed control, seeding and shrub planting; total costs for all reaches range from $3,523,485 for removal only to $16,215,443 for removal with weed control, seeding and shrub planting.

For 20% total tree removal, costs range from an average of $9,577,697 for removal only to $4,138,622 for removal with weed control, seeding and shrub planting; total costs for all reaches range from $9,577,697 for removal only to $45,524,846 for removal with weed control, seeding and shrub planting.

Table 2: Cost Estimates Based on Treatment Scenarios

Treatment	Reach	Acres Russian Olive	90% Mechanical Treatment and 10% Hand Removal				
			Removal Only	Removal w/50% Weed Control	Removal w/25% Weed Control	Removal w/25% Weed Control & Seeding	Removal w/25% Weed Control & Seeding & Shrub Planting
100% RO removal	**1**	19	$39,992	$44,932	$42,462	$54,961	$184,636
	2	3	$6,314	$7,094	$6,704	$8,579	$29,054
	3	8	$16,839	$18,919	$17,879	$22,878	$77,478
	4	16	$33,677	$37,837	$35,757	$45,756	$154,956
	5	474	$997,689	$1,120,929	$1,059,309	$1,355,535	$4,590,585
	6	527	$1,109,245	$1,246,265	$1,177,755	$1,507,728	$5,104,503
	7	19	$39,992	$44,932	$42,462	$54,961	$184,636
	8	71	$149,443	$167,903	$158,673	$203,669	$688,244
	9	40	$84,193	$94,593	$89,393	$114,391	$387,391
	10	490	$1,031,367	$1,158,767	$1,095,067	$1,401,292	$4,745,542
	11	7	$14,734	$16,554	$15,644	$20,643	$68,418
TOTAL All REACHES			**$3,523,485**	**$3,958,725**	**$3,741,105**	**$4,790,393**	**$16,215,443**
AVERAGE ALL REACHES			**$320,317**	**$359,884**	**$340,100**	**$435,490**	**$1,474,131**

Table 2 Continued: Cost Estimates Based on Treatment Scenarios							
Treatment	Reach	Acres Total Trees	90% Mechanical Treatment and 10% Hand Removal				
			Removal Only	Removal w/50% Weed Control	Removal w/25% Weed Control	Removal w/25% Weed Control & Seeding	Removal w/25% Weed Control & Seeding & Shrub Planting
20% Total Tree Removal	1	1095	$594,777	$868,527	$731,652	$1,390,252	$2,827,439
	2	37	$20,097	$29,347	$24,722	$47,557	$96,120
	3	257	$139,596	$203,846	$171,721	$326,756	$664,069
	4	471	$255,835	$373,585	$314,710	$598,341	$1,216,529
	5	3897	$2,116,753	$3,091,003	$2,603,878	$4,946,235	$10,061,047
	6	3136	$1,771,533	$2,586,983	$2,179,213	$4,139,053	$8,419,693
	7	515	$279,735	$408,485	$344,110	$654,181	$1,330,118
	8	1326	$749,060	$1,093,820	$921,440	$1,750,122	$3,560,112
	9	616	$347,980	$508,140	$428,060	$813,028	$1,653,868
	10	5667	$3,201,300	$4,674,720	$3,938,010	$7,480,221	$15,215,676
	11	186	$101,031	$147,531	$124,281	$236,050	$480,175
TOTAL All REACHES			$9,577,697	$13,985,987	$11,781,797	$22,381,796	$45,524,846
AVERAGE ALL REACHES			$870,700	$1,271,453	$1,071,072	$2,034,709	$4,138,622

Cost Calculator Example

Tamarisk Coalition Cost Calculator (South Platte Version)

Site Name:		
Average Tamarisk Canopy Cover (%)	0%	
Average Russian Olive Canopy Cover (%)	0%	
Total Site Acreage	0.0	

	Technologies for Control & Biomass Reduction	Percentage of Each Technology Recommended	Restoration Costs
Control & Biomass Reduction	T Hand control	0%	$0
	T Mechanical mulching control	0%	$0
	T Biological control	0%	$0
	Hand control	0%	$0
	Mechanical mulching control	0%	$0
	Secondary weed control - Percent area infested	0%	$0
	Subtotal Control & Biomass Reduction Costs for Site =		$0
	Maintenance: Resprout control	0%	$0
	Control & Biomass Reduction Costs for Site =		***$0***

	Technologies for Revegetation		Unit	Restoration Costs
Revegetation	Upland (averaged sandy and loamy) grass mix (broadc	0	acres	$0
	Upland (averaged sandy and loamy) grass mix (drill)	0	acres	$0
	Upland alkali grass mix (broadcast)	0	acres	$0
	Upland alkali grass mix (drill)	0	acres	$0
	Riparian grass mix (broadcast)	0	acres	$0
	Riparian grass mix (drill)	0	acres	$0
	Riparian shrubs	0	plants	$0
	Subtotal Revegetation Costs for Site =			$0
	Maintenance: Revegetation establishment	0%		$0
	Revegetation Costs for Site =			***$0***

Total Control, Biomass Reduction, & Revegetation Costs =	**$0**

Suggested Seeding Species by Habitat Type

Species	South Platte River				St. Vrain, Big & Little Thompson	
	Wetland/ Riparian	Upland Sandy	Upland Loamy	Upland Alkali	<5400'	>5400'
Alkali Bulrush	X					
Alkali Sacaton				X		
Alkaligrass				X		
Arizona Fescue						X
Baltic Rush	X					
Big Bluestem	X	X			X	
Blue Grama			X	X		X
Bottlebrush Squireltail				X		X
Buffalograss			X			
Canada Wildrye					X	
Galleta Grass				X		
Green Needlegrass						X
Indian Ricegrass		X				
Indiangrass	X					
Inland Saltgrass				X		
Lens Sedge	X					
Little Bluestem		X			X	X
Meadow Sedge	X					
Olney's Three Square Bulrush	X					
Popcorn Sedge	X					
Prairie Cordgrass	X					
Prairie Junegrass						X
Prairie Sandreed		X			X	
Sand Bluestem		X			X	
Sand Dropseed		X	X			
Sideoats Grama		X	X		X	
Softstem Bulrush	X					
Switchgrass		X			X	
Thickspike Wheatgrass					X	X
Three Square Bulrush	X					
Wedgeleaf Duck Potato	X					
Western Wheatgrass		X	X	X	X	X
Wolly Sedge	X					
Yellow Indiangrass		X			X	

Appendix 3

Tamarisk Coalition - Riparian Restoration Cost Calculator

The following information defines the assumptions, appropriate uses, and limitations of the cost estimates for tamarisk and Russian olive (TRO) control, biomass removal, revegetation, secondary weed control, and short and long-term monitoring and maintenance based on the Colorado River through the Grand Valley, Colorado:

1. Costs for tamarisk and Russian olive (TRO) control are for actual on-the-ground work, they do not include any pre-planning or site visit costs. These cost estimates reflect average contractor costs to manage and perform the work and includes contractor profit.
2. Remote settings may incur additional costs not reflected in these estimates for mobilization, demobilization, employee housing/per diem, and time to access remote sites (e.g., backpacking, horseback, or rafting into a site).
3. Site-specific conditions that may add costs are not included in these estimates. Examples include fencing for grazing exclusions and highway safety requirements when working adjacent to roadways.
4. Equipment is assumed to be sized to meet the conditions encountered; i.e., for mechanical mulching equipment horsepower and cutting head size are appropriate for density and/or trunk diameter of tamarisk encountered.
5. Each area that experiences tamarisk control will require post-control monitoring and assessment to determine the degree to which revegetation will be required. Adaptive management is thus a key ingredient to successful restoration efforts. In other areas it may be important to do more extensive revegetation which will increase costs above those estimated such as high public use areas.
6. Herbaceous weed management is centered on Russian knapweed since it represents the predominant secondary weed issue. Cost estimates include three seasons of herbicide application to reduce this and any other major secondary weed infestation to less than 15 percent cover.
7. The use of mechanical equipment, because of mobilization and demobilization costs, generally requires more sizable and contiguous tamarisk infestations to warrant their use.
8. The use of a combination of techniques for any one site will provide the best results for the least cost and should be chosen based on professional judgment. For example, a site that is suitable for mechanical equipment with some hand work, but is controlled only by hand methods will be effective at tamarisk control but extremely cost inefficient.
9. Other factors that may affect costs are land management desires such as using a site for training, education, and/or research all of which can increase costs. Also, some landowners may restrict the use of vehicular access across their property to access public land; thus, adding to the overall costs.

For more information, contact Tamarisk Coalition at 970.256.7400

Tamarisk Coalition
Restore. Connect. Innovate.

Tamarisk Coalition Cost Calculator (South Platte Version)

Site Name:		
Average Tamarisk Canopy Cover (%)	0%	
Average Russian Olive Canopy Cover (%)	0%	
Total Site Acreage	0.0	

	Technologies for Control & Biomass Reduction	Percentage of Each Technology Recommended	Restoration Costs
Control & Biomass Reduction	T Hand control	0%	$0
	T Mechanical mulching control	0%	$0
	T Biological control	0%	$0
	Hand control	0%	$0
	Mechanical mulching control	0%	$0
	Secondary weed control - Percent area infested	0%	$0
	Subtotal Control & Biomass Reduction Costs for Site =		$0
	Maintenance: Resprout control	0%	$0
	Control & Biomass Reduction Costs for Site =		***$0***

	Technologies for Revegetation	Unit	Restoration Costs
Revegetation	Upland (averaged sandy and loamy) grass mix (broadcast)	0 acres	$0
	Upland (averaged sandy and loamy) grass mix (drill)	0 acres	$0
	Upland alkali grass mix (broadcast)	0 acres	$0
	Upland alkali grass mix (drill)	0 acres	$0
	Riparian grass mix (broadcast)	0 acres	$0
	Riparian grass mix (drill)	0 acres	$0
	Riparian shrubs	0 plants	$0
	Subtotal Revegetation Costs for Site =		$0
	Maintenance: Revegetation establishment	0%	$0
	Revegetation Costs for Site =		***$0***

Total Control, Biomass Reduction, & Revegetation Costs =	**$0**

Notes: Fill in Green boxes

Canopy cover is the percent of the total area that is covered by tamarisk or Russian olive canopy

Should add up to 100% unless no tamarisk is present on the site

Should add up to 100% unless no Russian olive is present on the site

Enter the percent of area infested by any secondary weed

20%) are estimated at **20%** of the control costs, moderate infestations (21-50%) are estimated at **25%**, while heavy infestations (51-100%) are estimated at **30%**.

See seed list for species that are included in this estimate.

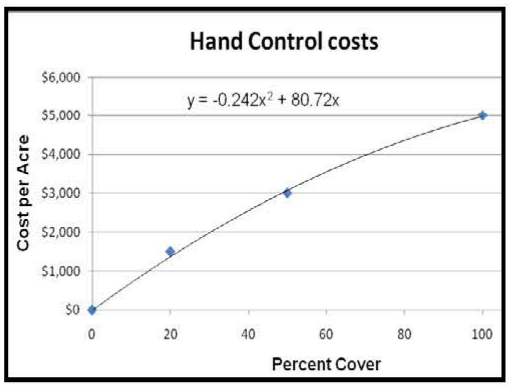
See seed list for species that are included in this estimate.

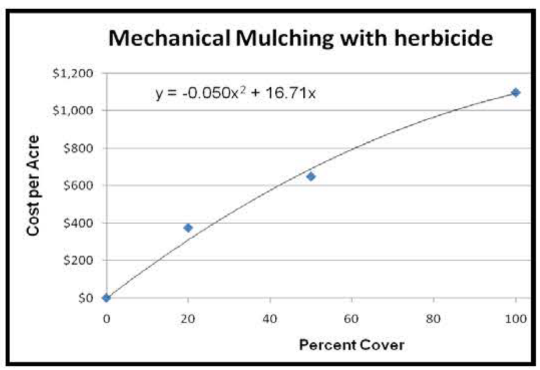
See seed list for recommended species

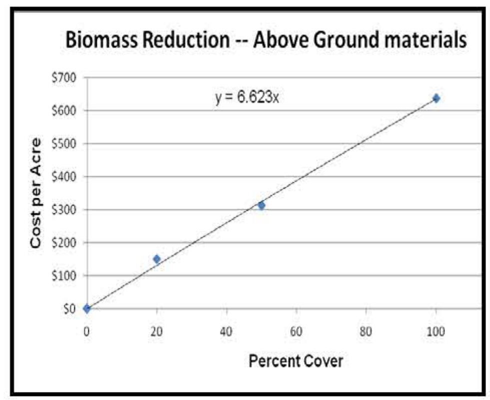
Calculates based on total site acres and canopy cover of tamarisk and Russian olive. Zero out if not planning on planting shrubs. Based on replacing 1 acre of solid Russian olive with 175 plants and 1 acre of tamarisk with 87.5 plants due to their different habitat values.

infestations (0-20%) are estimated at **20%** of the revegetation costs, moderate infestations (21-50%) are estimated at **25%**, while heavy infestations (51-100%) are estimated at **30%**.

Description of Cost	Cost($)/Unit	Unit	Notes
Hand Control	$y = -0.242x^2 + 80.72x$	x (% cover), y = cost/acre	Based on the cost curve developed by Tamarisk Coalition (see curve below)
Mechanical Mulching Control	$y = -0.050x^2 + 16.71x$	x (% cover), y = cost/acre	Based on the cost curve developed by Tamarisk Coalition (see curve below)
Biological Control	110	Acre	Identification of tamarisk leaf beetle establishment and dispersal
TRO Biomass reduction of hand controlled work by mulching	$y = 6.623x$	x (% cover), y = cost/acre	Based on the cost curve developed by Tamarisk Coalition (see curve below)
TRO Biomass reduction of hand controlled work by fire	150	Acre	Cost of burning TRO biomass
TRO Biomass reduction of hand controlled work by natural decomposition	0	Acre	Cost of stacking biomass in piles for wildlife habitat and natural decomposition is included in the hand cutting cost curve
Secondary weed control	400	Acre	This cost will cover herbicide application over three separate seasons and is based on recent work performed in western Colorado
Upland (averaged sandy and loamy) grass mix (broadcast)	131.46	Acre	
Upland (averaged sandy and loamy) grass mix (drill)	65.73	Acre	
Upland alkali grass mix (broadcast)	205.13	Acre	
Upland alkali grass mix (drill)	102.56	Acre	Costs of grass seeding are based on conversations with a grass seed company.
Riparian grass mix (broadcast)	700	Acre	Recommended species are provided in a separate table.
Riparian grass mix (drill)	350	Acre	
Labor for broadcast seeding	65	Acre	
Labor for drill seeding	65	Acre	
Riparian shrub, upland shrub and tree species	20	Plant	Costs of shrub and tree plantings are based on talking with Los Lunas Plant
Labor for planting riparian shrubs, upland shrubs and tree species	10	Plant	Materials Center and other contractors







Appendix 4

NOTE: The governor signed this measure on 6/6/2014.

An Act

SENATE BILL 14-195

BY SENATOR(S) Nicholson and Renfroe,;
also REPRESENTATIVE(S) Singer and Sonnenberg, DelGrosso, Foote, Humphrey, Young, Becker, Conti, Coram, Court, Fields, Gardner, Gerou, Ginal, Holbert, Kagan, Labuda, Landgraf, Lawrence, Lee, May, Melton, Murray, Pettersen, Primavera, Priola, Rosenthal, Saine, Salazar, Schafer, Scott, Stephens, Swalm, Vigil.

CONCERNING A STUDY OF PHREATOPHYTE GROWTH ALONG THE SOUTH PLATTE RIVER IN THE AFTERMATH OF THE SEPTEMBER 2013 FLOOD.

Be it enacted by the General Assembly of the State of Colorado:

SECTION 1. In Colorado Revised Statutes, 37-60-115, **add** (9) as follows:

37-60-115. Water studies - rules - repeal. (9) (a) THE BOARD SHALL CONDUCT AT LEAST THE PRELIMINARY STAGES OF A COMPREHENSIVE STUDY TO EVALUATE THE GROWTH AND IDENTIFICATION OF PHREATOPHYTES ALONG THE SOUTH PLATTE RIVER IN THE AFTERMATH OF THE SEPTEMBER 2013 FLOOD. IF APPROPRIATE, THE BOARD SHALL CONDUCT ALL STAGES OF THE STUDY. THE OBJECTIVES OF THE STUDY ARE:

(I) TO EVALUATE A PORTION OF THE WATERSHED ALONG THE SOUTH

Capital letters indicate new material added to existing statutes; dashes through words indicate deletions from existing statutes and such material not part of act.

PLATTE RIVER THAT WAS AFFECTED BY THE SEPTEMBER 2013 FLOOD TO DETERMINE THE RELATIONSHIP BETWEEN HIGH GROUNDWATER AND NONBENEFICIAL CONSUMPTIVE USE BY PHREATOPHYTES; AND

(II) UTILIZING THE DATA COMPILED FOR SUBPARAGRAPH (I) OF THIS PARAGRAPH (a), TO DEVELOP A COST ANALYSIS FOR THE REMOVAL OF UNWANTED PHREATOPHYTES ALONG THE SOUTH PLATTE RIVER.

(b) THE BOARD MAY ENTER INTO CONTRACTS WITH COLORADO STATE UNIVERSITY'S BIOAGRICULTURAL SCIENCES AND PEST MANAGEMENT PROGRAM TO CONDUCT, OVERSEE, AND COORDINATE ALL ASPECTS OF THE STUDY AND SHALL COORDINATE WITH THE DEPARTMENT OF AGRICULTURE AND WEED MANAGEMENT SPECIALISTS FROM AFFECTED LOCAL GOVERNMENTS.

(c) THE BOARD SHALL COMMISSION THE STUDY AS SOON AS PRACTICABLE. THE BOARD SHALL PREPARE A FINAL REPORT, INCLUDING ITS CONCLUSIONS, AND PRESENT IT TO THE GENERAL ASSEMBLY NO LATER THAN DECEMBER 31, 2016. THE BOARD SHALL PREPARE A PROGRESS REPORT AND PRESENT IT TO A JOINT MEETING OF THE HOUSE OF REPRESENTATIVES COMMITTEE ON AGRICULTURE, LIVESTOCK, AND NATURAL RESOURCES AND THE SENATE COMMITTEE ON AGRICULTURE, NATURAL RESOURCES, AND ENERGY, OR THEIR SUCCESSOR COMMITTEES, DURING THE SECOND REGULAR SESSION OF THE SEVENTIETH GENERAL ASSEMBLY IN 2016.

(d) THE BOARD IS AUTHORIZED TO ACCEPT AND EXPEND GIFTS, GRANTS, AND DONATIONS FOR THE PURPOSES OF THIS SUBSECTION (9). THE GENERAL ASSEMBLY FINDS THAT THE IMPLEMENTATION OF THIS SUBSECTION (9) IS NOT ENTIRELY DEPENDENT ON THE RECEIPT OF ANY GIFTS, GRANTS, AND DONATIONS. THE BOARD SHALL TRANSMIT ALL MONEYS RECEIVED THROUGH GIFTS, GRANTS, OR DONATIONS TO THE STATE TREASURER, WHO SHALL CREDIT THEM TO THE COLORADO WATER CONSERVATION BOARD CONSTRUCTION FUND CREATED IN SECTION 37-60-121.

(e) THIS SUBSECTION (9) IS REPEALED, EFFECTIVE JULY 1, 2017.

SECTION 2. In Session Laws of Colorado 2012S, section 7 of chapter 1, **amend** (1) as follows:

Section 7. **Phreatophyte control cost-sharing program -**

appropriation. (1) In addition to any other appropriation, there is hereby appropriated, out of any moneys in the Colorado water conservation board construction fund not otherwise appropriated, to the department of natural resources, for allocation to the Colorado water conservation board, for the fiscal year beginning July 1, 2012, the sum of $1,000,000, or so much thereof as may be necessary, for the board to continue financing phreatophyte control cost-sharing grants AND TO EVALUATE THE GROWTH AND IDENTIFICATION OF PHREATOPHYTES ALONG THE SOUTH PLATTE RIVER IN THE AFTERMATH OF THE SEPTEMBER 2013 FLOOD through any of the board's existing programs.

SECTION 3. Safety clause. The general assembly hereby finds, determines, and declares that this act is necessary for the immediate preservation of the public peace, health, and safety.

Morgan Carroll PRESIDENT OF THE SENATE	Mark Ferrandino SPEAKER OF THE HOUSE OF REPRESENTATIVES
Cindi L. Markwell SECRETARY OF THE SENATE	Marilyn Eddins CHIEF CLERK OF THE HOUSE OF REPRESENTATIVES

APPROVED____

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John W. Hickenlooper
GOVERNOR OF THE STATE OF COLORADO