THE GEOMORPHIC EFFECTS OF NATIVE AND INVASIVE RIPARIAN VEGETATION: SPRAGUE RIVER, OREGON

by

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A DISSERTATION

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DISSERTATION ABSTRACT

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Numerous studies have addressed the role of stream geomorphology on vegetation distribution. These studies have shown that channel morphology, including depositional and erosional processes, influence vegetation colonization. However, few studies have addressed the impact of vegetation on the geomorphic processes of streams. Vegetation has the ability to stabilize channel banks and alter stream hydrology and stream power. Little research has addressed the impact of invasive vegetation and its ability to change river channel processes. My research addresses the impact of the highly invasive *Phalaris arundinacea* and quantifies its influence on the stream channel form of the Sprague River, Oregon. I conducted field research that included root density and root strength surveys to determine the below ground influences of vegetation in terms of added bank cohesion provided by the invasive and two similar native species: *Eleocharis palustris* and *Carex vesicaria*. To ascertain differences between the species above ground characteristics and influences, I measured stem density and elasticity to calculate their roughness (Manning's *n)* and determine their potential impact on stream velocity. Finally, I used these vegetation characteristics to model stream velocity, water depth, and bed shear stress within the 2-D model MD-SWMS. Differences in root size were significant with *C. vesicaria* having the largest root diameters, largest root area ratio, and largest bank cohesion provided by roots. This was followed by the invasive and then *E. palustris.* *E. palustris* had the highest stem density, followed by *C. vesicaria* and *P. arundinacea.* The invasive had the highest stem stiffness. *E. palustris* was associated with the highest roughness value, closely followed by the invasive and *C. vesicaria.* Using modeling I found the presence of the invasive increased velocity compared to *E. palustris* and increased bed shear stress compared to *C. vesicaria.* Therefore, changes in species composition, such as a shift from either of the natives to the invasive, could affect channel morphology over time. By comparing the impact of this invasive to that of native grasses and sedges, this research provides insight into how further spread of the invasive may affect the Sprague River and other riparian ecotones.

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and

Kevin, my Samwise Gamgee. You are a hero to me.

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CHAPTER I

INTRODUCTION

Invasive species can cause major shifts in ecosystem dynamics, outcompete native species, and possibly produce other changes not recognized at present. With stream restoration efforts increasing across the United States, it is imperative that we understand the impact of invasive species. If an invasive species cannot be eliminated, for example, it may be impossible to restore a stream to its historical condition or even to reestablish some ecosystem functions. This doctoral research documents the impact of the invasive species *Phalaris arundinacea* (reed canarygrass) on the geomorphology of the low-energy, meandering Sprague River in eastern Oregon. Until recently, little research has focused on analyzing the influences of small, flexible vegetation on the geomorphic processes of fluvial systems. This project identifies and evaluates the vegetative and geomorphic processes taking place on the Sprague River. I use biogeomorphic techniques to answer three research questions (1) How does the stream bank stability provided by *P. arundinacea* compare to that provided by native vegetation *Eleocharis palustris* (creeping spikerush) and *Carex vesicaria* (inflated sedge)? (2) How does *P. arundinacea* impact stream velocity and deposition and does this differ from native vegetation? and (3) What is the potential impact of *P. arundinacea* on channel morphology? With restoration along the Sprague River underway and further projects planned, results from this study can affect how the invasive is addressed in these projects. In addition, with the pending removal of four Klamath dams downstream of the Sprague

River, historical salmon spawning habitat may return and the geomorphology and habitat characteristics of the stream are of extreme importance.

In Chapter II I examine the below-ground influences of the invasive and native vegetation. Understanding of the role invasive species play in geomorphic processes is important because riparian vegetation provides added bank stability and cohesion through its root matrix. Here I examine the geomorphic effect of *P. arundinacea* along the Sprague River, Oregon, and compare its effect with two species it is outcompeting in the area: *E palustris* and *C. vesicaria*. Root distribution values and root tensile strengths were used to determine the role *P. arundinacea* plays in bank cohesion and stability via two methods: the traditional Wu et al. (1979) method and the fiber bundle model RipRoot (Pollen and Simon, 2005). Root size distribution analyses show the invasive plant has a large amount of small diameter roots. Tensile strength values for all three species decrease with increasing root diameter, which is consistent with previous studies. In addition, the Wu et al. (1979) method overestimates cohesion when compared to RipRoot for the three species. Modeled cohesion is greatest for *C. vesicaria* and therefore this species provides higher levels of bank stability and resistance to erosion compared to the invasive. In addition, the invasive provides greater bank cohesion when compared to *E. palustris.*

In Chapter III I examine the above-ground influences of riparian vegetation along the Sprague River. Quantifying roughness in terms of riparian vegetation has largely been ignored or listed as a secondary characteristic on roughness reference tables. In methods used to calculate roughness mathematically, the added component of vegetation roughness is lacking. However, in instances where vegetation plays a dominant role in the riparian landscape and forms an important mechanism to reduce water velocity at high flows, its roughness is critical. I calculated vegetation roughness based on measurements of plant stem elasticity, plant frontal area, stem density and stem area of three dominant herbaceous plants along the Sprague River, Oregon: the invasive *P. arundinacea,* and natives *E. palustris,* and *C. vesicaria*. Results show slightly lower roughness values than those predicted for vegetation using reference tables. In addition, *E. palustris* and *P. arundinacea* exhibit higher and similar roughness values whereas *C. vesicaria* exhibits values lower than the other two species. These findings are of particular importance where the invasive *P. arundinacea* is outcompeting native *C. vesicaria* because with such colonization, roughness is increasing in channel zones and therefore is likely changing channel processes. Direct depositional measurements show similar results within stands of the invasive and *E. palustris.*

In Chapter IV I used the roughness values, stem density and plant height values calculated in Chapter III, as well as topography gathered along the Sprague using LiDAR and bathymetric methods, to model the channel changes associated with the three species of interest. Modeling is accomplished via two methods. First, current conditions are modeled by populating the channel banks with roughness, plant density and height of patches of vegetation mapped out during a raft trip down a representative reach of the Sprague. Next, modeling is carried out along the same reach with future conditions where the banks are populated by only one of the species. Modeling results for the two native species are then compared to results for the invasive to determine differences in water depth, velocity and bed shear stress. Current conditions show that the patches mapped have minimal interaction with the 10- and 25-year recurrence interval flow and further work should be conducted regarding the influence of the placement of vegetation. Idealized condition model runs show that plant density and roughness causes the native *E. palustris* to have the highest impact on stream velocity and bed shear stress. This is of particular importance where the invasive is outcompeting *E. palustris*. Such changes could cause increases in velocity and less stable bank surfaces.

Research of this nature has previously focused on large, woody species such as Tamarix (Graf, 1978). This research is one of the first studies to investigate the influence of a non-woody, but highly invasive vegetation species. Here I demonstrate that the invasive is significantly different in terms of above-ground and below-ground influences when compared to the natives. These differences, according to depositional measurements and modeling, can affect channel processes. With this study, we are only beginning to understand the impact of invasive species on stream geomorphology. To attempt to circumvent the negative impacts of invasive species, we must learn how to control them and reverse the changes already set in motion. This study begins to bridge the gap and discover how invasives may be altering geomorphic processes.

CHAPTER II

ROOT SIZE DISTRIBUTION AND ROOT TENSILE STRENGTH OF INVASIVE AND NATIVE RIPARIAN VEGETATION

1. Introduction

The encroachment of invasive species has become an increasingly apparent problem throughout ecosystems in North America. Invasives are often highly competitive and quickly take advantage of available habitat and resources. For this reason, invasive plant species are very well adapted for rapid dispersal and establishment in locations prone to disturbance (Sher et al. 2000; Tickner et al. 2001). For example, flood disturbances on river systems that remove native vegetation can accelerate the proliferation of competitive invasive vegetation (Cowell and Dyer 2002; Tickner et al. 2001; Sher et al. 2002).

Invasive and native vegetation has the ability to stabilize channel banks and alter stream hydrology, erosion, and deposition. Above ground biomass intercepts rainfall and interrupts streamflow, decreasing stream velocities and thus shear stress (Pollen et al. 2004; Hickin 1984; Corenblit et al. 2007; Bennett et al. 2007). Bank stability is enhanced by the roots of riparian vegetation that directly strengthens bank sediment and thus prevents instances of mass failure (Murray et al. 2008; Tal and Paola 2007). Stability of bank material is, in part, a function of root density distribution, root depth, root diameter and root tensile strength (e.g. Pollen and Simon 2005); other factors include soil moisture, sediment size, and soil cohesion. Roots enhance the tensile strength and elasticity of soils, distributing stresses throughout, allowing for increased shear strength, and creating failure resistant zones (Gran and Paola 2001; Murray et al. 2008; Perucca et al. 2007; Tal et al. 2004). Often, these zones form islands where flow is diverted in other, less resistant directions and thus they alter stream channel dimensions, sinuosity, and other characteristics (Nanson and Knighton 1996). *Tamarisk* was found to decrease channel widths by 27% along the Green River, Utah (Graf 1978) by stabilizing bar and bench surfaces. Pollen and Simon (2005) applied a fiber bundle approach to measure the tensile strength of 12, primarily woody, riparian species. Simon et al. (2006) found that Lemmons willow (*Salix lemmonii*) root reinforcement capabilities were an order of magnitude greater than that of lodgepole pine (*Pinus contorta*) along the Upper Truckee River, California, and therefore decreased the frequency of bank failure and delivery of fine grained sediment.

In addition to bank stability, vegetation provides protection against erosion by fluid forces both through its aboveground biomass and anchoring by roots (Murray et al. 2008; Smith 1976). Along the Alexandra River, Alberta, the roots of plants on vegetated banks were found to enhance erosion resistance up to 20,000 times more than unvegetated banks. This caused a decrease in lateral channel migration (Smith 1976; Nanson and Knighton 1996; Graf 1978). In the Northern Plains of Australia, various grasses were found to provide higher levels of stability and erosion protection than trees and shrubs due to their substantial biomass and continuous root networks (Tooth and Nanson 1999). In addition, De Baets et al. (2007; 2008) found that 6 out of the 7 grasses they tested in gully environments had a “High” to “Very High” erosion reducing potential whereas the majority of shrubs and trees tested in the study ranged from “Very Low” to “High” erosion reducing potential. These studies show that riparian vegetation influences geomorphic processes, and these influences can be different depending on the species colonizing the channel banks.

Understanding the physical effects of invasive species in the riparian zone is important because changes in plant species composition as invasive species colonize riparian areas may result in changes in bank stability and resistance to erosion. Changes in these processes may lead to alterations in channel form and habitat characteristics. Therefore, objectives for this paper are to (1) determine the root characteristics of the invasive (*Phalaris arundinacea)* and two similar native species (*Eleocharis palustris* and *Carex vesicaria)* occupying similar areas along the Sprague River, Oregon and (2) determine the added bank cohesion the invasive and native species provide along the Sprague River using the Wu et al. (1979) method and the Pollen and Simon (2005) fiber bundle model RipRoot.

2. Background

Root structure and architecture have long been recognized to influence bank and slope stability (Greenway 1987; Bethalahmy 1962; Bishop and Stevens 1964; Kaul 1965). Roots are strong in tension and weak in compression while soil is weak in tension and strong in compression. These combined factors allow roots to provide reinforcement within the soil matrix (De Baets et al. 2007; De Baets et al. 2008; Pollen et al. 2004; Simon and Collison 2002; Simon et al. 2006; Greenway 1987). Root strength is a function of root diameter with finer roots exhibiting higher tensile strengths per unit root area than those with larger diameters (De Baets et al. 2008; Gray and Barker 2004; Operstein and Frydman 2000). In addition to root strength, root distribution significantly affects bank and slope stability. Abernethy and Rutherford (2001) found interspecies differences in root distribution to affect bank stability more than interspecies differences in root tensile strength. Several studies have suggested the use of Root Area Ratio (the ratio of root cross sectional area to soil cross sectional area; RAR) to estimate root contribution to soil strength (Abernathy and Rutherford 2001).

Estimations of bank reinforcement consider root cohesion as a factor of soil shear strength and thus incorporate it into the Coulomb equation (Waldron 1977; Wu et al. 1979):

$$S = c + \sigma_N tan\phi \qquad (1)$$

where S is soil shearing resistance (kPa), c is cohesion (kPa), σ_N is normal stress on the shear plane (kPa), and ϕ is soil friction angle (Pollen-Bankhead and Simon 2009). Waldron (1977) and others modified the equation to account for increased shear strength due to roots:

$$S = c + \Delta S + \sigma_N \ tan \ \phi \qquad (2)$$

where ΔS is increased shear strength due to roots (kPa). ΔS can be further estimated by accounting for the tangential component resisting shear and the normal component increasing the confining pressure on the shear plane:

$$\Delta S = T_r \ (sin\theta + cos\theta tan\phi)(\frac{A_R}{A}) \qquad (3)$$

where T_r is average tensile strength of roots per unit area of soil (kPa), θ is the angle of shear distortion in the shear zone, and A_r/A is root area ratio. Work by Gray (1974) and Wu et al. (1979) further simplified this relationship by reporting that the effect of roots on the angle of internal friction is minor and the resulting shear strength due to roots is not sensitive to normal changes in θ and ϕ. Therefore, the equation simplifies to:

$$\Delta S = 1.2T_R(\frac{A_R}{A}) \tag{4}$$

where the added cohesion due to roots is dependent on the size, distribution and strength of roots. This type of model is considered “static” (Pollen and Simon 2005) because it captures root reinforcement for a single moment in time and assumes all roots reach their maximum tensile strength simultaneously (Greenway 1987).

Subsequent studies have found the Wu et al. (1979) model overestimates soil shear strength by up to 91% (Pollen et al. 2004) and the values are often used as maximums (De Baets et al. 2008; Simon and Pollen 2006). More recently, Pollen et al. (2004) developed a fiber bundle model, RipRoot, that adopts the global load sharing (GLS) approach to account for the progressive breakage of roots within the soil matrix (Pollen and Simon 2005; Pollen et al. 2004; Simon and Pollen 2006). As one root breaks, the stress is redistributed to the remaining roots within the soil matrix. In addition, RipRoot accounts for two overlooked mechanisms within soil shearing and root strength, that of root breaking and root pullout. Therefore, recent versions of the RipRoot model now account for root pullout forces, a function of the bond between the roots and soil, and the soil moisture (Pollen-Bankhead and Simon 2009). To demonstrate this empirically, I chose the Sprague River, Oregon, which exhibits large stands of the invasive *P. arundinacea* and other similar native species.

3. Study Site

The Sprague River, a tributary of the Upper Klamath River, (Figure 2.1.) lies at 1270 to 1350 m elevation on the volcanic plateau east of the Cascade Range in southern Oregon. The flow regime is snowmelt dominated with cold, wet winters and mild, dry summers. High flow predominates from February to May and low flows from July to September (Hay et al. 2009; Risley et al. 2005). Precipitation averages approximately 50 cm per year (Loy et al. 2001). The area has shifted to a wetter climate over the last 500 years (likely leading to increases in discharge) with a warming and drying period occurring in the last 150 years (Briles et al. 2008). Historical land uses include irrigated agriculture, cattle grazing, ranching, and timber production (Friedrichsen 1997). Because the growing season is too short for most crops, riparian areas continue to be used mainly for summer pasture. The Sprague River has broad floodplains dominated by herbaceous meadows and wetlands (O'Connor et al. forthcoming 2013). Snowmelt floods regularly inundate parts of the floodplain during late spring. Shrub and tree cover on the floodplain is very low, except in a few narrow valley reaches, which support several willow species and quaking aspen (*Populus tremuloides*). The floodplains are dominated by native herbs, including *Eleocharis palustris* (spikerush), *Mentha sp.* (mint), *Polygonum sp.* (smartweed), *P. arundinacea* (reed canarygrass), *Solidago sp.* (goldenrod), *Epilobium sp.*, and a variety of Juncaceae (rushes), and Cyperaceae (sedges, eg. *Carex vesicaria*) (Rasmussen 2011). The three dominant riparian species typically inundated during high flows are *P. arundinacea*, *E. palustris*, and *C. vesicaria*. *P. arundinacea* and *E. palustris* dominate Site 1 and the invasive and *C. vesicaria* dominate sites 2 and 3 (Figure 2.1). Work regarding the geomorphic influence of vegetation on this river is of particular importance due to the pending removal of four dams on the Klamath River downstream of the Sprague, which would reopen the river to salmon. Therefore, there is particular concern about river channel and habitat characteristics and any future alterations in geomorphic characteristics due to invasive plants.

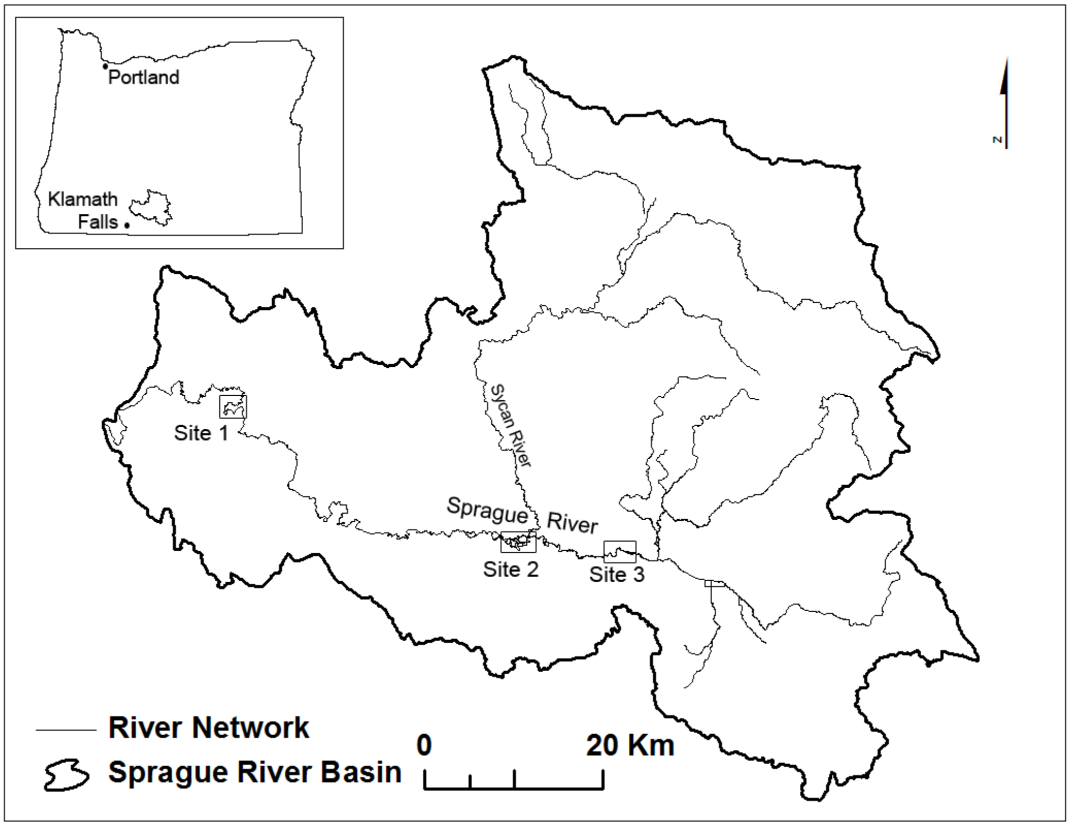

Figure 2.1. Sprague River Basin and three study sites used in this study.

4. Plant Species

4.1. Reed Canarygrass (*Phalaris arundinacea* L.)

P. arundinacea (Figure 2.2a.), recognized as one of the most invasive plants in North American wetlands (Lavoie et al. 2005), is a cool season, sod forming, perennial grass found in wetlands, riparian areas, and prairies throughout North America. *P. arundinacea* was first introduced by Euro-American settlers in the Pacific Northwest for stream channel stabilization, erosion control, wastewater treatment, and forage in 1918 (Anderson 1961; Marten and Heath 1973; Naglich 1994). Reproduction occurs both sexually and through rhizomatous propagation with the rhizomes accounting for over 70% of new shoot growth (Antieau, 2004). In the Sprague River basin, *P. arundinacea* is taller (up to 1.5 m) than the native riparian herbaceous species (0.3 m). *P. arundinacea* invades vegetated areas after significant hydrological alterations (Galatowitsch et al. 1999). It outcompetes native vegetation by having a high tolerance for inundation, reproducing competitively, and developing a thick sod layer from the previous season leaf growth. This sod layer decreases available habitat for native species. Its ability to grow rapidly early in its life cycle and tolerance for anoxic soil conditions also provide an advantage for survival (Antieau 2004; Apfelbaum and Sams 1987; Foster and Wetzel 2005; Kercher and Zedler 2004) and its presence has been correlated with decreases in vegetation species richness (Fierke and Kauffman 2006). Studies have suggested *P. arundinacea* can reduce stream velocity, decrease suspended sediment, and increase sediment deposition (Tourbier and Westmacott 1981). Along the Sprague River, *P. arundinacea* occupies elevations up to 1m vertical from bankfull and up to 5m horizontally away from the bankfull line. Native species *E. palustris* and *C. vesicaria* occupy areas similar to the invasive. All three sites used in this study (Figure 2.1.) contain stands of the invasive species.

4.2. Creeping Spikerush (*Eleocharis palustris* L.)

E. palustris (Figure 2.2b.) occurs in wet meadows, vernal pools, fields, pastures, brackish tidal marshes and shallow water globally (Pojar and MacKinnon 1994). Stems are typically 10-30 cm tall and leaves are primarily basal sheaths. Along the Sprague River, *E. palustris* inhabits areas continually inundated with water but can survive further from the channel in areas not inundated during low flows (Guard 1995; Pojar and MacKinnon 1994). Along the Sprague River, *E. palustris* inhabits elevations up to 0.3m vertically from Bankfull and often immediately along the channel water line. All three sites (Figure 2.1.) contain stands of *E. palustris,* though it is more dominant of the natives at Site 1.

4.3. Inflated Sedge (*Carex vesicaria* L.)

C. vesicaria (Figure 2.2c.) inhabits wetlands, ponds, lake shores, and river margins throughout eastern Oregon and Washington. As is typical of other *Carex* species, it has 1.8-6.5 mm wide leaves extending from the base of the plant and can be up to 60 cm tall. Along the Sprague River, *C. vesicaria* occupies shallow water areas directly adjacent to the channel and is often inundated during low flows. These areas are can be up to 0.3m higher in elevation than the bankfull line and within 1m horizontal from the bankfull line. *P. arundinacea* has been known to outcompete *C. vesicaria* in areas where water table lowering has occurred (Wilson et al. 2008). Sites 2 and 3 (Figure 2.1.) contain stands of *C. vesicaria*.

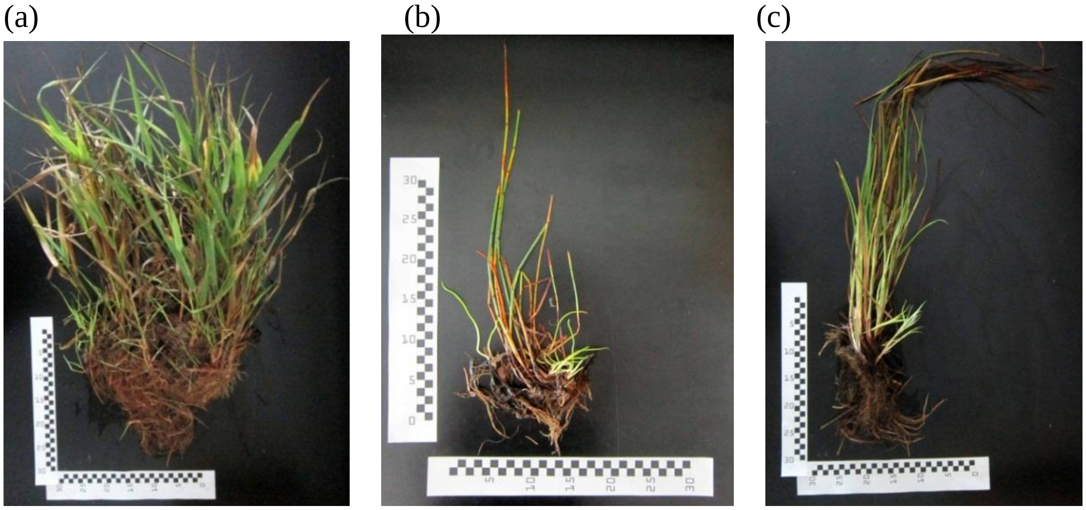

Figure 2.2. Root and stem systems of partial plants (a) *P. arundinacea*, (b) *E. palustris*, and (c) *C. vesicaria*. Squares on the scale are centimeters.

5. Methods

5.1. Root Distribution and Root Area Ratio

Root distribution was assessed at three locations for each species using the wall profile method described in Bohm (1979). In this study, each wall profile (hereafter referred to as a pit) represents the root characteristics of one plant. I selected the sites located along the banks within plant stands likely to be inundated during winter high flows. In addition, sites had to contain plants stands that were dominated by the species of interest with few or no other species present. Three soil pits were dug for each species of interest. Soil pits were dispersed among the three sites based on species dominance and where the team had permission to dig. The three soil pits for each of the *P. arundinacea* and *E. palustris* species were located at Site 1. Two soil pits for C. *vesicaria* were located at Site 2 and one at Site 3. Soil pits measured 0.5 x 0.5 x 0.5 m, which allowed the recording of the location (depth) and size of all roots that intersected the vertical profile wall. Root diameters were measured and recorded according to their distance from the ground surface (depth). Then the root diameter and location for each species at 10cm depth increments were used to calculate RAR, or the ratio between the sum of the cross-sectional area of roots intersecting the profile wall and the area of the profile wall (Abernathy and Rutherford 2001; Gray and Leiser 1982).

Root distribution, strength, and added cohesion due to roots can vary greatly according to moisture content, growing season, root bark characteristics, nutrient availability, and the angle of the root relative to the trench wall (Pollen and Simon 2005; Greenway 1987). For these reasons, sampling was carried out in the riparian environment where I am addressing the stabilizing effects of vegetation. Therefore, moisture and nutrient values should be typical of other riparian locations along the Sprague River. In addition, sampling was conducted during the same period of the season for all plants and pits. Root bark characteristics likely vary by species and not by site or season and care was taken to pull the roots at the angle they were oriented to the pit wall. Therefore sampling is representative of the conditions I am attempting to capture in this study.

5.2. Root Strength

Root strength was measured using the methods outlined in Abernethy and Rutherford (2001) and Pollen and Simon (2005). A 100 lb load cell was attached to a root exposed on the same profile wall of pits previously dug for root distribution surveys. Approximately 30-50 roots per profile wall were tested for each plant depending on the number of available roots and their condition after digging. Individual roots were pulled to their breaking point and the peak force required to break each root was recorded. In addition, the diameter of the root at the breaking point was recorded. I tested 98, 82, and 119 roots for *P. arundinacea, E. palustris,* and *C. vesicaria,* respectively. The peak force required to break each root of known diameter was then used to calculate tensile strength (Bischetti et al. 2005):

$$T_r = \frac{F_{Max}}{\Pi \frac{D^2}{4}} \tag{5}$$

Where F_{max} is the peak force (N) needed to break the root, and D is the root diameter (m) at the breaking point. These values were used to develop power relationships for each species relating root tensile strength to root diameter to input into the model RipRoot.

5.3. Cohesion Due to Roots

Previous studies have observed that root strength per unit area of root decreases with increasing root diameter (e.g., Pollen and Simon 2005). This is due to higher cellulose content in smaller roots making them stronger per unit area than larger roots of the same species (Pollen and Simon 2005; De Baets et al. 2008; Greenway et al. 1984; Wu 1976; Burroughs and Thomas 1977; Bischetti et al. 2005). The relationship takes the form of a power law:

$$T_r = a\, D^{-b} \tag{6}$$

Where T_r is root tensile strength and D is root diameter. The power relationship coefficients for each of the three species, along with root diameter distributions (number and diameter of roots present), and soil type (moderate silt), were input into the model RipRoot (Pollen and Simon 2005; Pollen-Bankhead and Simon 2009) to quantify the added cohesion provided by each species tested.

For comparative purposes, root tensile strength measurements were also used to calculate cohesion using the Wu et al. (1979) method (equation (4)). This method simplifies the tangential component resisting shear and the normal component increasing the confining pressure on the shear plane (equation (3)) and assumes all roots break simultaneously.

6. Results

6.1. Root Distribution and Root Area Ratio

Root size distributions show variability within species (Figure 2.3.), but general trends are apparent. The residuals of the sizes of the three species were not normally

Table 2.1. Roots per pit and root diameter size for three species.

	# Roots/Pit	**Median Root Diameter (mm)**
P. arundinacea Pit 1	292	0.03
P. arundinacea Pit 2	268	0.12
P. arundinacea Pit 3	165	0.1
Average	241.67	0.08
E. palustris Pit 1	127	0.22
E. palustris Pit 2	113	0.11
E. palustris Pit 3	73	0.17
Average	104.33	0.17
C. vesicaria Pit 1	89	0.4
C. vesicaria Pit 2	146	0.49
C. vesicaria Pit 3	333	0.49
Average	189.33	0.46

distributed, therefore I used the Mann-Whitney-Wilcox statistical test to determine whether root sizes were significantly different between species. The three species have significantly different root sizes ($p<0.001$, Table 2.1).

Root Area Ratio distribution with depth for the three species is shown in Figure 2.4. RAR values per soil depth class are average values over the 3 plants for that species. Overall, roots of all three species occupy less than 0.05% of the soil area. As expected, the RAR decreases with depth for each species. *C. vesicaria* has a higher RAR than the other two species. Standard errors for the measurements range from 1.05×10^{-9} to 2.13×10^{-4}. The three species have different RAR values in the upper 0.3m of soil where most root strength lies with little to no overlap among the species, given the standard error. *C. vesicaria* has the highest potential for cohesion based on RAR alone, whereas the invasive and native *E. palustris* have lower RAR.

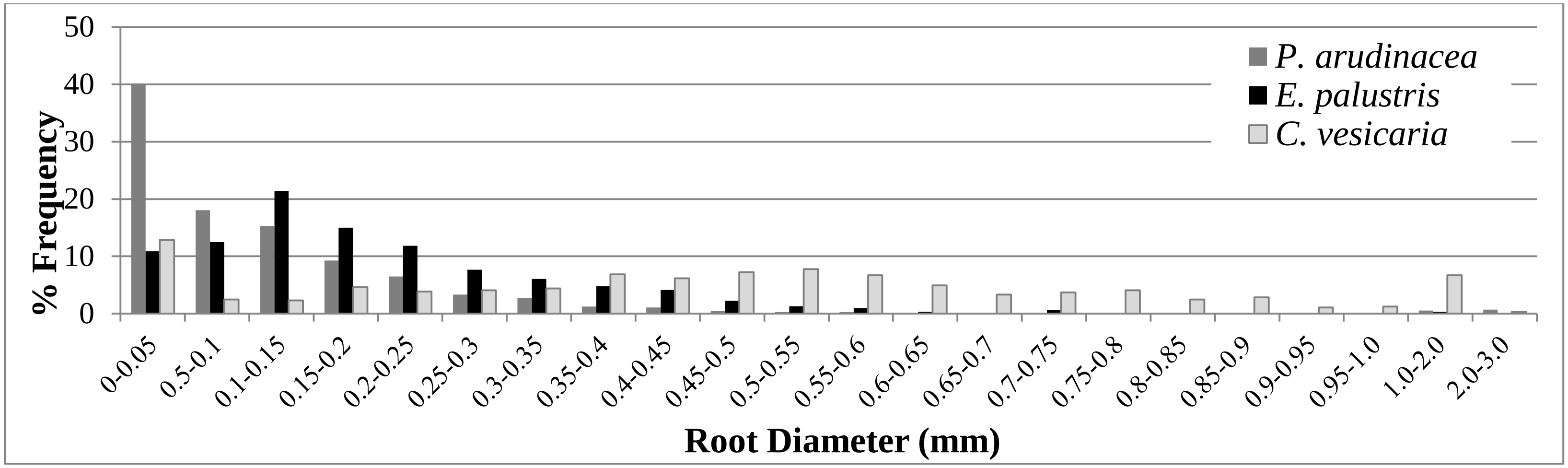

Figure 2.3. Root diameter histogram for three species of interest

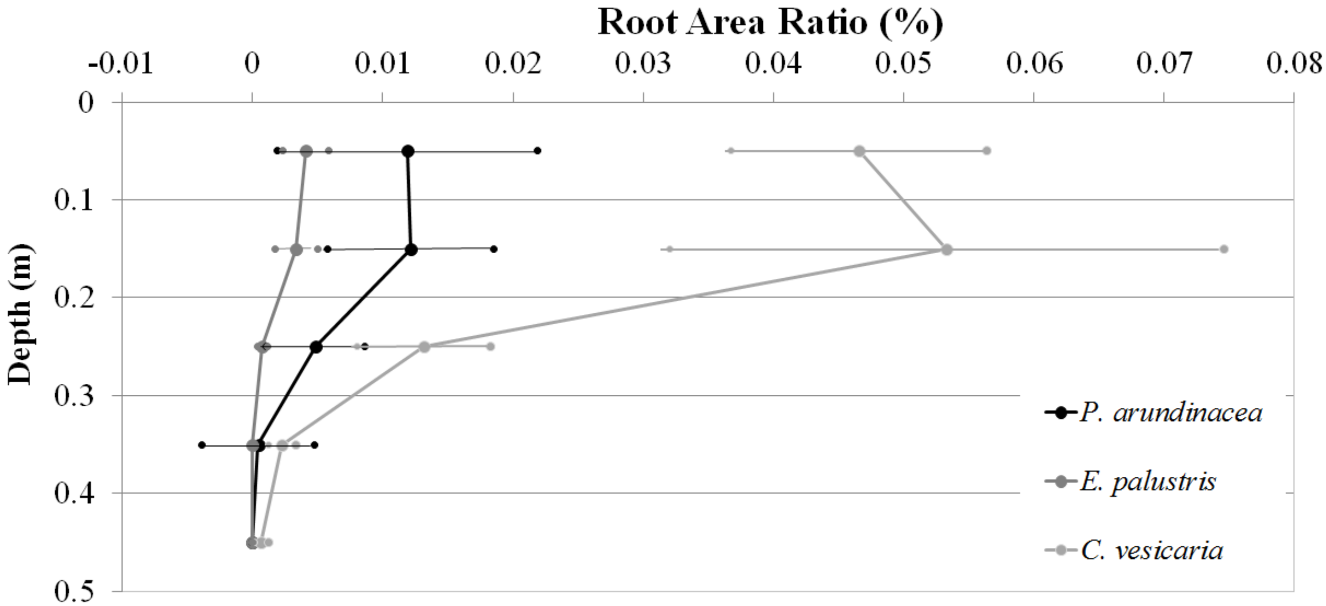

Figure 2.4. RAR distribution by depth for *P. arundinacea*, *E. palustris*, and *C. vesicaria*. Standard errors of RAR are presented by the extending lines.

6.2. Root Strength and Cohesion

Statistical tests (Mann-Whitney-Wilcox) show that *P. arundinacea* and *E. palustris* tensile strengths (Table 2.2) are significantly different ($p<0.01$). *P. arundinacea* and *C. vesicaria* tensile strengths are not significantly different ($p=0.086$). As found in previous studies (Pollen and Simon 2005; De Baets et al. 2007; De Baets et al. 2008), root tensile strength per unit root area decreases with increasing root diameter in the form of a power relationship for each of the three species. Table 2.3 lists the parameters (a and b), root diameter range, tensile strength range, R^2 values for each power relationship, and the number of roots tested for each species. Power relationship curves for each species are shown in Figure 2.5.

The power relationships for each species, in addition to root size distribution for each of the three plants per species, were input into the model RipRoot to obtain cohesion values for each respective plant (Table 2.4). For comparison purposes, additional cohesion provided by roots was also calculated using the Wu et al. (1979) method. Using RipRoot, the results show that *C. vesicaria,* with an average of 0.88 kPa has the highest added cohesion due to roots. *P. arundinacea*, closely follows this with an average of 0.81 kPa. Both these values are much higher than *E. palustris,* which averages 0.30kPa. In addition, cohesion calculated using the Wu et al. model are greater for all excavated pits and species when compared to the RipRoot values.

Table 2.2. Root diameter and root tensile strength distributions for three species of interest

	Root Diameter (mm)				Root Tensile Strength (Mpa)			
Species	**Median**	**SD**	**Max**	**Min**	**Median**	**SD**	**Max**	**Min**
P. arundinacea	0.44	0.27	1.26	0.08	24.36	30.88	156.83	1.92
E. palustris	0.25	0.17	0.90	0.07	32.55	79.69	567.61	0.80
C. vesicaria	0.50	0.40	1.88	0.01	24.88	92.98	635.28	1.56

SD=Standard Deviation

Table 2.3. Diameter and tensile strength power relationship variables for three species of interest

Plant Species	Vegetation type	a	b	n	R^2
P. arundinacea	Grass	0.0027	1.160	98	0.5352
E. palustris	Sedge	0.0003	1.732	82	0.5346
C. vesicaria	Sedge	0.0107	1.012	119	0.6536

Table 2.4. RipRoot and Wu et al. value comparisons of added cohesion due to roots.

Species	RipRoot, kPa	Wu et al., kPa	RipRoot/Wu et al.	Wu et. al Overestimation (%)
P. arundinacea Pit 1	0.59	2.99	0.20	408.67
P. arundinacea Pit 2	0.96	4.91	0.20	411.93
P. arundinacea Pit 3	0.88	4.54	0.19	417.49
E. palustris Pit 1	0.30	0.76	0.39	157.59
E. palustris Pit 2	0.36	0.93	0.38	160.79
E. palustris Pit 3	0.25	0.63	0.39	155.81
C. vesicaria Pit 1	1.14	7.70	0.15	577.46
C. vesicaria Pit 2	0.52	3.58	0.14	591.16
C. vesicaria Pit 3	0.99	6.67	0.15	571.93

7. Discussion

Median and mean values of root diameter reported for similar grass species in other studies (Table 2.5) are larger than diameters reported in this study. In addition, previous work does not show significant differences in tree and herbaceous (grass) vegetation root diameters. The smaller root sizes reported here could be attributed to

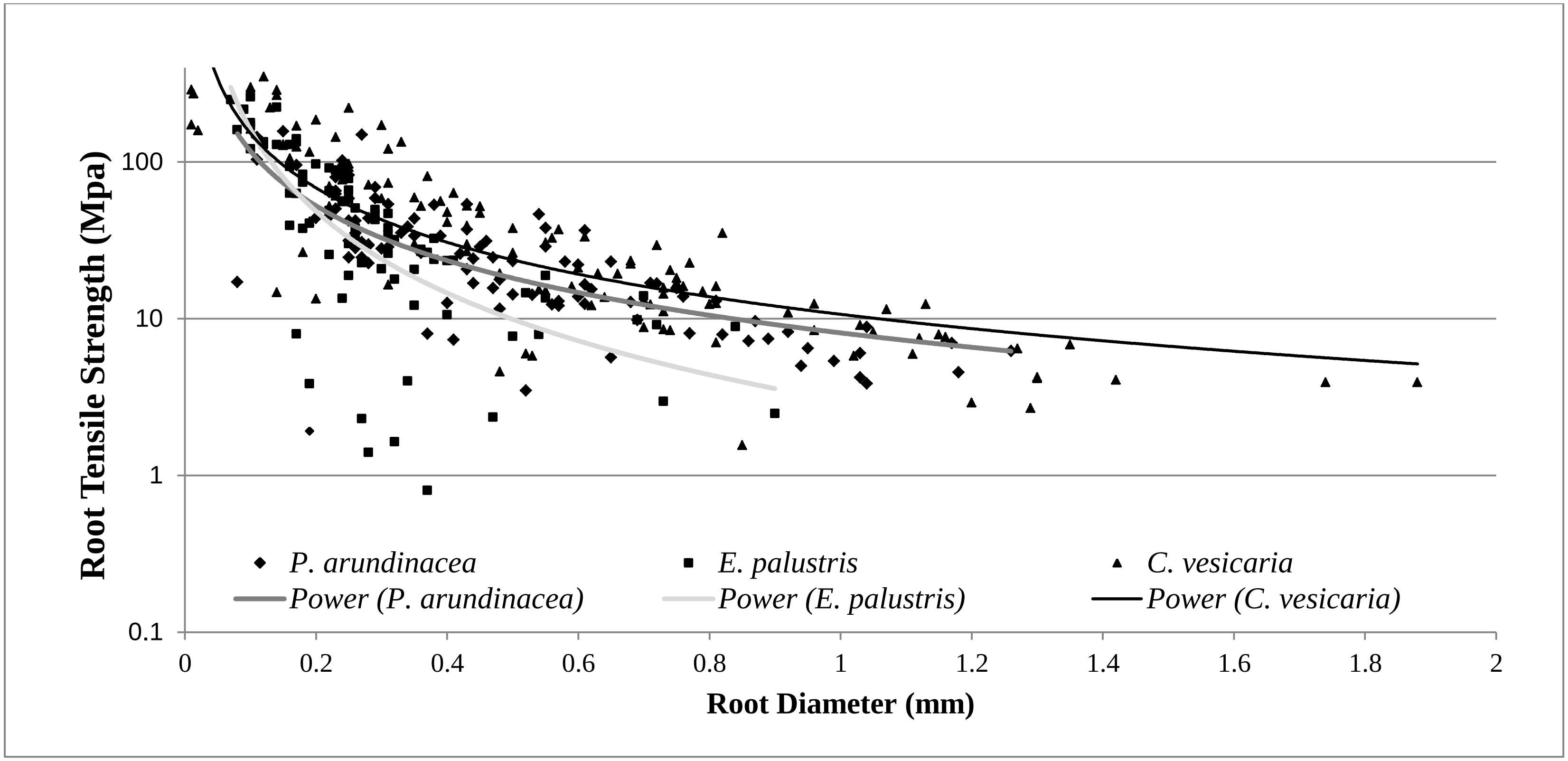

Figure 2.5. Root diameter and root tensile strength power relationship for *P. arundinacea*, *E. palustris*, and *C. vesicaria*

both species differences and environmental differences like nutrient and water availability, and soil type. Previous studies have shown that erosion resistance is highly influenced by fine root density (<5mm).

The overall trend in RAR is a general decrease with depth for the three species in question, with most of the RAR in the upper 30 cm of soil. Previous work shows a general decrease in RAR with depth, although woody species and some herbaceous species show more roots below 30 cm than the species in this study. For example, a number of tree and shrub species studied in DeBaets et al. (2007) showed roots to a depth of 0.4 to 0.8m. Similar to findings in this study, grass, herb, and reed species in De Baets et al. (2007) showed roots to depths of 0.15 to 0.35m. Young lodgepole pine showed roots to 0.85m deep (Simon et al. 2006) and Wynn et al. (2004) found herbaceous vegetation root volume ratios (a value comparable to RAR) up to 0.9m deep. Each of the species examined in this study shows a slight increase in RAR between 0.1-0.2m deep. Other studies have also shown a slight increase in RAR below the surface layer, followed by a decrease in RAR with increasing depth. For example, beech trees had a slight increase in RAR to 0.3m deep and then a gradually decrease to 1.10m deep. In addition, Norway spruce increased to 0.2m and then decreased to 1m below the surface (Bischetti et al. 2005). Other studies have found no patterns in RAR with depth (Abernathy and Rutherford 2001; Simon et al. 2006). As with root diameter, RAR with depth can depend on soil characteristics and nutrient availability.

Previous studies regarding root tensile strength have shown similar results to those presented here for herbaceous plants (Table 2.5, switchgrass and gamma grass).

According to these other studies, tree species have higher root tensile strength values than herbaceous species and grasses.

When compared to previous studies, the three species in this study show slightly lower cohesion values both when using the RipRoot model and the Wu et al. (1979) method (Table 2.6). The Wu et al. overestimation is consistent with previous literature (e.g. Pollen et al. 2004) and is due to the static model's inability to account for the progressive breakage of roots.

Many of the species previously studied are trees, though grass cohesion values reported in other studies are also higher than those found in this study. This may be due to the large number of small diameter roots found in this study. Also, unlike previous studies, roots in this study are not present in great numbers at depths greater than 0.35m, which likely deflates cohesion values (De Baets et al. 2007). Although small roots provide the most cohesion, the absence of larger roots could be significant and therefore affect overall cohesion. In addition, we used the pit excavation method and did not measure all roots present within a plant, which could underestimate total cohesion provided by roots. Further work should be conducted involving complete plant excavation.

7.1. Cohesion Due to Roots

Cohesion is a function of three factors: root size distribution, RAR, and the tensile strength of individual roots. Root size distributions show the invasive *P. arundinacea* is dominated by the smallest root sizes. *E. palustris* is dominated by roots of medium-small size whereas *C. vesicaria* has the widest range of root diameters and, unlike the other two species, is dominated by medium sized roots. RAR for the invasive *P. arundinacea* lies between that ofnative *E. palustris* and *C. vesicaria* with the latter exhibiting much higher RAR values at depths not exceeding 0.2 m. Therefore, in areas where the invasive is outcompeting native species, it is increasing RAR compared to *E. palustris* and decreasing RAR compared to *C. vesicaria*.

Within the power law equation for root tensile strength the exponent b, relating tensile strength and root diameter, controls the rate of the decline of strength with diameter, and the constant a is a scale factor in the relationship (Bischetti et al. 2005). The species with the highest scale factor and lowest decay rate, *C. vesicaria,* is the species that provides most resistance to failure and erosion. The less resistant species, or that species with the lowest scale factor and highest exponent, is *E. palustris.* Therefore, the power equations show that for a given root diameter, *C. vesicaria* has the highest tensile strength. This is closely followed by the invasive *P. arundinacea* and the native *E. palustris.*

Table 2.5. Root diameter and strength of other species

Species Name	**Vegetation Type**	**Diameter (mm)**	**Root Tensile Strength (Mpa)**
Fagus sylvatica[a]	Tree	1.33	57.47
Salix purpurea[a]	Tree	1.28	51.47
Salix caprea[a]	Tree	1.42	47.8
Fraxinus excelsa[a]	Tree	1.95	36.86
Larix decidua[a]	Tree	1.68	66.14
Switchgrass[b]	Grass	1.3	19
Gamma grass[b]	Grass	1.4	27.7
Swamp Paperbark[c]	Tree	7.4	14.3
River Red Gum[c]	Tree	5.7	19.4

[a] Bischetti et al. 2005, [b] Simon and collision 2002, [c] Abernethy and Rutherford 2001

Table 2.6. Vegetation type and cohesion of other species

Species Name	**Vegetation Type**	**Cohesion (RipRoot, kPa)**	**Cohesion (Wu et al, kPa)**
Variety of Grasses[a]	Grass		100 - 244
Juncus acutus[a]	Rush		304
Anthyllis cytisoides [a]	Shrub		< 160
River birch[b]	Tree	1.75	28.9
Black Willow[b]	Tree	1.75	20
Sycamore[b]	Tree	1.75	24.9
Switchgrass[b]	Grass	1.85	50.5
Longleaf pine[b]	Tree	1.75	14.2
Norway Spruce[c]	Tree		14.3 - 58.6
European beech[c]	Tree		40 - 100
European larch[c]	Tree		15 - 60
Sweet Chestnut[c]	Tree		6.4 - 19.0
European hop-hornbeam[c]	Tree		5.4 - 30
Sweetgum[d]	Tree		4
Eastern gamma grass[d]	Grass		6
Switch grass[d]	Grass		18
Tamarisk[e]	Tree	0 - 6.9	
Russian-olive[e]	Tree	0 -14.2	

[a] De Baets et al. 2008, [b] Pollen and Simon 2005, bank height is 1m, [c] Bischetti et al. 2009, conversion factor used to prevent Wu et al 1979 overestimation, [d] Simon and Collison 2002, [e] Pollen-Bankhead et al. 2009

Regarding cohesion obtained from the model RipRoot, the high cohesion values for *C. vesicaria* result from a combination of the medium density of large roots and the largest RAR. *P. arundinacea* exhibits a high cohesion value as well due to the presence of a large number of small roots. *E. palustris* plants provide the lowest amount of soil cohesion due to roots because, although its roots exhibit large tensile strengths, it has the lowest number of roots and they are small in diameter.

7.2. Restoration Implications

Quantifying the root cohesion of riparian species is important because shifts in species dominance may change bank stability and bank erosion processes. Reaches occupied by the invasive that were previously inhabited by the native *E. palustris* are experiencing up to three times increased bank stability and resistance to erosion. Measurements conducted in this study primarily focus resistance to erosion via roots. However, the aboveground biomass of the vegetation also has the ability to cause geomorphological changes by altering roughness and trapping sediment. *P. arundinacea,* unlike the native species studied here, develops a sod layer that protects bank surfaces from erosion. In future work, the aboveground structures of the species should be examined to address this question. This may include quantification of sod layer properties and differences between the species using laboratory flume methods or field measurements.

Changes in bank stability and bank erosion resulting from vegetation species shift can lead to changes in channel form. Expansion of *P. arundinacea* may reduce the ability of floods to uproot vegetation along the channel margin and therefore reduce the erosional effectiveness of floods. Increasing bank stability and decreasing erosion in these areas means channel width is more likely to remain static or even decrease (Myers and Swanson 1992, 1996; Duff 1977; Overton et al. 1994). With narrower channels, increased shear stress on the channel bed may result in incision, and increased stream depth that may ultimately affect fish habitat.

Changes in channel form, either decreased channel width or increased channel depth, may help to decrease stream temperatures (Matthews 1996; White and Brynildson

1967). With the pending removal of dams downstream of the Sprague River and the potential for salmon presence in the future, changes in channel form that affect habitat, particularly water temperature, are important. Currently, the Sprague River exceeds summer water temperature standards, and decreasing water temperatures may be important for salmon survival (Beschta et al. 1987; Bjornn and Reiser 1991; Boyd and Kasper 2002). Ultimately, decreases in stream temperatures will result in more hospitable conditions for salmon in this area (Boyd and Kasper 2002).

Values reported here for the Sprague River are likely applicable across different locations in some instances. Tensile strength measurements and power relationships are consistent within species; however, root distribution can be highly variable depending on substrate and local nutrient and water availability (see model RipRoot and Pollen and Simon 2005). Soil pits for this study were located on depositional surfaces and therefore close to the water table where roots were not required to extend to great depths. I have observed that when occupying cutbanks, the invasive has developed longer, deeper root systems to reach water levels and would therefore likely have different root distributions than when inhabiting depositional surfaces. Therefore, care should be taken when comparing results across habitats and watersheds.

8. Conclusions

Few studies have examined the impact of small, non-woody riparian vegetation on stream bank stability and resistance to erosion. We have shown that differences in root size, root distribution, root strength, and root cohesion exist between the invasive *P. arundinacea* and natives *E. palustris* and *C. vesicaria,* the most significant of which is the high bank stability and resistance to erosion properties of *P. arundinacea* compared to the native *E. palustris*. The increased level of cohesion in areas where the invasive is outcompeting the native species may be leading to zones of decreased erosion. The change in bank cohesion is likely to cause the most effect in areas where *P. arundinacea* is outcompeting *E. palustris* because the cohesion values of the invasive are almost three times greater. Such changes in bank stability could lead to channel narrowing and other channel form water temperature regime changes that would improve salmon habitat which is critical given the planned removal of four Klamath River dams Therefore, it is important to determine the past and predict the future effect of the invasive *P. arundinacea* on channel morphology.

CHAPTER III

QUANTIFYING ROUGHNESS: FLEXIBLE RIPARIAN VEGETATION AND MANNING'S *n*

1. Introduction

Manning's *n* is used to quantify hydraulic resistance to flow, determine flow velocities, and calculate discharge. However, accurately estimating this parameter is a difficult task. Roughness can be influenced by vegetation, bedforms, sinuosity, obstructions (e.g. wood), bedrock outcrops, and skin friction (Simon and Castro, 2003; Gilley and Finkner, 1991; Roberson and Crowe, 1993). Researchers have continually modified and developed methods, the majority of which are based on statistical relationships with other hydraulic variables or based on the topographic characteristics of the channel, to combat the uncertainties in roughness calculations. However, few of these account for the added roughness provided by plant stands.

Riparian vegetation passively engineers rivers (Viles, 1988) by increasing roughness through above ground biomass (Gurnell et al., 2010; McKenney et al., 1995; Perucca et al., 2007). The degree to which vegetation influences flow velocities is dependent on the density and height of plants and their stiffness, or resistance to flow (Gleason et al., 1979; Gran and Paola, 2001). Aquatic macrophyte shoot density and shape were found to influence flow velocity and therefore sediment deposition (Asaeda et al., 2010; Clarke et al., 2004; Schulz et al., 2003). Submerged bur-reed shoots with simple stems and no leaves increased fine sediment deposition within the vegetation stand. Within *Callitriche cophacarpa* stands, Sand-Jensen and Mebus (1996) found an eleven-fold decrease in stream velocity due to the establishment of dense stands and shoots. Within tidal marsh landscapes, grasses were found to decrease velocity and near-bed turbulence (Leonard and Luther, 1995), cause sediment deposition and divert flow around vegetation patches (Reinhardt et al., 2010; Temmerman et al., 2006; Van Hulzen et al., 2007).

Small changes in deposition and erosion brought on by vegetation can lead to changes in channel form (Corenblit et al., 2008; Gurnell, 1997; Perucca et al., 2007). *Spartina anglica* (common cordgrass) in a tidal marsh landscape both increased deposition by reducing velocities within the plant stand and caused scour outside the stand by diverting flow outside of the canopy (Van Hulzen et al., 2007). In rivers, channel width and wetted perimeter values are lower in channels with banks that contain a high percent of vegetation cover while depth tends to increase with increased levels of vegetation cover (Hey and Thorne, 1986; Millar and Quick, 1998). Studies show that channel widths in rivers lined with grass can be up to three times as wide for a given discharge as those covered with trees (Millar and Quick, 1998). In addition, vegetation can control channel planform and pattern (Millar, 2000; Millar, 2005; Nevins, 1969; Tal and Paola, 2007) and can shift braided channels to single thread channels (Murray et al., 2008; Tal and Paola, 2010). Therefore, quantifying vegetation roughness can be useful for predicting deposition, erosion, and channel planform changes.

Changes in species composition and the subsequent change in roughness values is of particular importance where invasive species are rapidly outcompeting native species and establishing monocultures. Along the Sprague River in southeastern, Oregon, the invasive *Phalaris arundinacea* (reed canarygrass) occupies similar microsites as those occupied by dominant natives *Eleocharis palustris* (creeping spikerush), and *Carex* *vesicaria* (inflated sedge) and is outcompeting these species within the riparian zone. If these species have different roughness values, changes in species composition can change deposition and erosion along the stream channel and thus alter channel morphology and aquatic habitat.

Our goal is to determine differences in plant characteristics and roughness properties of *P. arundinacea* and native species *C. vesicaria* and *E. palustris.* Here I measure the stem stiffness and other plant characteristics of multiple individuals of each of the three species. These variables are used to calculate the associated roughness values for the three species to predict changes in roughness where the invasive is outcompeting native species. In addition, I directly measured deposition within plant stands in riparian areas using deposition pins and mats.

2. Methods

2.1. Site Selection

I chose sites located on depositional surfaces below bankfull stage that contained representative plant stands dominated by the three species of interest. Plant stands were located approximately 1m above the channel bed (thalweg) and vegetation roughness, or n_{veg}, was calculated for partially submerged vegetation. Twelve, 10, and 8 plants for *P. arundinacea, E. palustris,* and *C. vesicaria,* respectively were chosen at three main sites within the Sprague River Basin (Figure 2.1.). Sites were selected based on location access and presence of dominant plant stands that contained few or no other species within the stand. In addition, all sites were located on depositional surfaces at similar elevations along the banks of the river where high flows would interact with the vegetation.

2.2. Plant Characteristics and Other Variables

I measured the modulus of plant stiffness (E_s, N/m^2), plant area (m^2), plant density (#plants/ m^2), plant frontal area (m^2), stem density (#stems/ m^2), and total cross-sectional area of all the stems of an individual plant, (m^2) for each of the three species. The modulus of plant stiffness, E_s (Rahmeyer et al., 1999; Kouwen, 1988), or stem stiffness, was measured by securing a 100lb load cell at half the height of the vegetation stem to determine the force required to bend to an angle of 45°. Ten plants with a total of 137 stems were tested for *E. palustris,* eight plants with a total of 160 stems were tested for *C. vesicaria,* and 12 plants with a total of 181 stems were tested for *P. arundinacea.* I converted this load to Newtons and input it into the equation (Freeman et al., 2000; Rahmeyer et al., 1999: refer to Table 3.1 for variables):

$$E_s = 6.791\ \frac{F_{45}H^2}{D_s^4} \qquad (1)$$

to calculate the modulus of plant stiffness (E_s, N/m^2). A high E_s value would mean higher stiffness, or lower flexibility, of the plant stem.

I estimated roughness based on the above discussed stem stiffness for each of these plant stands, and the total plant area occupied by each individual plant and determined plant density (number of plants/m^2). Plant frontal area was measured using a 50cm x 1.5m coverboard (Sage et al., 2004; Nudds, 1977; Griffith and Youtie, 1988). Plant frontal area was recorded as the percent cover of each 50cm x 10cm panel for each of the 10cm height increments from the ground up to the height of the plant. Percent was then converted to area of coverage to determine total plant frontal area for the plant at 80% of its height (input required for partially submerged vegetation). Plant area was measured as total canopy cover.

Table 3.1. Variables for equations and associated descriptions.

Variable	Description
n	Manning's roughness term
H	Average undeflected plant height, m
A_i^*	Net submerged frontal area of partially submerged plant, m2
A_s	Total cross-sectional area of all the stems of an individual plant, m2
D_s	Stem diameter, at a height of H/2, m
E_s	Modulus of plant stiffness, N/m2
F_{45}	Horizontal force to bend stem 45°, N
K_n	Unit conversion factor 1.0m1/3/sec
M	Relative plant density, m2
p	Fluid density, 1000 kg/m3
R_h	Hydraulic radius, m
S	Slope
V_*	Shear velocity, m/s
v	Fluid dynamic viscosity, m2/s,

Additionally, I measured stem density by counting the number of stems within a 0.1 x 0.1 m sampling plot. I measured stem diameter at ¼ the height from the ground for each stem, as is required according to equation protocol. Total cross sectional area of stems was measured within this plot by summing the stem diameters and extrapolating this to the total size of the plant, per equation protocol.

2.3. Calculating Roughness

In addition to the above measured variables, standard variables were determined for this river system using accepted hydraulic values and measurements on topographic maps, sonar data, and digital elevation models. These include: hydraulic radius (R_h, 1m), fluid density (ρ, 1000 kg/m^3), slope (0.0002 m/m), shear velocity, (V_*, 0.0443 m/s), and fluid dynamic viscosity (v, 1 m^2/s).

For each plant of each of the three species of interest, roughness with regard to vegetation alone (ignoring channel characteristics), n_{veg}, for partially submerged vegetation (inundating the vegetation up to 80% of its height) was calculated using equation (2) (Rahmeyer et al., 1999) and the median E_s value for that plant stand. This resulted in a unitless roughness value for each plant stand of interest (refer to section 6 for variables).

$$n_{veg} = K_n 9.159\text{x}10^{-5} \left(\frac{E_S A_S}{\rho A_i^* V_*^2}\right)^{0.207} (MA_i^*)^{0.0547} \left(\frac{V_* R_h}{v}\right)^{0.490} \frac{\left(R_h^{2/3} S^{1/2}\right)}{V_*} \tag{2}$$

2.4. Measuring Deposition

To directly measure deposition with invasive and native plants stands, I set up four sampling stations for sediment deposition rates from mid October 2011 to late July 2012 using two methods: deposition pins and mats (Gurnell et al., 2006a; Gurnell and Petts, 2006). Each station consisted of 1 stand of the invasive species and a nearby stand of a native species at a similar bank elevation (Figure 3.1.). Two stations consisted of a pairing of the invasive *P. arundinacea* and *E. palustris* and two stations of *P. arundinacea* and *C. vesicaria.* Within each of the plant stands, I used two types of 9cm x 6cm mat pieces to minimize flow interruption within the plant stand: artificial turf and a rubber mat. In addition, at each stand, I inserted six deposition pins and the distance from the top of the pin to the current ground level was recorded for each pin. Both the mats and deposition pins were left in place through the flood season (Figure 3.2.) to determine sediment deposition after significant flows. Sites were inundated with up to

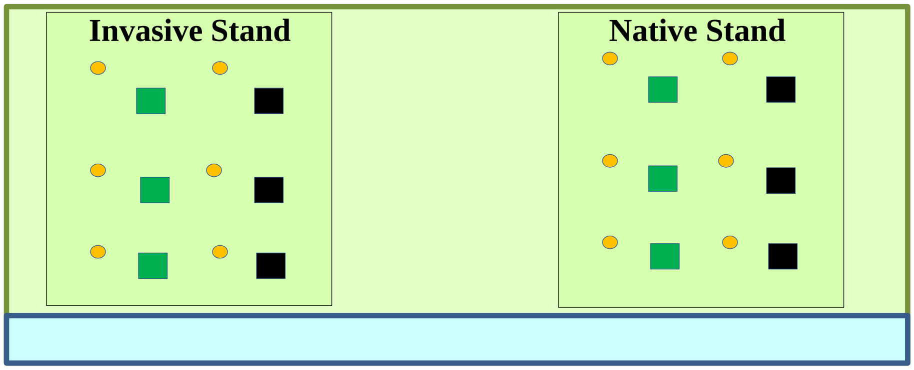

Figure 3.1. Deposition pin (yellow circles) and mat (green=turf mats, black=rubber mats) setup along the banks of the Sprague River (light blue polygon).

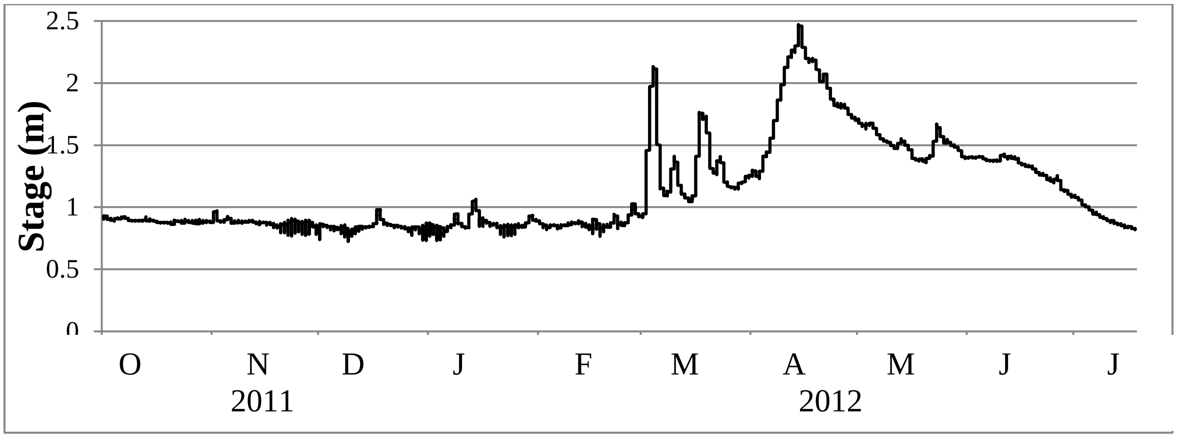

Figure 3.2. Stage heights for period of time deposition pins and turf mats were in place. Stage data obtained from Oregon Water Resources Department (OWRD) gage station 11497500 near Beatty, Oregon.

1.5m of water given that they were placed approximately 1m above the channel bed. I collected the mats after the flood season and separated the sediment. Sediment was dried, weighed, and converted to volume using a bulk density of 1.3g/cm^3. Deposition pins were measured and recorded with regard to the current ground level after the flood season.

3. Results

3.1. Plant Characteristics

I measured 43 stem density plots for *P. arundinacea,* 33 for *E. palustris*, and 36 for *C. vesicaria*. Median stem density values were 800, 4800, and 2850 stems per m^2, for *P. arundinacea, E. palustris,* and *C. vesicaria,* respectively (Figure 3.3.). Overall, *E. palustris* showed the highest stem density and the invasive *P. arundinacea* showed consistently lower stem densities than the two natives. The invasive had significantly different stem density values compared to each of the native species ($p<0.001$).

Stem stiffness values varied greatly for each species (Figure 3.4). I tested a total of 270, 214, and 230 stems for *P. arundinacea*, *E. palustris*, and *C. vesicaria*, respectively. Stem stiffness was highest for the invasive. This was followed by *E. palustris* and then *C. vesicaria. P. arundinacea* had significantly different stem stiffness compared to both of the native species ($p<0.001$).

Table 3.2. shows the total plant area, plant density based on plant area, and plant frontal area for the three species. *P. arundinacea,* on average, had the largest frontal area. This is followed by *C. vesicaria,* and then *E. palustris,* which had the smallest frontal area. Additionally, cross sectional area of stems for all three species are displayed on Table 3.2. *P. arundinacea* and *C. vesicaria* averaged similar cross sectional areas while *E. palustris* averaged a much higher cross sectional area.

3.2. Roughness

Vegetation roughness values for each plant within each species were calculated with the median stem stiffness values of that plant and their respective variables including plant area, plant density, plant frontal area and stem cross sectional area, along with the standard variables established for hydraulic radius, slope, shear velocity and fluid dynamic viscosity, using equation (2). A boxplot of the associated vegetation roughness for each species is shown in Figure 3.5. *E. palustris* showed the highest vegetation roughness values with a median of 0.000323. It also had the largest range of values, which is due to its high range in stem stiffness. The invasive had a roughness median of 0.000304 and had a smaller range of values. *E. palustris* and *P. arundinacea* roughness values were not significantly different (Mann-Whitney-Wilcox, p=0.6277). *C. vesicaria* had the lowest roughness values with a median of 0.000132 and was significantly different from the invasive (p<0.001).

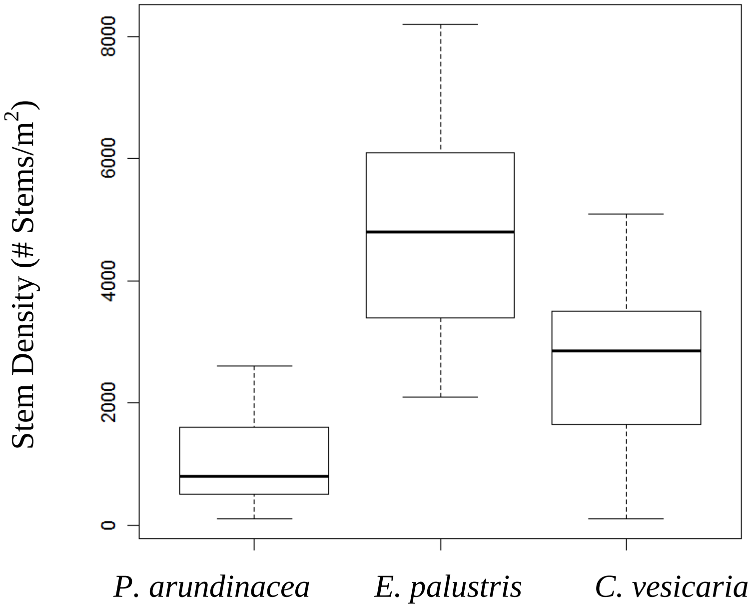

Figure 3.3. Box plots of stem density. The bold line represents median values and the top and bottom box edges represent the 75th and 25th percentiles, respectively. Whiskers represent the range of data.

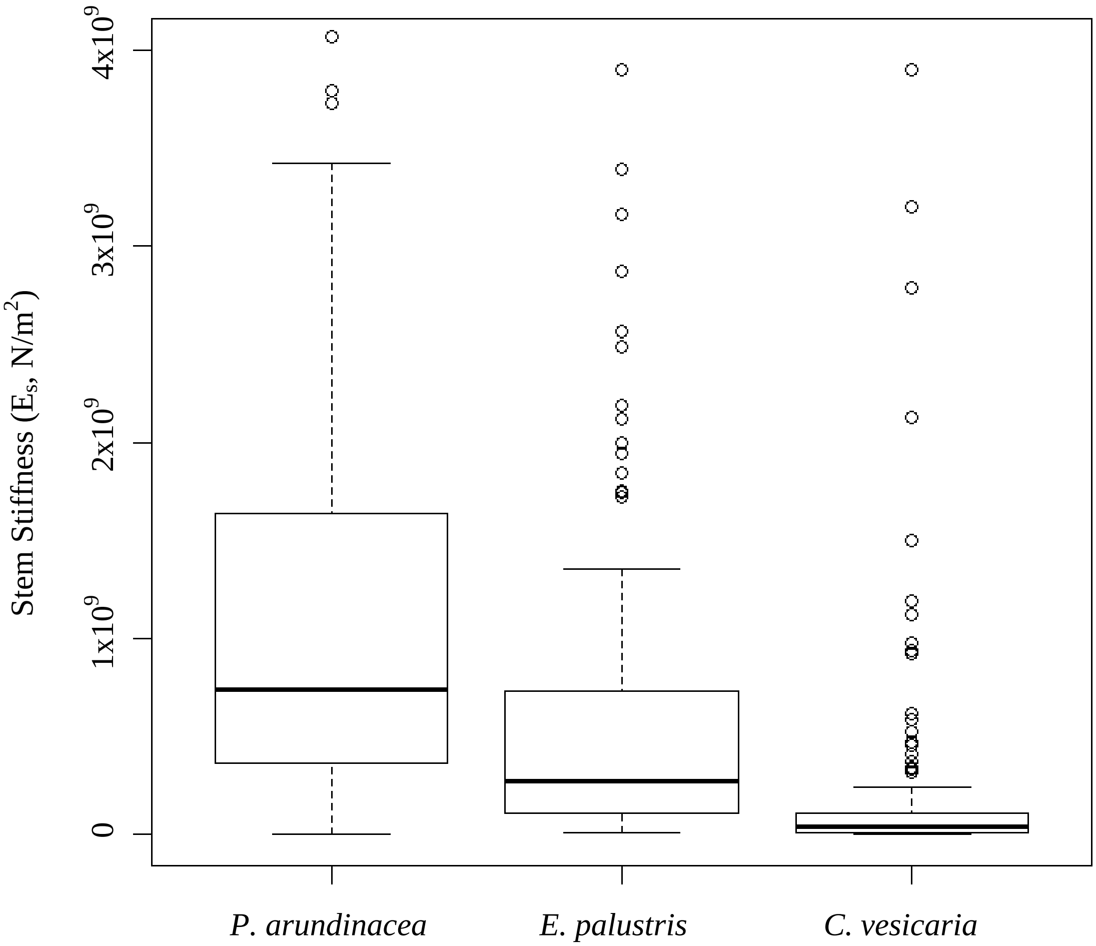

Figure 3.4. Stem stiffness for three species of interest. The bold line represents the median value and the top and bottom box edges represent the 75th and 25th percentiles, respectively. Whiskers represent the upper and lower quartiles to the nearest data point not beyond 1.5 times the inter-quartile range. Outliers are shown as open circles beyond the whiskers.

Table 3.2. Frontal and cross-sectional area characteristics for three species

	Total Plant Area (m^2)	**Plant density (#plants/m^2)**	**Plant Frontal Area (m^2, 80% height of plant)**	**Cross Sectional Area of Stems (m^2, whole plant)**
P. arundinacea				
Plant A	3.46	0.29	0.62	0.03
Plant B	3.46	0.29	0.62	0.02
Plant C	5.04	0.20	1.60	0.03
Plant D	5.04	0.20	1.60	0.04
Plant E	9.00	0.11	0.83	0.04
Plant F	2.00	0.50	0.56	0.04
Plant G	9.00	0.11	0.81	0.04
Plant H	14.00	0.07	0.81	0.04
Plant I	6.00	0.17	0.96	0.04
Plant J	12.00	0.08	1.86	0.04
Plant K	2.50	0.40	0.71	0.04
Plant L	9.00	0.11	1.31	0.04
Median	***5.52***	***0.18***	***0.82***	***0.04***
E. palustris				
Plant A	4.35	0.23	0.49	0.16
Plant B	4.35	0.23	0.49	0.01
Plant C	0.06	16.67	0.04	0.0005
Plant D	0.03	31.25	0.02	0.0002
Plant E	3.90	0.26	0.33	0.05
Plant F	3.90	0.26	0.33	0.02
Plant G	0.75	1.33	0.11	0.21
Plant H	0.50	2.00	0.21	0.21
Plant I	10.00	0.10	0.36	0.21
Plant J	14.00	0.07	0.71	0.21
Median	***3.90***	***0.26***	***0.33***	***0.13***
C. vesicaria				
Plant A	2.34	0.43	0.78	0.08
Plant B	2.34	0.43	0.78	0.03
Plant C	3.65	0.27	0.77	0.04
Plant D	3.65	0.27	0.77	0.02
Plant E	1.38	0.72	0.77	0.02
Plant F	1.38	0.72	0.77	0.01
Plant G	6.00	0.17	0.37	0.03
Plant H	9.00	0.11	0.71	0.03
Median	***3.00***	***0.35***	***0.77***	***0.03***

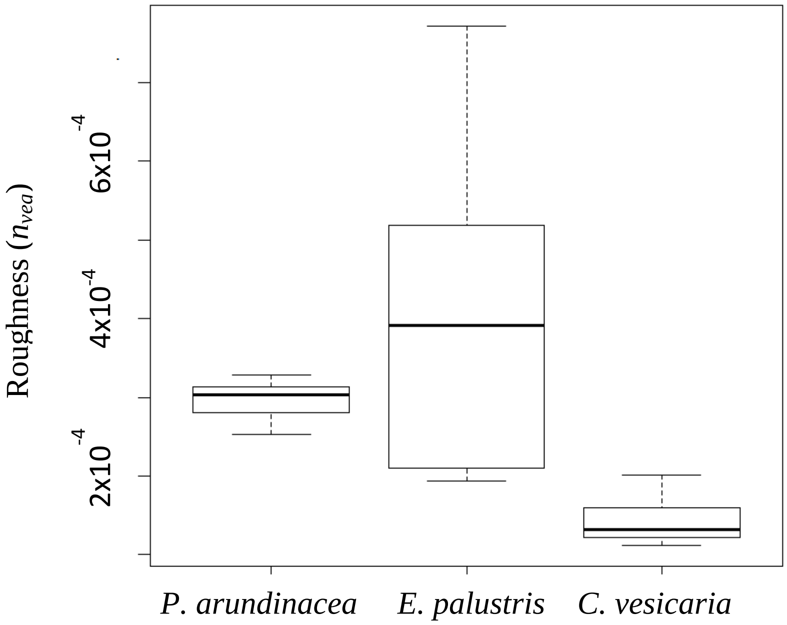

Figure 3.5. Vegetation roughness values for three species. The bold line represents median values and the top and bottom box edges represent the 75th and 25th percentiles, respectively. Whiskers represent the range of data.

3.3. Deposition

Deposition likely occurred during the receding limb of the hydrograph from late April to late July (Figure 3.2.) and consisted of fine-grained sediment (silts and sands). Pin measurements showed a dominance in deposition within all plant stands with the exception of the *C. vesicaria* stand in Plant Stand D (Figure 3.6.). Deposition depths were similar within stands of the invasive and *E. palustris* and greater within the invasive when compared to *C. vesicaria.* Turf mat volumes were standardized by the area of the turf mat (volume of sediment divided by 54cm^2). Sediment deposited on the mats showed some patterns (Figure 3.7). *P. arundinacea* stands showed similar deposition values as those in *E. palustris* stands. In addition, *P. arundinacea* stands showed higher deposition values than *C. vesicaria* in Plant Stand C. Plant stand D seems to be anomalous given that the deposition values obtained from the pins and mats disagree. There did not appear to be a significant difference between mat types (turf mats are bars 1, 2, and 3 while rubber mats are bars 3, 4 and 5 in each cluster of species, Figure 3.7.)

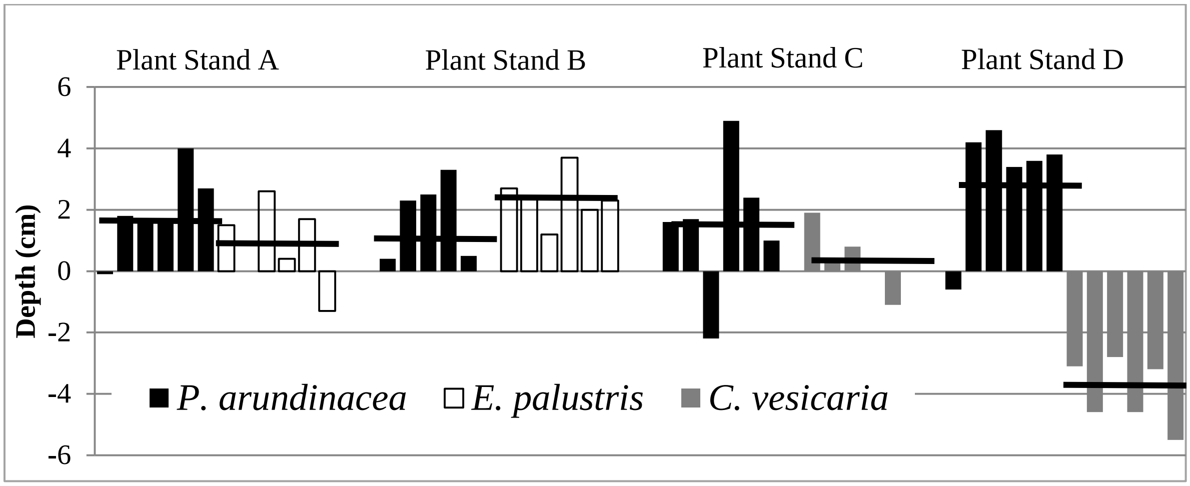

Figure 3.6. Deposition (+) and erosion (-) depths for plant stands using pins. Horizontal bars represent average for the species within that plant stand.

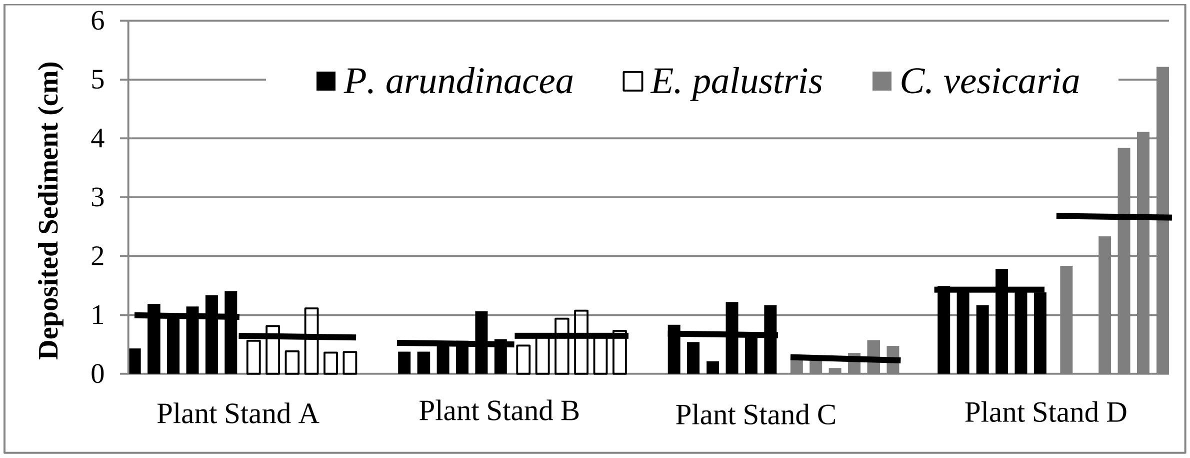

Figure 3.7. Deposition using turf mats for four plant stands. Horizontal bars represent average for the species within that plant stand.

4. Discussion

4.1. Plant Characteristics

P. arundinacea showed the lowest stem densities of the three species of interest. *C. vesicaria* stems exhibited low to medium stem densities while *E. palustris* exhibited the highest stem densities of all three species. Therefore, solely based on stem densities, *E. palustris* has a higher ability than the other species to interrupt flow, which may lead to higher roughness numbers and increased sediment deposition within plant stands.

Stem stiffness values for *E. palustris* were the highest among the three species followed by *P. arundinacea* and *C. vesicaria*. *P. arundinacea*, though it exhibited mid-range stiffness values, also exhibited a large number of higher range values. Therefore, solely due to stem stiffness, *P. arundinacea* has a higher ability to interrupt flow. Stem stiffness values found in this study are an order of magnitude larger than those of woody species (Table 3.3). This is due to the smaller stem diameters present in the denominator of the E_s equation (equation 1), which inflates stiffness values.

Table 3.3. Stem stiffness values for woody species published in previous work.

Species	**Stem Stiffness, E_s ($N/m^2 x10^8$)**
Yellow Twig dogwood[1]	3.210
Berried Elderberry[1]	0.526
Purpleleaf Euonymus[1]	4.140
Red Twig Dogwood[1]	10.200
Yellow Twig Dogwood[1]	29.900
Mulefat[1]	5.950
Alder[1]	17.000
Valley Elderberry[1]	16.500
Willow (Salix exigua)[2]	1.470
Willow (Salix lasiandra)[2]	0.747
Composite Willow[2]	1.390

[1]Values based on Freeman et al.(2000), [2]Values based on Freeman et al (1998)

On average, *P. arundinacea* had the highest plant frontal area (m^2) values of the three species. This was followed by *C. vesicaria* and then *E. palustris*. Observations in the field coincide with this measurement. Often the invasive occupied the largest area and was the tallest. *E. palustris* on the other hand, was the smallest plant in terms of height and, unlike the invasive, has no leaves which would create higher plant frontal area measurements. *C. vesicaria*, had a large frontal area but is often no taller than 0.5m. In terms of its impact on roughness values based on frontal area, the invasive has a higher potential to interrupt flow and create larger obstructions to flow, thus causing deposition. In contrast to this, stem cross sectional area was highest in stands of *E. palustris.* This was followed by *P. arundinacea* and *C. vesicaria* which exhibited very similar values.

Overall, *E. palustris* exhibited values for stem density, and cross sectional area of stems that will lead to the increased possibility of flow interruption and therefore the highest numbers in roughness values based on plant characteristics. *P. arundinacea*, on the other hand, exhibited the highest values for stem stiffness and plant frontal area because it was the tallest and occupied the largest area.

Values presented here for the Sprague may be highly correlated with substrate characteristics, and nutrient and water availability, and therefore may not be applicable in other locations. In addition, measured variables, including stem stiffness, may differ depending on the season data is gathered. For example, new stems may be smaller with lower biomass and therefore lower plant frontal area. In addition, these stems may be more flexible than what would be encountered later in the season. Further work should take care, as this study did, to observe and record plant characteristics similar to those that will be present during flows in which the vegetation is inundated. Additional work could be conducted that compared the variables in different growth stages.

4.2. Roughness

P. arundinacea and *E. palustris* vegetation roughness values are not significantly different though in some cases *E. palustris* may exhibit higher roughness (Figure 3.5.). The invasive and *C. vesicaria* show significant differences in roughness. If *P. arundinacea* dominates and replaces *E. palustris*, roughness values will likely remain the same or only decrease slightly. However, if *P. arundinacea* is dominating *C. vesicaria*, roughness values will be significantly higher than previously. Differences in stem elasticity and stem cross-sectional area seem to have the largest influence on vegetation roughness. High stem densities within *E. palustris* (Figure 3.3.) likely account for its high roughness values while the low stem stiffness of *C. vesicaria* (Figure 3.4.) likely accounts for its low vegetation roughness.

These roughness values account for only vegetation roughness. To fully predict channel changes, a composite roughness should be calculated. Values for portions of stream banks occupied by the invasive or native vegetation, the vegetation roughness much be treated as an added factor and combined with other roughness factors for the reach of interest. Previous work has illustrated the concept of an additive roughness value by establishing a roughness base value and adding roughness values for surface irregularities, channel shape and size, obstructions, vegetation, and meandering (Arcement and Schneider, 1989; Cowan, 1956; Chow, 1959; Aldridge and Garrett, 1973). Using this method, low gradient, sinuous reaches of the Sprague River in this study would yield roughness values displayed in Table 3.4. The median roughness values for each species were added to this roughness value to obtain a composite channel roughness value which yields a roughness 0.0238 for areas occupied by *P. arundinacea,* 0.0240 for *E. palustris,* and 0.0235 for *C. vesicaria.*

Table 3.4. Additive roughness values for the Sprague River.

Roughness Component	**Sprague River Value**	**Description**
nb: base roughness	0.012	smallest sand size, straight uniform channel
n1: surface irregularities	0.002	carefully degraded channel with slightly eroded or scoured sideslopes (0.001-0.005)
n2: variations in channel shape	0.002	large and small cross sections alternate occasionally, main flow shifts from side to side (0.001-0.005)
n3: obstructions	0.002	obstructions occupy <5% of cross section area (0-0.004)
m: meandering correction	1.3	sinuosity >1.5

The roughness values established here are comparable to those established in previous studies (Table 3.5). With regard to n_{veg}, all species are comparable to previously established n_{veg} values (Gordon et al., 2004; Jarrett, 1984). The vegetation roughness for all three species falls below the “small” composite n value for vegetation ranging from 0.002-0.010 (Arcement and Schneider, 1989). The “small” level corresponds with dense growth of flexible turf grass and though our species are similar to turf grass, stem density is not as high and the three species would therefore have lower roughness values. In addition, additive roughness values estimated in this study are comparable to roughness values for streams similar to the Sprague River in published photo reference guides (Table 3.6).

4.3. Deposition

Deposition depths measured with deposition pins within *P. arundinacea* and *E. palustris* plant stands shows similar patterns. *P. arundinacea* plant stands show higher deposition values than their comparable *C. vesicaria* plant stands.

Deposition measured on turf mats within *P. arundinacea* and *E. palustris* plant stands are also similar and correlate with the deposition pin findings. In addition, they are comparable to previous studies on other rivers (Gurnell et al., 2006b). Deposition values within Plant Stand C comparing the invasive and *C. vesicaria* are comparable to the pin results showing more deposition within the invasive. However, in Plant Stand D, *C. vesicaria* shows a higher deposition value based on the mats being deposited than *P. arundinacea* and these findings disagree with the deposition pin findings at the same plant stand. According to previous studies, deposition mats can accurately capture deposition but not erosion occurring on a site because they provide surface roughness that

Table 3.5. Previously established roughness values for other vegetation

Description/Species	**Minimum**
Additive vegetation values[1]:	
Supple seedlings or dense grass/weeds	0.0005-0.010
Brushy growths, no growth in streambed; grass height of flow	0.01-.025
Young trees intergrown with weeds; grass twice depth of flow	0.025-0.05
Brushy growth on banks, dense growth in stream; trees with weeds; full foliage	0.05-0.1
Yellow Twig dogwood[2]	0.043
Purpleleaf Euonymus[2]	0.041
Red Twig Dogwood[2]	0.07
Yellow Twig Dogwood[2]	0.053
Mulefat[2]	0.035
Alder[2]	0.07
Valley Elderberry[2]	0.072
Composite willow (Salix exigua & lasiandra)[3]	0.138
51 cm Dogwood[4]	0.034 (nveg)
71 cm Elderberry[4]	0.033 (nveg)
97cm Dogwood[4]	0.079 (nveg)

[1]Values based on Gordon et al. (2004) which establishes values based on Cowan (1956) and Jarrett (1984)., [2]Freeman et al. (2000), [3]Freeman et al. (Freeman et al., 1998), [4]Rahmeyer et al. (1999)

Table 3.6. Rivers similar to the Sprague River and their associated roughness values via photo reference guides.

River and Location	**Roughness Value**
Oakden Canal at Oakden Culvert (68521)[1]	0.033
Loganburn at Gorge Downstream (74347)[1]	0.020
Piako at Paeroa-Tahuna Bridge (9140)[1]	0.030
Indian Bend Wash above Curry Road[2]	0.036
Verge River near Paulden[2]	0.029
Onondoga Creek at Dorwin Ave[3]	0.027
Champlin Creek near Colorado City, Tx[4]	0.027
Clearwater River at Kamiah, Idaho[4]	0.033

[1] values based on Hicks and Mason (1998), [2] values based on Phillips and Ingersoll (1998), [3] values based on Coon (1998), [4] values based on Barnes (1967)

traps sediment (Steiger et al., 2003). It is possible that erosion, and not deposition is the dominant processes with *C. vesicaria* at this site. However, deposition pin results may be anomalous given that the field crew observed possible evidence of heave or disruption of the pins by cattle and the invasive and *C. vesicaria* stands are at significantly different elevations, unlike the other plant stands. Further study is required to ascertain a complete picture on the amount of deposition occurring within *C. vesicaria* stands.

Deposition depths via the pin and mat method correlate adequately well with roughness calculations conducted for this study. *P. arundinacea* roughness values (n_{veg}), although smaller than *E. palustris*, fall within the range of the native. Depositions are similarly comparable with one stand showing on average more deposited sediment in the invasive (Plant Stand A) and one stand showing less (Plant Stand B). *C. vesicaria* roughness values fall below the other two species as is reflected in Plant Stand C where deposition depths based on the mats are lower in the native stand. Therefore, the roughness values correlate with observed deposition and further emphasize the point that Plant Stand D may be anomalous due to hydraulic differences in stand placements.

Given these depositions and conditions over time, including flow levels, and sod layer conditions, these results would likely mean aggrading banks on these depositional surfaces on the order of 1cm per year for *P. arundinacea* and *E. palustris.* Over time, this may cause a narrowing of the channel in areas where the invasive has outcompeted *C. vesicaria.*

5. Conclusion

Quantifying roughness is a complicated, multi-dimensional problem within river science. However, it is necessary for indirectly estimating discharge, channel capacity and water surface elevations, among many other variables of use. In addition, accounting for the influence of vegetation further complicates the determination of Manning's *n* and estimations regarding this complication are almost nonexistent (Copeland, 2000). However, few are attempting to determine how vegetation affects channel flows and thus channel processes. Research regarding the effect of vegetation on channel processes has primarily considered riparian zones dominated by trees (e.g. Gurnell and Petts, 2006) and large woody shrubs such as *Tamarix* (e.g. Graf, 1978), rather than weaker and more flexible herbaceous vegetation. Previously, flume studies on groundcover plants (Rahmeyer et al., 1999), small trees and shrubs (Copeland, 2000; Freeman et al., 2000) have been conducted to determine resistance due to vegetation. Non-woody species, such as *P. arundinacea*, may have the ability to alter river channel form and process when present in extensive stands, particularly in a low energy river such as the Sprague. Furthermore, invasive vegetation may influence geomorphic processes differently than native vegetation because of its ability to outcompete other vegetation, its tendency to develop monocultures, and the difficulty encountered in its removal. In this case, *P. arundinacea* has a significantly higher roughness value than the native *C. vesicaria* which means river channel processes are being altered in areas where it is outcompeting the native.

Boyd and Kasper (2002) suggested that past channel widening along the Sprague River has been associated with negative effects on water temperature and fish habitat. However, the findings presented here reveal that areas with established invasive stands may begin to narrow. With the potential removal of Klamath dams downstream of the Sprague and the reopening of salmon habitat, it is important to determine the past and predict the future effect of the invasive on channel morphology. Establishing measurements of plant characteristics and roughness values is the first step in this endeavor. Future research includes modeling the effect of these roughness differences on channel morphology as well as long term monitoring of channel characteristics and channel changes.

CHAPTER IV

INVASIVE AND NATIVE RIPARIAN VEGETATION: MODELING CHANNEL HYDRAULICS WITH CURRENT AND FUTURE VEGETATION CONDITIONS

1. Introduction

Vegetation along stream banks has the ability to change channel morphology characteristics by altering velocity patterns and changing deposition and erosion. Recent research has focused on quantifying the effects of woody, rigid species (Petryk and Bosmajian, 1975; Pasche and Rouve, 1985; Musleh and Cruise, 2006), rather than flexible vegetation (Kouwen and Unny, 1973; Kouwen et al., 1969; Carollo et al., 2005) or a combination of the two (Freeman et al., 2000; Järvelä, 2004). However, in low gradient streams, dominant flexible vegetation can affect deposition when little to no rigid species are present. Here I examine the impact of the invasive and flexible *Phalaris arundinacea* L. (reed canarygrass) on channel morphology of the low-energy, meandering, Sprague River in eastern Oregon by modeling its effect on water depth, velocity, and bed shear stress within the 2-D model MD-SWMS (Multi-Dimensional Surface-Water Modeling System). In addition, I compare its geomorphic effect to that of native *Eleocharis palustris* (creeping spikerush) and *Carex vesicaria* (inflated sedge). In the near future, four dams along the Klamath River, downstream of the Sprague, will be removed and will open the area to salmon. Any trends in geomorphic processes that may develop or have developed in the past as a result of invasive species colonization are critical to understanding this system.

2. Background

Investigating the effect of invasive riparian vegetation is critical because invasive species can cause major shifts in ecosystem dynamics, outcompete native species, and produce many other changes of which we are still not yet aware. This is of particular importance when the species has the potential to become an ecosystem engineer. Ecosystem engineers are organisms that control the availability of resources by causing changes in biotic or abiotic materials (Jones et al., 1994; Jones et al., 1997; Corenblit et al., 2008). Rather than directly supply these resources, ecosystem engineers are those organisms that adjust or transform them. Ecosystem engineers can control energy, materials, space, food organisms, or any combination of these resources.

Within fluvial geomorphology, researchers study two aspects of vegetation ecosystem engineers: those vegetation characteristics that modify the environment either actively or passively (Corenblit et al., 2009). Riparian vegetation actively modifies the environment by establishing root systems that influence the cohesive properties of channel bed and bank materials (Prosser et al., 1995; De Baets et al., 2006). Vegetation passively modifies the environment by providing roughness within the channel bed or along the banks, decreasing flow velocity and increasing sediment deposition (Corenblit et al., 2009).

Roughness can manifest itself and alter the river system in multiple ways. Here I provide some insight into studies regarding flexible vegetation though more work is available regarding rigid woody species (e.g., Gran and Paola, 2001; Edwards et al., 1999; Graf, 1978). Macrophyte shoot density and shape influence flow velocity and therefore, deposition (Schulz et al., 2003; Clarke et al., 2004; Asaeda et al., 2010). For example, submerged *Sparganium erectum* shoots were found to increase fine sediment deposition within the vegetation stand. Following increased growth in the spring the shoots emerged from the water column which raised the water level and subsequently reduced water velocities (Asaeda et al., 2010). Gurnell et al. (2010) examined multiple macrophytes across 467 British rivers and found they have the ability to trap fine sediment and cause channel form changes. Within *Callitriche cophacarpa* stands, Sand-Jensen and Mebus (1996) found an eleven-fold decrease in stream velocity due to the establishment of dense stands and shoots.

Various studies have also examined bank and island vegetation. On the Northern Plains of Australia, various grasses along channel banks and floodplains were found to provide higher levels of stability and erosion protection than trees and shrubs in the area due to their substantial biomass and expansive root networks (Tooth and Nanson, 1999). *Carex nudata* in California creates substrate upon which other species can colonize as well. Although *Carex* occupied only 33.05% of the channel area on the South Fork Eel River, California, the 13 most common species had an average of 84% of their individuals on *Carex* tussocks. Therefore, the substrate stabilization of *Carex* was vitally important to the survival of other species (Levine, 2000).

The small changes in depositional and erosional processes brought on by the active and passive abilities of vegetative ecosystem engineers can lead to changes in channel form (Perucca et al., 2007; Corenblit et al., 2008; Gurnell, 1997). The deposition and erosion brought on by roughness and flow velocity around riparian trees and wood are critical in developing island dominated, anabranching rivers (Gurnell and Petts, 2006; Tooth and Nanson, 2000; Tooth and Nanson, 1999). Often, an initial deposit is formed downstream of a tree or other roughness feature. Vegetation then begins to colonize this feature and additional deposition occurs enabling the formation of a ridge or island (Tooth and Nanson, 2000). Vegetation also has the ability to narrow stream channels. After a large flood, Plum Creek, Colorado, experienced significant widening. Multiple years of low flow following a major flood allowed vegetation to establish along stream banks creating stable, erosion resistant channels (Friedman et al., 1996). Using flume experiments, Tal et al. (2004) found that vegetation decreases channel width, braiding index and mobility.

Despite these studies, when compared to woody riparian species, flexible channel bank and island vegetation and their effect on channel morphology and processes have been largely neglected. In particular, the geomorphic effect of an invasive species is important because they tend to dominate the landscape developing monocultures that outcompete native vegetation. One such species is *P. arundinacea* along the Sprague River, Oregon.

3. Methods

3.1. MD-SWMS (Multi-Dimensional Surface-Water Modeling System)

MD-SWMS is a two dimensional depth-averaged hydraulic model developed by the USGS to model surface water hydraulics (McDonald et al., 2005). A two dimensional model was chosen because it can produce downstream velocity, depth, and shear stress at each point within a grid or mesh throughout the channel. In addition, two dimensional models are ideal for noting changes in water depth or velocity in and around two dimensional features like bars and islands (Nelson et al., 2003). I used Morpho 2D within MD-SWMS because Morpho-2D accounts for vegetation characteristics, a variable that few models incorporate into their calculations. Vegetation can be represented in the model either as vegetation height and density inputs, or within the roughness values. When modeling with roughness inputs, the model produces output on bed shear stress in addition to water depth and velocity. Morpho-2D mimics the interaction between mixed grain sediment and vegetation (Nelson and McDonald, 2010). It calculates two-dimensional horizontal velocity and flow depth for grid nodes (built via a mesh) defined by the user (Nelson et al., 2003). The model does not alter bed morphology.

The Klamath Tribes Research Station gathered Lidar and bathymetric topography data at a 0.5m resolution for the site of interest (Figure 4.1a.) along the Sprague River in the spring of 2005. For the purposes of modeling smaller portions of the channel, one straight reach was chosen (Figure 4.1.). This straight reach was chosen based on its close proximity to a gaging station and because it was located in an area with minimal interference with adjacent meanders. In addition, this reach contains stands of all three species of interest. For input into MD-SWMS, the topography data in the form of a DEM was converted to point data and imported into MD-SWMS. A mesh grid was created within MD-SWMS by digitizing a channel centerline and establishing grid parameters (Table 4.1.). Topography was mapped to the grid to create initial conditions upon which the model could operate.

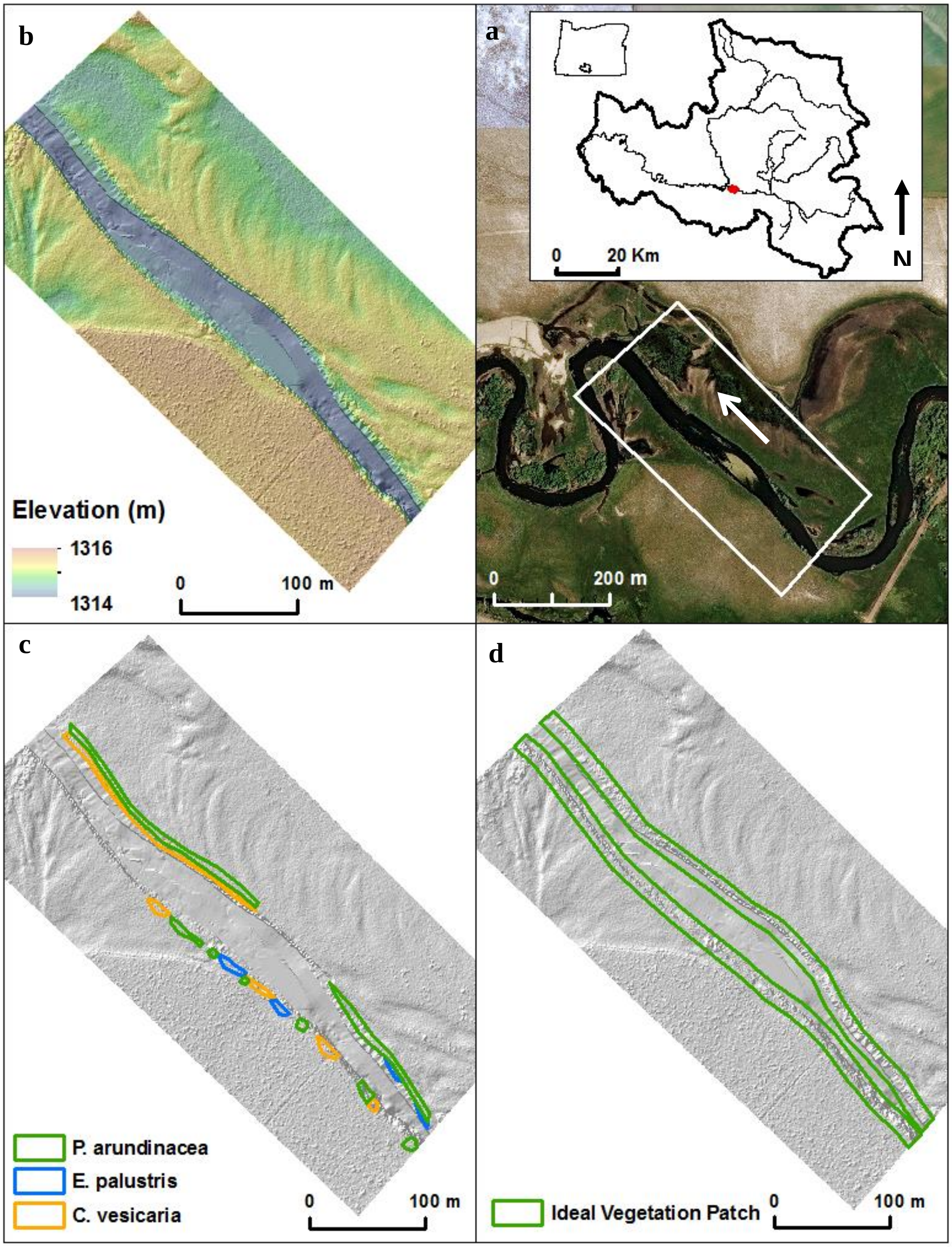

Figure 4.1. Sprague River Basin and associated study site: (a) Basin and sample reach, (b) Lidar and bathymetry showing channel topography, (c) current vegetation patches mapped in the field, (d) future scenario vegetation patches. Arrow indicates flow direction.

Polygons representing current vegetation condition in the reach were developed by mapping stands on the channel banks of 2 m^2 or more in area in the field using aerial photographs (Figure 4.1.). This mapping only encompassed the banks and did not extent onto the floodplain. Then I applied the measured vegetation height, density and roughness (Chapter 3) to the polygons for use in the model. Roughness values were calculated by first establishing a base roughness value for the channel without vegetation using the additive procedure outline in Arcement and Schneider (1989) and others. A roughness value for vegetation was then added to this value using the n_{veg} equation in Rahmeyer et. al. (1999), which incorporates vegetation density, frontal area and stem flexibility (Table 4.3., Martinez, 2013). In addition, three future scenarios of vegetation occupation were created to simulate channel changes when channel banks were dominated completely by one of the three species (Figure 4.1d.). In these scenarios, vegetation polygons that extended approximately ¼ of the way into and out of the channel banks from the bank-full line were developed. In areas outside of the mapped patches and outside of the channel, a medium roughness was used along with a vegetation density and height for basic turf grass (Other value in Table 4.3.; Maurer et al., 2001). For the future scenarios, results for *P. arundinacea* were subtracted from each of the native species to determine differences between the invasive and each native species for each of the outputs: depth, velocity, and bed shear stress.

The model was run at two different discharges, 10yr and 25yr recurrence intervals to capture circumstances under which the vegetation would be inundated. In addition, the model was run for current conditions and future conditions for each of the three species of interest: *P. arundinacea*, *E. palustris*, and *C. vesicaria*. Discharge data were obtained from the closest gaging station to the site (Table 4.2.; Station 11497500; OWRD, 2013). This set of runs was carried out once to determine outputs (velocity and depth) with regard to each species' roughness (section 4.1. below), and then again with regard to each species height and density (section 4.2. below), for a total of 16 runs. In addition, median sediment size from a nearby location was used as input into the model: d_{50}= 1mm (T. LaGreca, Klamath Tribes Research Station, personal communication).

Table 4.1. Model grid parameters

	Reach Size		**Grid Cell Spacing**		
	Length (m)	**Width (m)**	**Stream-wise (m)**	**Stream-normal (m)**	**# Grid Cells**
Straight Reach	520	180	3	2	2400

Table 4.2. Discharge and associated boundary conditions.

Recurrence Interval	**Discharge (cms)**	**Downstream Channel Bottom Elevation (m)**	**Stage (m)**
10 yr	89.34	1313	2.9
25yr	113.00	1313	3.2
50yr	191.26	1313	3.85

Table 4.3. Roughness, vegetation height and density for each species.

Species	**Mannings *n***	**Vegetation Density (m2/m2)**	**Vegetation Height (m)**
P. arundinacea	0.018328	0.04	0.92
E. palustris	0.018431	0.13	0.54
C. vesicaria	0.018135	0.03	0.74
Other	0.018300	0.90	0.30

3.2. Modeling with Roughness

To model changes in hydraulic conditions due to the effects of each species , I varied roughness (Manning's *n*), according to changing species cover. The model was run using current condition vegetation stands and future condition vegetation stands with the respective roughness for each of the three species of interest.

3.3. Modeling with Vegetation Density and Height

Vegetation height and density values for each species were obtained through previous field work (Martinez, 2013). Vegetation height is the average height (meters) for each plant and vegetation density is the percentage of area occupied by stems. For areas outside of the patches mapped in the field (Fig. 1c), height and density of turf grass was used (Maurer et al., 2001). As above, the model was run for current conditions and for future conditions for each species, at each of the two recurrence intervals. These outputs were differenced to obtain the marginal effect of the invasive relative to each native species.

Validation data for 10- and 25-year flows were not available, so a validation could not be carried out. However, comparison among species and not validation of specific hydraulic conditions is the goal for this study.

4. Results

Overall, MD-SWMS provided a useful platform upon which to model vegetation characteristic changes on hydraulic conditions. Given that the model is two dimensional, it provided the ability to model along a reach with various features and changes in channel width and depth. Results for depth and velocity were generally consistent and, for the most part, the model followed the general rules of at-a-station hydraulic relationships. However, some limits were reached when modeling high flows. At the 50 year recurrence interval, a ponding effect occurred where, despite increases in depth, and therefore discharge, velocity decreased. This problem with Morpho-2D has been previously noted (R. McDonald, USGS, personal communication). In addition, edges were not adequately represented within the model. This seemed to be limited to 50 - 75m from the upstream and downstream edge of the modeled reach. Despite this, the middle portion of the reach followed the expected hydraulic relationships well, the results of which will be the bulk of the discussion here.

4.1. Current Conditions

4.1.1. Modeling based on vegetation density and height

In the 10-year flow, velocities within vegetation patches were on the order of 0.6 m/s to 0.7m/s (Figure 4.2 a2.). High velocities on the order of 0.8m/s and 1.2 m/s were exhibited towards the downstream end of the channel within *P. arundinacea* and *C. vesicaria* patches, respectively, though these anomalously high results were likely due to edge effects. In the 25-year flow, velocities in the invasive were as high as 1.07 m/s within the center of the channel (Figure 4.2 b2.).

4.1.2. Modeling based on vegetation roughness

Water depth values were on the order of 0.1 to 0.2 m lower than those depths obtained from the vegetation density and height runs (Figure 4.3 a1 and b1). A similar range in velocity was obtained in the roughness runs as those observed in the vegetation height and density runs. However, some limited areas experienced higher velocity values in the roughness runs. These were present within the center of the channel and away from vegetation patches (4.3 b1 and b2). In addition to velocity and depth outputs, the roughness runs allowed for bed shear stress mapping. Similar shear stresses are exhibited in the 10 and 25-year flows with the exception of slight increases in high shear stress

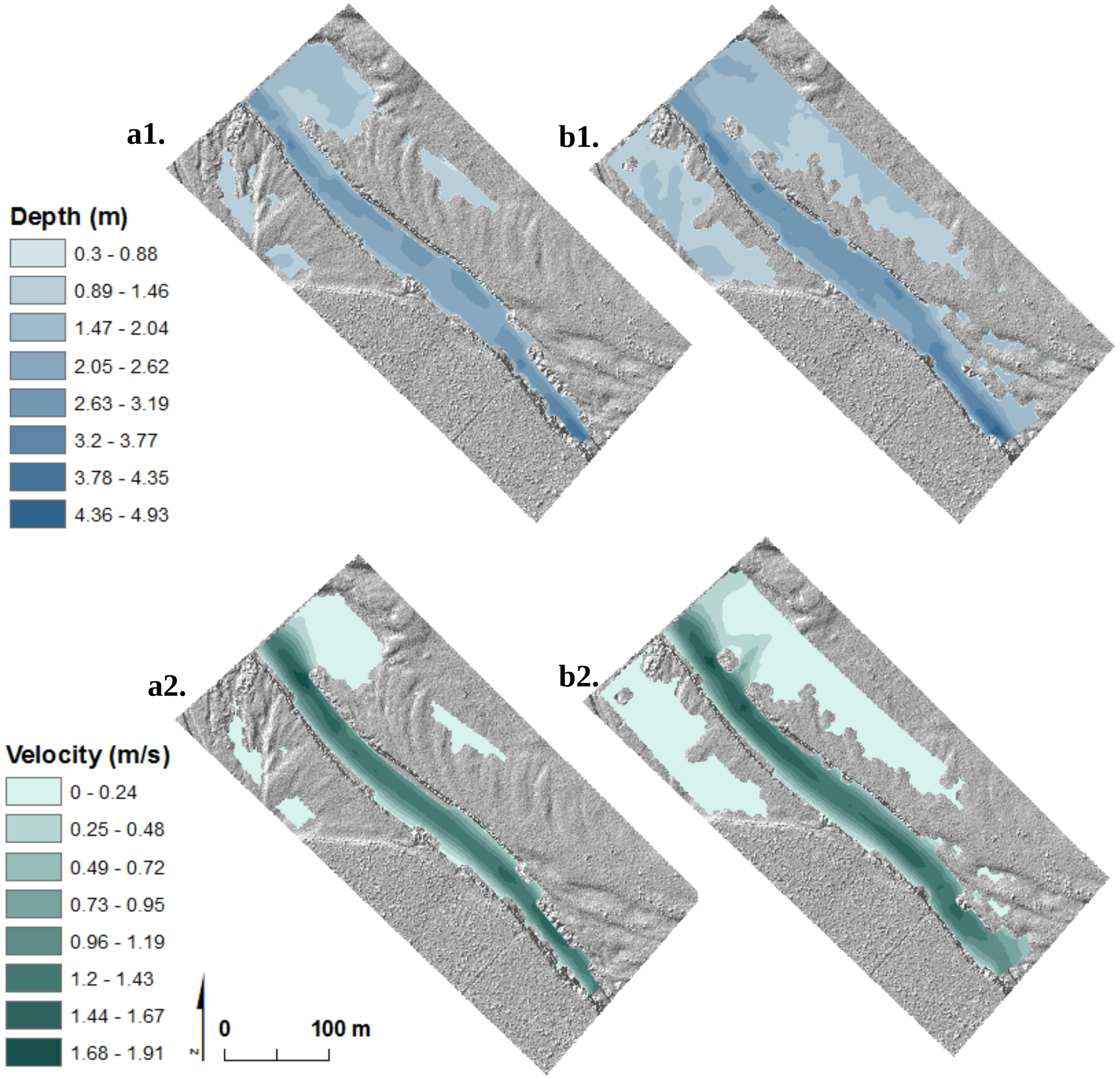

Figure 4.2. Current conditions modeled given vegetation height and density under 10 year (a1 and a2), and 25-year recurrence interval flows (b1 and b2).

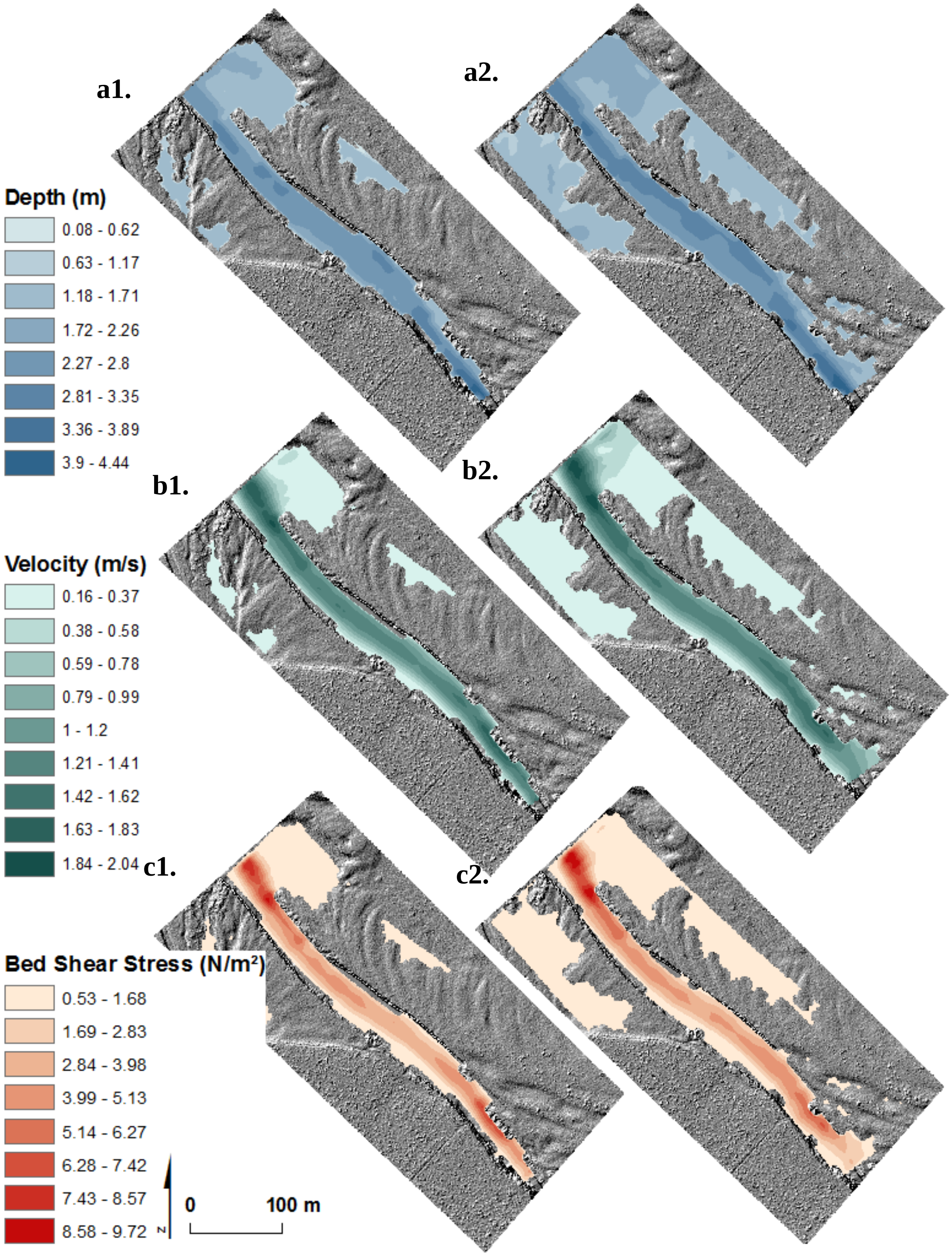

Figure 4.3. Current conditions modeled given vegetation roughness under 10-year recurrence interval (a1, b1, c1) and 25-year recurrence interval (a2, b2, c2).

areas in the 25-year flow (4.3 c1 and c2). These were concentrated toward the center of the channel and ranged from 3.76 to 4.24 N/m^2.

4.2. Future Conditions

4.2.1. Modeling based on vegetation density and height

Hereafter, I will mainly focus on how flows within vegetation patches differ with regard to species. Velocity values in the 10-year flow were higher within *P. arundinacea* stands than *E. palustris* (Figure 4.4 b1.) by up to 0.09m/s. This value was large considering velocities along these areas at the channel margins were fairly low (0.6-1m/s). Velocity under the invasive and *C. vesicaria* stands were similar (Fig. 4.4 b2). In the 25-year flow, velocity results were similar between the invasive and natives.

Regarding water depth within the vegetation patches, *P. arundinacea* and *E. palustris* performed similarly in the 10-year flow (Figure 4.4 a1.). On the other hand, flow depths under *C. vesicaria* were slightly shallower (0.007 to 0.01m shallower) than when the invasive was modeled (Figure 4.4 a2.). This was most pronounced at the upstream portion of the reach, which may be anomalous due to edge effects, but continued through the center of the channel for much of the reach. When compared to *C. vesicaria,* the invasive affected the overall hydraulics of flow through the channel, but this is not evident when the invasive is compared to *E. palustris.* In the 25-year flow, results showed that the flow depth within the invasive was shallower than either of the two natives (Figure 4.5 a1. and a2.). Some differences existed between the invasive and *C. vesicaria* at the upstream end of the reach, but this may be due to edge effects. There is little difference in velocity between the invasive and either of the native species.

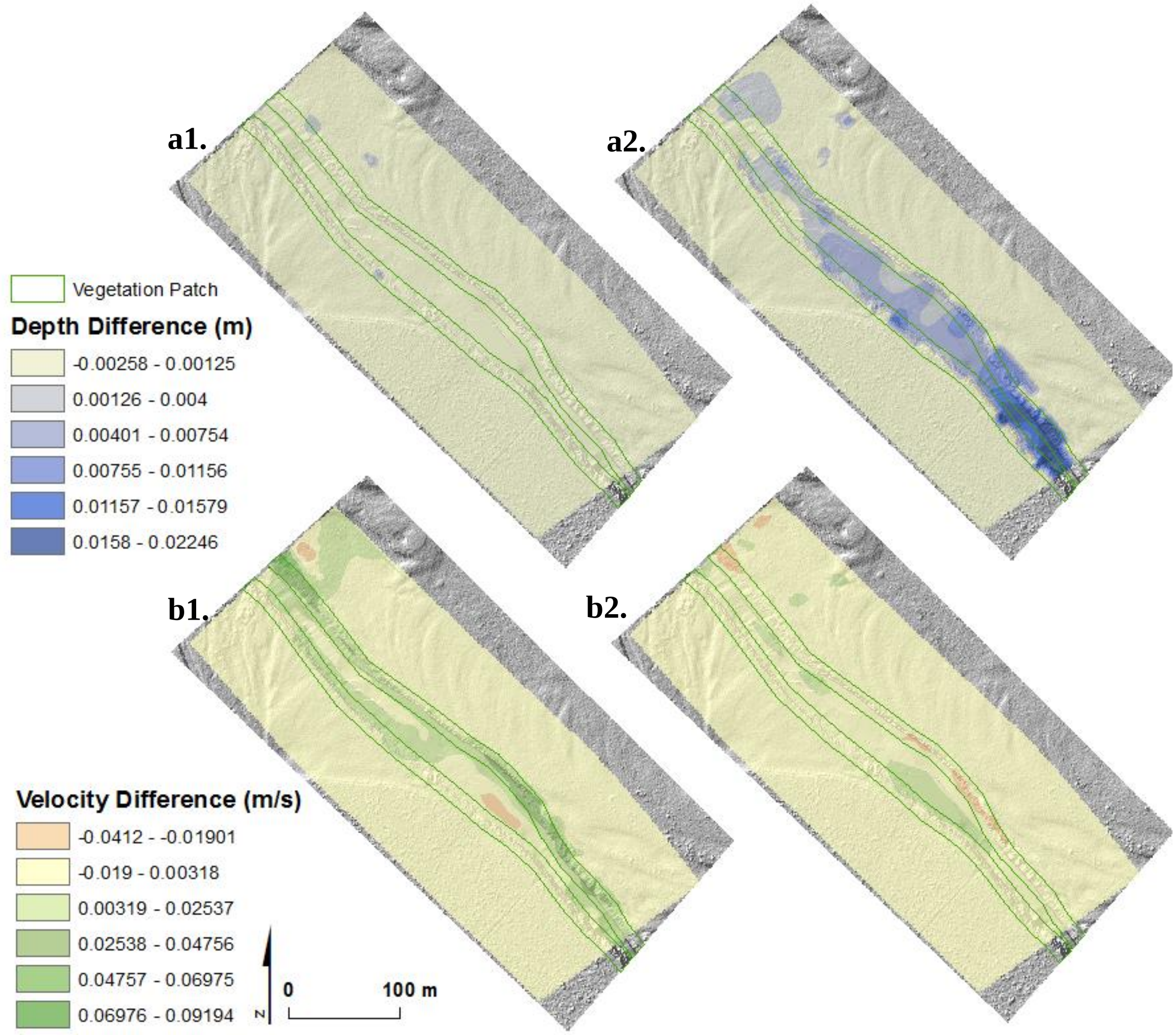

Figure 4.4. Future conditions modeled given vegetation height and density under 10-year recurrence interval flow: *P. arundinacea* – *E. palustris* (a1 and b1), *P. arundinacea* – *C. vesicaria* (a2 and b2).

4.2.2. Modeling based on vegetation roughness

In the 10-year flow, velocity results showed generally faster values for the invasive than the two native species, though these results were patchy and not banded as they were in the vegetation height and density runs (Figure 4.6 b1. and b2.). Bed shear stresses in were higher in *E. palustris* stands than the invasive and were lower within *C.*

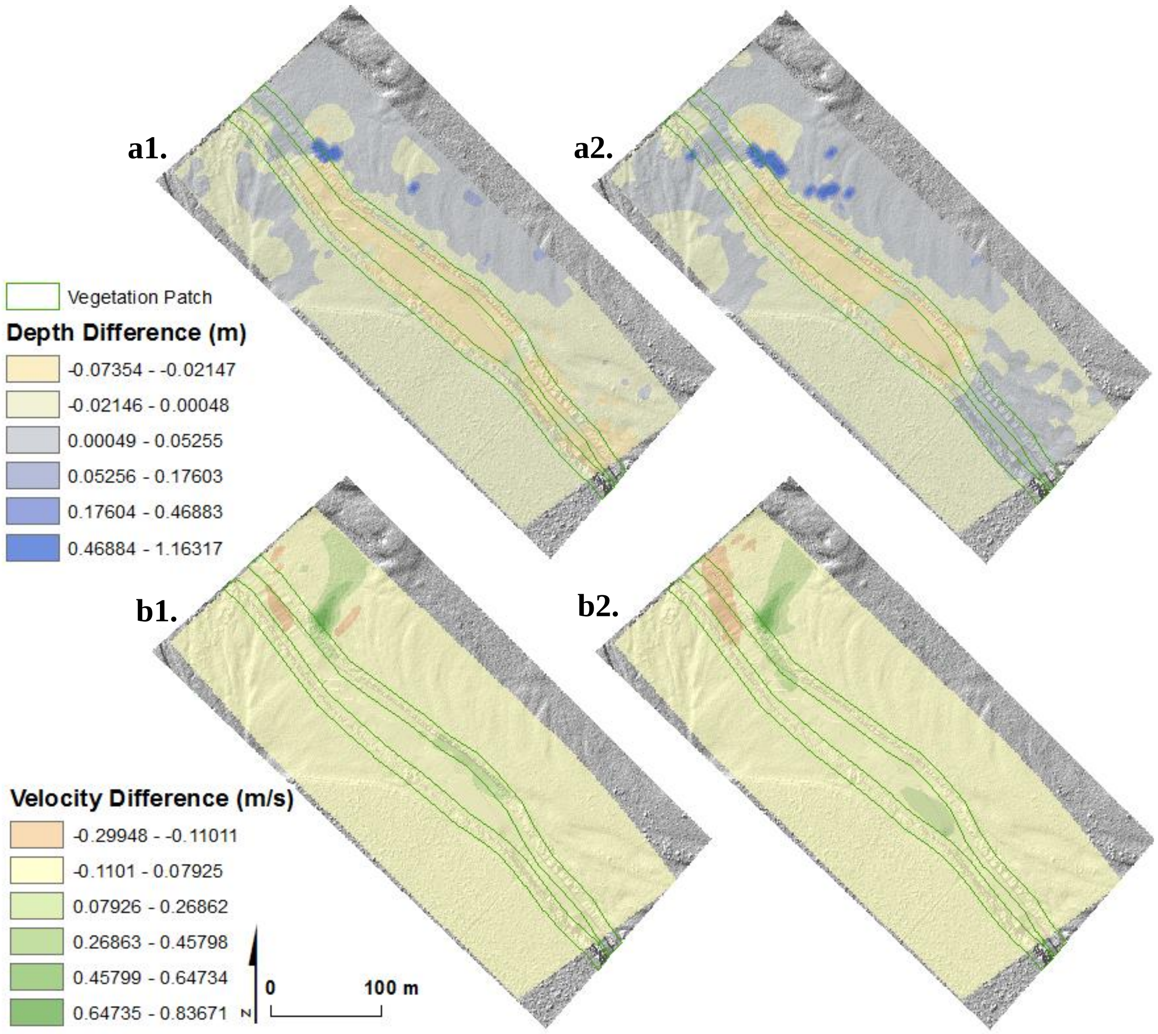

Figure 4.5. Future conditions modeled given vegetation height and density under 25-year recurrence interval flow: *P. arundinacea – E. palustris* (a1, and b1), *P. arundinacea – C. vesicaria* (a2 and b2).

vesicaria stands than the invasive (Figure 4.6 c1. and c2.). Differences in depth were confined to edges and backwater areas (Figure 4.6 a1. and a2.).

In the 25-year flow, the effect of the vegetation was less pronounced and depth and velocity results were similar between the invasive and natives (Figure 4.7 a1., a2., b1. and b2.). Bed shear stress was highest in *E. palustris* stands, intermediate in *P. arundinacea*, and lowest in *C. vesicaria*.

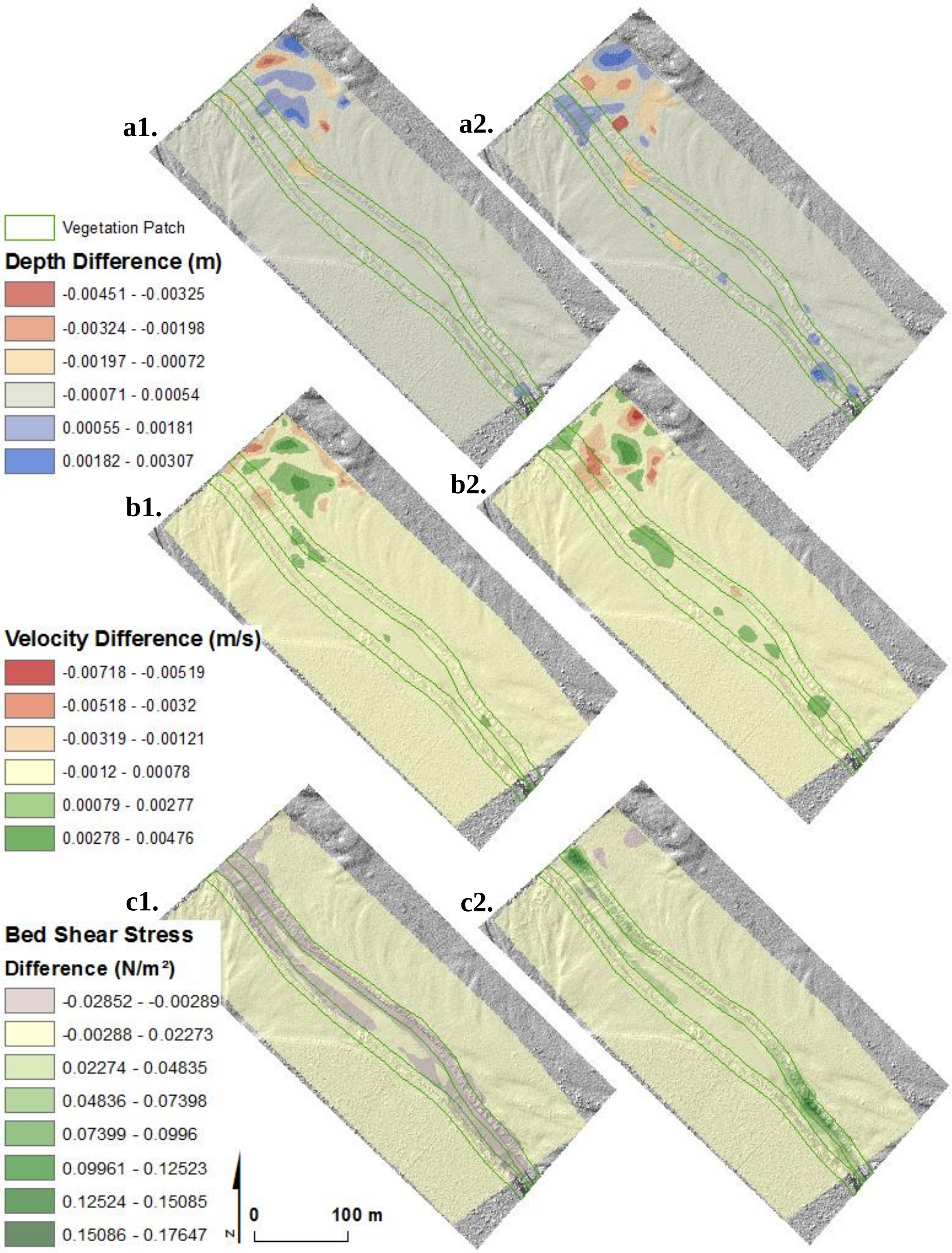

Figure 4.6. Future conditions modeled given roughness under 10-year recurrence interval flow: *P. arundinacea – E. palustris* (a1, b1, c1), *P. arundinacea – C. vesicaria* (a2, b2, c2).

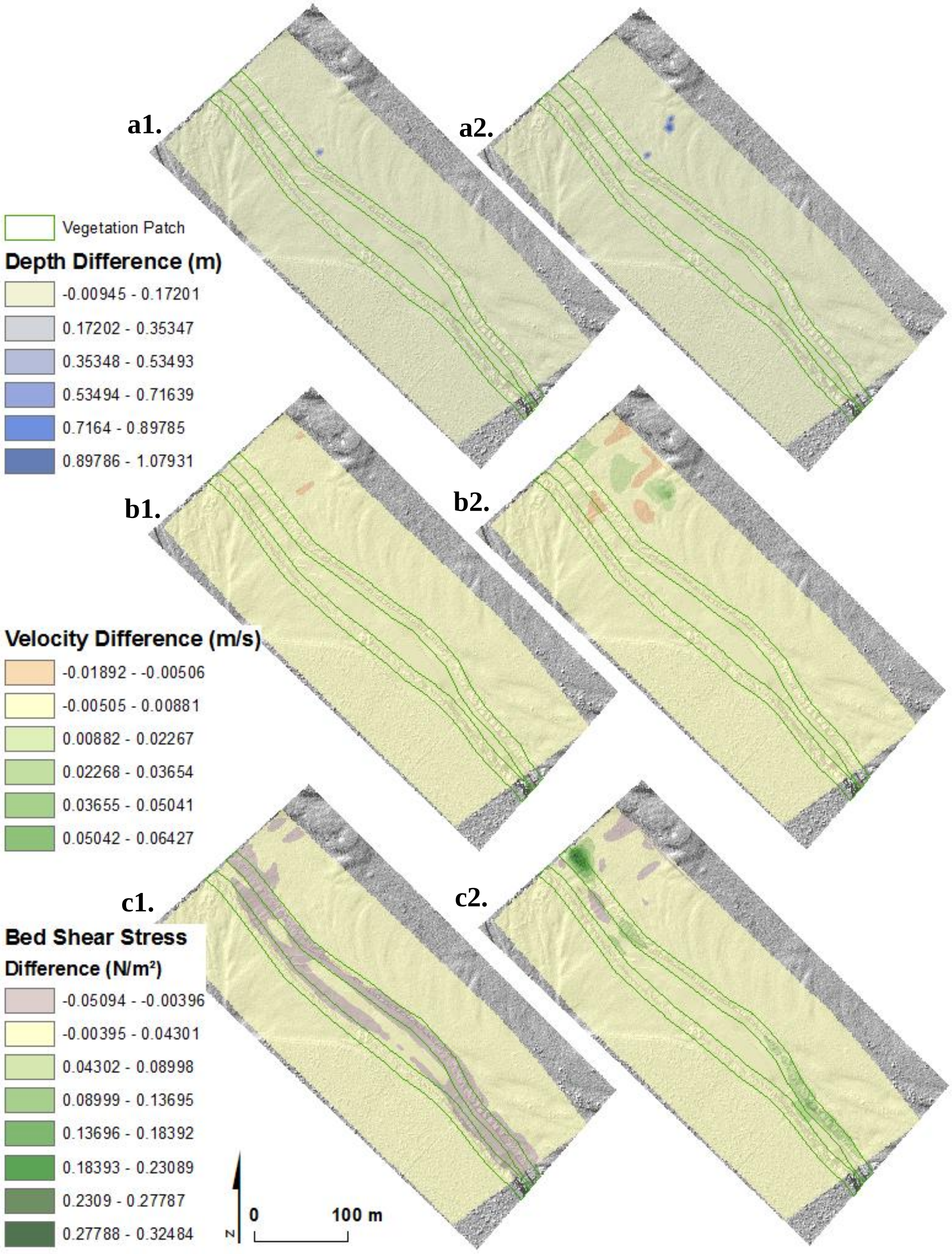

Figure 4.7. Future conditions modeled given roughness under 25-year recurrence interval flow: *P. arundinacea – E. palustris* (a1, b1, c1), *P. arundinacea – C. vesicaria* (a2, b2, c2).

5. Discussion

5.1. Model Performance

In general, the model produced realistic results regarding water depth, velocity and bed shear stress. Similarly realistic results were also produced within the vegetation patches. For example, the 10-year recurrence interval flow results agree, showing a decrease in bed shear stress (Figure 4.4.) and an increase in velocity (Figure 4.3.) with a switch in species composition from *E. palustris* to the invasive given roughness conditions (Figure 4.2.) and vegetation height and density (Figure 4.3.), respectively. The magnitude of the results in the vegetation runs were comparable to results obtained in the future condition model runs. According to sampling via ADV (Acoustic Doppler Velocimeter, M. Dawson, Klamath tribes Research Station, personal communication), velocities along the Sprague at these flows are similar to those modeled. In addition, shear stress results are consistent with what would be expected in this environment. In the shift from the 10-year to 25-year flow, an increase in discharge was accommodated by increases in both water depth and velocity, though depth increased more than velocity.

The most realistic results were likely those run with the roughness calculations because these roughness values incorporate vegetation characteristics such as vegetation height and density as well as general channel characteristics. The roughness runs also provide the user with an additional output, bed shear stress, which can be useful when studying a particular system. However, anomalies were evident when comparing the vegetation height and density runs to the roughness runs. For example, vegetation height caused a significant difference in water depth when comparing the invasive and *C. vesicaria* in the 10-year flow. However, this difference was not present in the roughness runs. Similarly, vegetation density altered velocity more significantly within *E. palustris* stands compared to *P. arundinacea* but this difference was not apparent in roughness runs.

5.2. Interpretation of Results

5.2.1. Modeling based on vegetation height and density

When modeling hydraulic conditions under 10-year flows, water depths within *C. vesicaria* stands were lower than those found in the invasive. This was likely due to the invasive's greater height which enhanced water flow interruption compared to the shorter *C. vesicaria.* Thus, the invasive caused the water to adjust vertically, creating higher water depths when it was occupying the channel. In this case, depths modeled with the invasive were on average 0.2m higher than those in the native. Both species were inundated within the main channel boundaries and less inundated with increasing distance from the thalweg and were likely to be partially bent down by the flow, though the model has no way to account for stem flexibility. Velocities were not significantly different.

When comparing the invasive and *E. palustris* stands at the 10-year flow, the native experienced higher velocities, due to its lower density, but little to no difference in water depth. The model likely adjusted water depth given differences in vegetation height, thus accounting for higher vegetation stands and their interruption to the water flow by extending the water surface vertically. Velocity, which is primarily affected by the density of stems and plants within a stand, decreased more in regions where density was higher. I saw greater differences between the invasive and *E. palustris* stands than between the invasive and *C. vesicaria* stands because vegetation density is more influential in the model than plant height. According to Gran and Paola (2001), the degree to which vegetation influences flow velocities is dependent on the density of plants and stems. Results from this model are consistent with this idea. In the future, a decrease in stem density resulting from a shift from *E. palustris* to the invasive may mean a decrease in flow interruption that will likely result in increases in velocity. Such changes in velocity could lead to decreased deposition and enhanced erosion.

5.2.2. Modeling based on vegetation roughness

P. arundinacea had higher shear stress than *C. vesicaria* with differences on the order of 0.10 N/m^2. This was due to a higher roughness within *P. arundinacea* stands. Differences in bed shear stress when comparing the invasive and *E. palustris* were small, at a maximum, 0.02 N/m^2 different. Therefore, according to changes in shear stress, if the invasive outcompetes *E. palustris,* shear stresses are likely to remain similar or decrease only slightly and geomorphic processes will continue to operate as they are currently. However, if the invasive outcompetes *C. vesicaria*, shear stress will increase, leading to lower velocities and possibly deposition within the invasive stand. Deposition could form higher banks that are less resistant to erosion, which may translate to increased channel bed erosion creating deeper, narrower channels in areas where *C. vesicaria* has been overtaken by the invasive.

In the 25-year flow, differences in bed shear stress still existed but were less marked which was likely due to a dampening effect as discharge increased; as discharge and water depth increased, plants became fully submerged in the water column and had less of an impact on velocity and shear stress within the channel (Wu et al., 1999). In effect, vegetation was felt less as flow conditions overcame the height of the vegetation patch. Depth was approximately 0.3m deeper in the 25-year flow which was fairly consistent throughout the channel. Velocity showed more scatter in difference and was anywhere from 5 to 30% greater in the 25-year flow.

Finally, some attention should be placed on the location, rather than just the mere presence of particular species given that the invasive occupies specific areas along the channel banks (Figure 4.8.). This could be important given that the channel experiences higher velocities closer to the thalweg. If the invasive continues to occupy areas previously occupied by natives, it will begin encroaching further into the channel and decreasing velocity in these areas due to its higher roughness compared to *C. vesicaria.* Furthermore, the dominant native in the upper reaches of the Sprague (near the study site, Figure 4.1a) is *C. vesicaria,* while *E. palustris* is the primary dominant native in lower reaches of the river. In addition, previous work regarding the bank cohesion provided by roots for these three species has shown that *P. arundinacea* and *C. vesicaria* have similarly high cohesive properties. However, *E. palustris* has much lower cohesion abilities. Therefore, in areas where the invasive is outcompeting *E. palustris,* it is increasing bank stability and resisting erosion by fluid forces. This could mean more stable surfaces in these areas. Further work must be conducted to fully understand these processes.

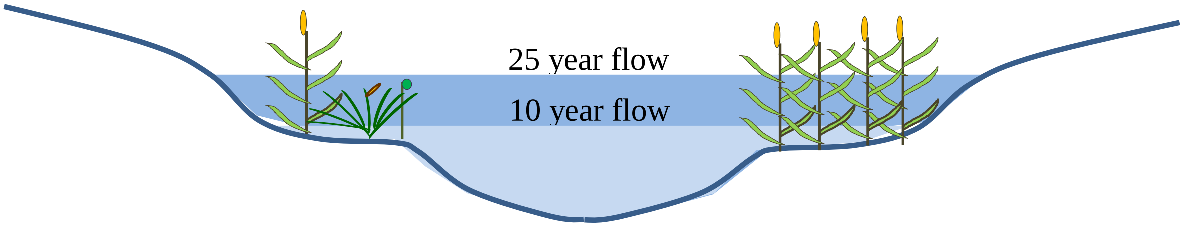

Figure 4.8. *P. arundinacea, C. vesicaria* and *E. palustris* occupying typical channel locations (left bank), and conditions if the invasive outcompetes both of the natives (right bank).

6. Conclusion

Differences in vegetation characteristics such as density, height, and roughness, can cause changes in stream channel velocity and bed shear stress that may lead to changes in channel morphology as a result of invasive species occupation. Along the Sprague River, Oregon, *P. arundinacea* is outcompeting native species *E. palustris* and *C. vesicaria.* Previous work regarding the effect of vegetation on channel processes has primarily considered woody vegetation. However, dominant, herbaceous, flexible vegetation, in low gradient streams such as the Sprague can influence roughness and therefore channel processes. In systems dominated by flexible vegetation, species composition changes from native plants to the invasive *P. arundinacea,* can affect channel morphology in the future. With a shift from native *E. palustris* to *P. arundinacea* a decrease in vegetation density will increase water velocities. A shift from *C. vesicaria* to the invasive will increase roughness. Based on the results, this shift will manifest itself as an increase in bed shear stress. These vegetation characteristics and hydraulic changes will cause changes in channel morphology that will affect habitat and therefore, must be taken into account as the invasive continues to expand in this environment.

CHAPTER V

SUMMARY

In this dissertation, I examined the above ground and below ground influences of native and riparian herbaceous vegetation on the geomorphology of the Sprague River, Oregon. Previous research of this nature has focused on large, woody species such as *Tamarix*. This research is one of the first studies to investigate the influence of a small, but highly invasive vegetation. Despite its similarity to the native species *E. palustris* and *C. vesicaria*, the invasive *P. arundinacea* has the potential to influence erosional and depositional processes differently than the native species. This could be causing an alteration in geomorphic processes where the invasive is outcompeting the natives.

In Chapter II, I evaluated the below ground effects of the invasive and native species using traditional root distribution surveys, root tensile strength measurements, and the model RipRoot to estimate added bank cohesion due to roots. All three species in this study had smaller root diameters than comparable species in previous research. Root depths in this study, however, were comparable to other studies that have examined herbaceous vegetation. Root Area Ratio values showed general trends that have been observed in previous work as well. Among the three species, the native *C. vesicaria* exhibited the largest root sizes and largest RAR. *C. vesicaria* had the highest tensile strength associated with its roots. This was followed by *P. arundinacea* and *E. palustris*. Cohesion, which is highly influenced by root size distribution, was highest for *C. vesicaria* and was followed by *P. arundinacea* and *E. palustris.* The additional cohesion provided by the invasive when compared to *E. palustris* means that roots are enhancing bank stability in areas where the invasive has outcompeted the native. This could mean a decrease in lateral channel migration, a decrease in the likelihood of channel widening, and may lead to increased shear stress on the channel bed that will result in incision and increased stream depth. This may enhance salmon habitat since water temperature, which is highly influenced by channel depth, is of concern.

The above ground influences of the invasive and native species were addressed in Chapter III. In the field, I measured stem density, stem stiffness, plant density, height, and frontal area for input into an equation to determine roughness provided by the invasive and native species. Stem density was significantly higher in stands of the native *E. palustris and* was followed by *C. vesicaria* and *P. arundinacea.* Measured stem stiffness was highest for the invasive. The native *E. palustris* had the highest roughness which was likely due to its high stem density values. This was followed by the invasive which had high stem stiffness values. *C. vesicaria* had the lowest vegetation roughness value and was significantly different than the other two species. The roughness values obtained via this method were slightly smaller but still comparable to other roughness values calculated for similar vegetation. To obtain a complete channel roughness, I used the additive approach to determine base channel roughness and then added the calculated vegetation roughness. Deposition was also directly measured within the plant stands and correlates with calculated roughness values. Given these roughness values and observed deposition, these results would mean aggrading banks on depositional surfaces on the order of 1cm per year for the invasive and *E. palustris.* Over time, this may cause narrowing of the channel in areas where the invasive has outcompeted *C. vesicaria.*

In Chapter IV, I utilize the data gathered in Chapter III to model channel depth, water velocity and bed shear stress along two reaches of the Sprague River to simulate changes over time due to vegetation colonization. I modeled water depth and velocity by first occupying the channel with vegetation heights and densities currently present. Another set of runs was completed under future conditions involving complete colonization by each of the three species along the banks to determine changes in depth and velocity if one species completely colonizes the channel banks. I also preformed separate runs in which I varied roughness for the current and future conditions. *E. palustris*, given its high vegetation density and roughness, had the greatest ability to alter stream velocity and bed shear stress. Therefore, if the invasive continues to occupy and overtake areas previously inhabited by *E. palustris,* increases in velocity and decreases in bed shear stress will result.

Overall, I have found that the invasive differs significantly in both above ground and below ground characteristics when compared to native species. Therefore, its geomorphic effects over time could be significant. These include a strengthening of channel banks against erosion when the invasive occupies areas previously occupied by *E. palustris*. In addition, channel roughness, and therefore likely deposition, will increase in areas where the invasive is outcompeting *C. vesicaria*. Finally, I showed via modeling that differences in vegetation density and roughness cause changes in water velocity and bed shear stress.

With the number of restoration projects increasing throughout the United States and elsewhere, an understanding of the role invasive species play in our stream systems is important. Human modifications have changed streams so drastically that returning them to their historical conditions is not possible. The introduction of invasive species is one such modification. In ecosystems like the Sprague River, it is no longer feasible to completely remove the invasive vegetation. Instead, its past and future effects on the channel must be understood to incorporate this knowledge into restoration planning. Only then can sustainable restoration practices have the potential to be successful.

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