DETERMINING THE MOST IMPACTFUL INVASIVE VEGETATIVE SPECIES ON FRESHWATER SALMON HABITAT IN WESTERN WASHINGTON DURING 2021: USING LITERATURE AND SURVEYING PROFESSIONALS

by

Danielle Green

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Danielle Green

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by

Kathleen Saul, PhD
Member of the Faculty

Date

ABSTRACT

Determining the Most Impactful Invasive Vegetative Species on Freshwater Salmon Habitat in Western Washington During 2021: Using Literature and Surveying Professionals

Danielle Green

Invasive vegetation is a growing problem in Western Washington. As invasive vegetative species (IVS) proliferate freshwater environments, they negatively impact ecosystems at an increasing rate. The iconic Pacific salmon (*Oncorhynchus* spp.) provide significant economic, environmental, and cultural values in Western Washington. Protecting dwindling salmon populations is more of a priority than ever before, since many species groups are currently endangered or threatened. The Salmon have experienced recent habitat degradation as a direct result of IVS domination and yet IVS has been commonly overlooked as a factor for salmon population decline. This study surveyed professionals and synthesized the relevant literature to gain a deeper understanding of IVS impacts on freshwater salmon habitat. The survey results narrowed down 52 noxious weeds to the following top four most impactful IVS: knotweed (*Fallopia* spp.), reed canarygrass (*Phalaris arundinacea*), yellow flag iris (*Iris pseudacorus*), and Brazilian elodea (*Egeria densa*). Using criteria derived from previous literature, based on salmon biology and environmental requirements, these four invasive plants were critiqued on their impacts towards overall biodiversity, sediment loads, stream chemistry, water flow regimes, stream temperatures, shelter abundance, migration route obstruction, and predator habitat. While knotweed and reed canary grass have been generally well-documented in scientific literature, substantial knowledge gaps appeared in the literature on yellow flag iris and Brazilian elodea research. Ultimately, the goal is to present this body of work to the public so that interested parties can collaborate more effectively, thereby enhancing efforts in Pacific salmon conservation and the fight against invasive species.

Presentation Link: https://arcg.is/1njGC8

Keywords: *invasive vegetation, noxious weeds, Pacific salmon, Western Washington, freshwater habitat, survey, reed canarygrass, yellow iris, Brazilian elodea, knotweed*

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Glossary

Allochthonous: *Originating or formed in a place other than where found* (Braatne et al., 2007; Custer et al., 2017)

Anadromous: *(of a fish such as the salmon) migrating up rivers from the sea to spawn. The opposite of catadromous* ([1]Oxford English Dictionary, n.d.).

Andisols: *soils derived from glass, pumice, and short-range minerals* (Bockheim et al., 2014).

Anthropochory: *The dispersal of seeds, spores, or fruit by humans* ([1]Definitions.net, n.d.).

Epilimnion: *The upper layer of water in a stratified lake* ([2]Oxford English Dictionary, n.d.).

Hydrochory: *The dispersal of seeds, spores, or fruit by water* ([2]Definitions.net, n.d.).

Hypolimnion: *The lower layer of water in a stratified lake, typically cooler than the water above and relatively stagnant* ([3]Oxford English Dictionary, n.d.).

Invasion Ecology (aka Invasion Biology): *the study of the establishment, spread, and ecological impact of species translocated from one region or continent to another by humans* (Sol, 2001 as cited in Henderson et al., 2006).

Invasive Vegetative Species (IVS): *any foreign/alien/non-native vegetation brought over from other regions of origin since European colonization of the United States, both intentionally and unintentionally, that cause human, environmental, or economic harm and has the ability to rapidly spread and reproduce, are characteristically adaptable, have a broad niche, appear aggressive, and are typically r-selected species. 'Invasive vegetative species' does not include intentionally planted agronomic crops or non-harmful exotic organisms* (Executive Order 13112 - 1. Definitions). **The terms Invasive Vegetative Species and Noxious Weeds are synonymous.*

Lacustrine: *Relating to or associated with lakes* ([4]Oxford English Dictionary, n.d.).

Lentic: *(of organisms or habitats) inhabiting or situated in still fresh water* ([5]Oxford English Dictionary, n.d.).

Lotic: *(of organisms or habitats) inhabiting or situated in rapidly moving fresh water* ([6]Oxford English Dictionary, n.d.).

North-of-Falcon (NOF): *public planning forum in which federal, state and tribal fish managers meet in tandem with PFMC deliberations on ocean seasons, to set recreational and commercial salmon fisheries for waters within three miles of the coast of Washington and northern Oregon, as well as Puget Sound. The North of Falcon season setting process occurs in a series of public meetings each spring, attended by federal, state, tribal and commercial fishing industry representatives and concerned citizens.* (Iverson, 2008). For more information visit: https://wdfw.wa.gov/fishing/management/north-falcon

Nutritional Pulses: "*Pulses are a low-fat source of protein with high levels of protein and fibre* [sic]. *Pulses also contain important vitamins and minerals like iron, potassium and folate* [sic]*.*" (Global Pulse Confederation [GPC], n.d.).

Oligotrophic: "*(of lakes and similar habitats) poor in nutrients and plant life and rich in oxygen: Compare eutrophic."* (Dictionary.com, n.d.)

Phenotypic plasticity: *Phenotypic plasticity is the ability of the same genotype to produce a different phenotype under different environmental conditions* (Waples et al., 2009).

Phytomining: *"the production of a `crop' of a metal by growing high-biomass plants that accumulate high metal concentrations"* (Brooks et al., 1998).

Population (in reference to salmon): "*a scientifically designated, biologically distinct group of individuals (e.g., Lower Columbia River Spring Chinook, Skagit River coho) adapted to life in the special conditions of our state's rivers and estuaries*" (Washington Department of Fish and Wildlife [WDFW], 2011).

Resilience: "*the amount of disturbance that an ecosystem can accommodate without shifting to a different regime or stability domain as characterized by a fundamentally different structure, function, and feedback mechanisms"* (Walker et al., 2004, as cited in Bottom et al., 2009, introduction section).

Response diversity: "*Variation in response to environmental change among species with the same ecosystem function" (Elmqvist et al., 2003, abstract). "Diverse life histories within and among Pacific salmon species are a population-level example of response diversity"* (Bottom, et al., 2009, response diversity section).

Salmon ecosystem: "*an integrated system of people and environments that are directly linked to anadromous salmon populations or groups of populations within geographic areas"* (Bottom et al., 2009, introduction section).

Salmon ecosystem resilience: "*…a measure of whether this integrated and adaptive system can reorganize, renew, and persist following disturbance"* (Bottom et al., 2009, introduction section).

Semelparity: *the reproductive process that includes death soon after mating* (Quinn, 2005).

Stakeholder: *any individual/entity that has an interest or concern about the health of the environment; including residents, such as animals, plants, micro- and macro- organisms, etc. The word stakeholder, in the context of this thesis, is synonymous with 'concerned party', be it an agency, company, group, or individual. Therefore, the term stakeholders, in this sense, align with the parties who are affected by the economics, environmental impacts, political implications, public health impacts, etc. of activities related to Pacific salmon and/or invasive vegetation.*

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The Road Not Taken
Robert Frost (1874-1963)

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

Chapter 1: Introduction

This thesis project answers the question, which invasive vegetative species have the greatest negative impact on Western Washington's freshwater salmon habitat in 2021 by using literature and surveying professionals. To best implement such a topic, I have broken up the thesis into chapters. **Chapter 1** will include the significance of this research, my statement of positionality, an overview of the study area, a brief history on salmon and invasive vegetation, and a look at the partnerships involved. **Chapter 2** consists of an extensive literature review on salmon, invasive vegetation, salmon habitat, and stakeholder relationships; each of these will have their own sub-sections as well. **Chapter 3** encompasses the methods used for this thesis. **Chapter 4** covers the results and discussion from both the literature as well as a survey completed by field professionals, going into detail on each of the top species and their potential impacts to salmon habitat. Finally, **Chapter 5** provides the conclusion for this thesis, forms logical correlations between the topmost impactful invasive vegetative species and Pacific salmon habitat, and recommends future research where knowledge gaps may exist. References made within the text to various sections of this thesis, such as Chapters, Figures, Tables, Appendices, etc. will be in bold font. Furthermore, this thesis does not discern between "wild" or hatchery populations of salmon as the focus is on habitat, which both populations use.

1.1 Significance of Research

Studies indicate that salmon have been extirpated from approximately 40% of their historic range in the Pacific Northwest (Stark, n.d.; Zemek, 2019). As keystone species, these animals persist as vital importance to the ecosystems in which they exist.

Salmon facilitate several natural processes, such as providing a primary seasonal food source to many predatory species of fauna, including orcas, bears, raptors, and others, deposition of marine nutrients into terrestrial environments, and by regulating macroinvertebrate populations. Past experimentation has taught ecologists and conservationists that abrupt removal of a keystone species has generally precipitated catastrophic collapse of its native ecosystem (Mills et al., 1993). Public outcry from ecologists, environmental professionals, indigenous communities, and the general public has encouraged salmon recovery programs and preservation of this iconic species.

Plants are taxonomic group with the highest abundance for non-indigenous species in Washington, Oregon, and Idaho (**Figure 1**) (Sanderson et al., 2009). Since the advent of invasion ecology, around the turn of the millennia, there has been a growing body of evidence which points to invasive vegetation as a contributing factor in salmon habitat degradation. The implications of invasive vegetative species on the health of Pacific salmon habitat have not been thoroughly studied. However, it remains imperative that science ultimately quantify these effects so that environmental agencies, ecological organizations, and conservation groups possess the knowledge necessary to confront the looming crisis of Pacific salmon population decline.

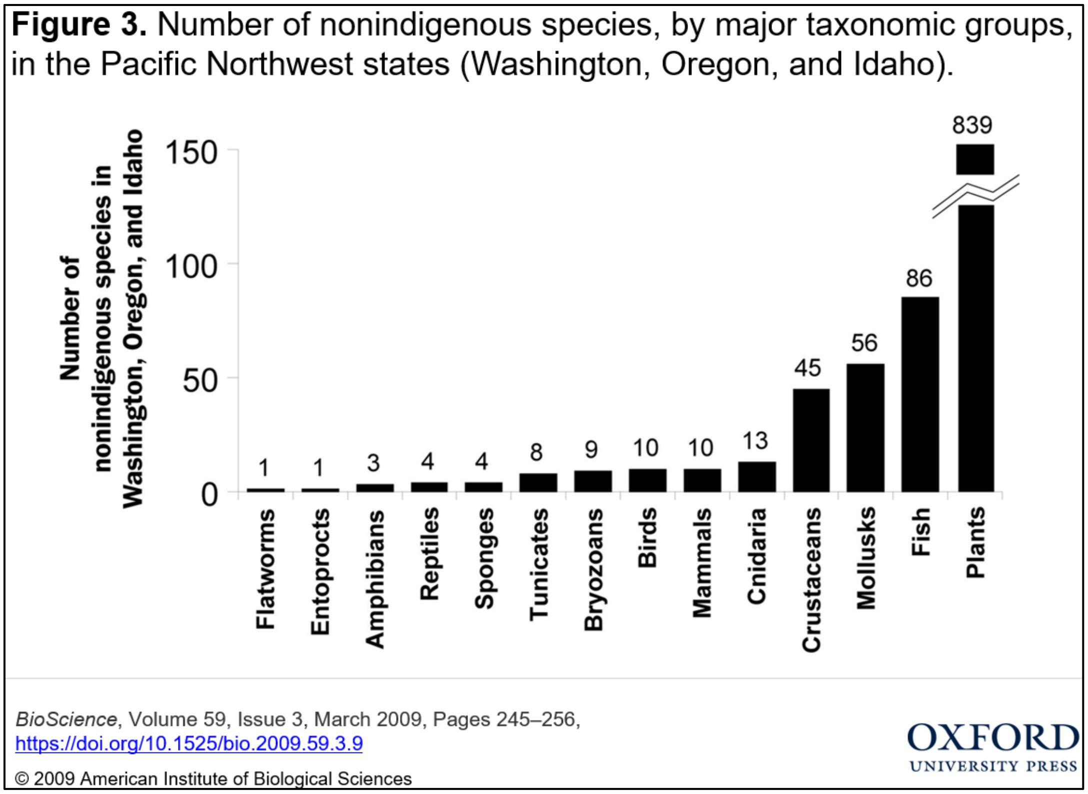


Figure 3. Number of nonindigenous species, by major taxonomic groups, in the Pacific Northwest states (Washington, Oregon, and Idaho).

BioScience, Volume 59, Issue 3, March 2009, Pages 245–256,
https://doi.org/10.1525/bio.2009.59.3.9

Figure 1: Non-indigenous ranking of taxonomic groups in PNW.
Plants are the highest-ranking taxonomic group for most species non-indigenous to Washington (WA), Oregon (OR), and Idaho (ID) (Sanderson et al., 2009, Figure 3).

Salmon have continued to be especially sensitive to various environmental conditions, including overall biodiversity (such as macroinvertebrate and flora populations), sediment loads, stream chemistry (such as DO and pH), water flow regimes, stream temperatures, shelter abundance (such as down woody debris (DWD)), migration route obstruction, and predator habitat. As of yet, there is not significant research into how certain types of IVS impact each of these factors. This study only addresses the highest priority invasive vegetative species and their inherent impacts to salmon habitat. Not only is this thesis taking on a novel concept by relating invasive vegetation and their specific ecological impacts to salmon habitat, but by narrowing the focus to such precise conditions, as well as compiling all of the information into a single document, will better allow various agencies to efficiently combine efforts and resources. An interdisciplinary approach will be necessary to effectively apply these findings to a salmon habitat management strategy.

1.2 Statement of Positionality

Growing up as a natural born American white female I no doubt had privilege, but that was often obscured by my rough upbringing. As a result, I tended to gravitate more towards nature for companionship while hiding from the human world. I owe a lot of who I am to mother nature, especially as somebody who grew up without a mother of my own. I have had to overcome many personal struggles; of which, I always seemed to gravitate towards nature to heal myself… or for safer shelter.

While attending Green River College (GRC) in the Natural Resource Department, I was able to attain four associate of applied science degrees, including Associate of Applied Science (AAS) degrees in the fields of 1) Forestry, 2) Geographic Information System (GIS), 3) Park Management, and 4) Water Quality, as well as one Bachelor of Applied Science (BAS) degree in Forest Resource Management. I was also a tutor for many of my classes, as I have a strong passion for helping others. Furthermore, I was a guest speaker multiple times, and later an adjunct instructor, for the five-credit class: 'Bio-Invasions: Invasive Species Management' class (NATRS 386).

During my graduate course at The Evergreen State College (TESC), I focused all of my assignments around the topic of 'invasion ecology' and thus began working on this thesis. Because of my background, I see invasive vegetation as the "bullies" of the vegetation world. I strongly believe that invasive vegetative species (IVS), when in their natural environment, can shine with all their glory and be admired for all of which they provide; but as the saying goes, 'there exists a time and place for everything'; and in many habitats IVS are definitely out of place. For instance, I acknowledge that Himalayan blackberry (*Rubus bifrons*) provides nutritional value as delicious antioxidant-rich aggregate fruits. I also understand that while in North America, this blackberry constantly "bullies" its native counterpart, by outcompeting for available resources, reproducing vigorously, and depleting soil nutrients. Throughout my academic career I have seen ample evidence for a need to manage noxious weeds in order to preserve the majestic native ecosystems of Western Washington.

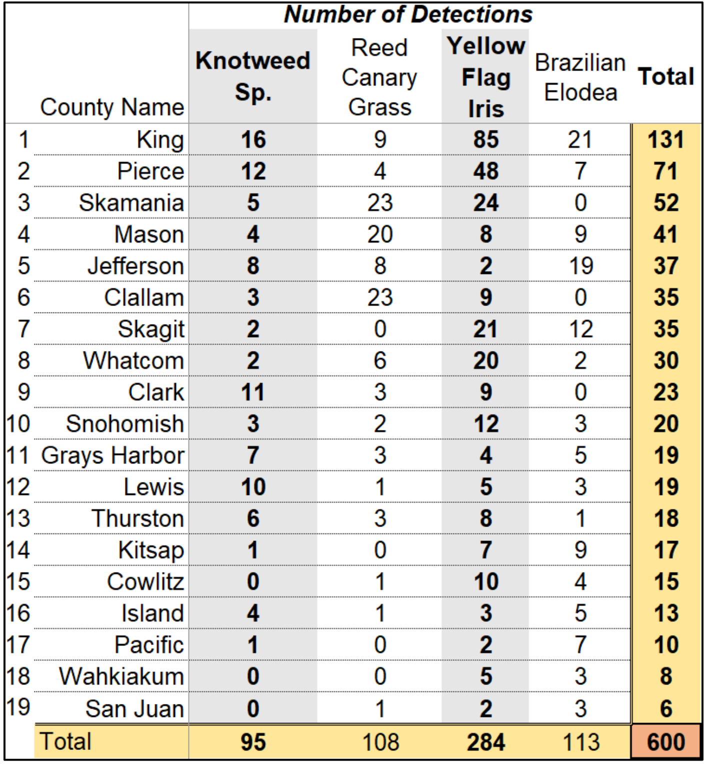
1.3 Study Area

Western Washington consists of a diverse landscape situated between the Puget Sound lowlands and the Pacific Ocean to the west and stretches to the high elevation peaks of the Cascade Mountain Range to the east. The historic ecological composition of the Pacific Northwest (PNW) is dominated by sprawling mixed forests of conifer and deciduous tree species. The dominant soils of Western Washington originate from igneous parent material deposited from marine encroachment, glacial activities, and volcanic processes (Littke et al., 2011). These primary Andisols, created by the tectonic process of subduction and seismic uplift, as well as the upwelling of molten material under the North American plate, form the foundation of diverse ecology in Western Washington (Pazzaglia & Brandon, 2001; Brockway, 1998). Washington has a temperate climate, due to its latitudinal position between the 46° and 49° parallels (Western Regional Climate Center [WRCC], n.d.). Precipitation falls as both rain and snow; although, the mountains accumulate most of the snowfall. A single year's maximum rainfall intensities, out of a ten-year period, can be as much as one inch in a single hour or up to seven inches over twelve hours, with the higher intensities occurring along the windward slopes of the mountains (WRCC, n.d.). Thunderstorms and hailstorms have been infrequent to Western Washington (WRCC, n.d.). Monthly sunshine can average "from approximately 25 percent in winter to 60 percent in summer" (WRCC, n.d., Western Washington section). The 19 counties situated within this study area (**Appendix E1**) include: Clallam, Clark, Cowlitz, Grays Harbor, Island, Jefferson, King, Kitsap, Lewis, Mason, Pacific, Pierce, San Juan, Skagit, Skamania, Snohomish, Thurston, Wahkiakum, and Whatcom.

Using stream data collected from the Department of Natural Resources, there exists an estimated total of over 164,000 miles of streams within Western Washington. Of these streams roughly 24%, are Type F, also known as fish-bearing streams. Fish-bearing streams were calculated from the water-courses shapefile on WA DNR's Open GIS Data Portal. According to the Washington Department of Fish and Wildlife (WDFW), "There are eight species of native "salmonids" in Washington [and] approximately 486 known "populations"": Chinook (*Oncorhynchus tshawytscha*) (**Appendix E2**), Chum (*O. keta*) (**Appendix E3**), Coho (*O. kisutch*) (**Appendix E4**), Pink (*O. gorbuscha*) (**Appendix E5**), Sockeye (*O. nerka*) (**Appendix E6**), Steelhead (*O. mykiss*) (**Appendix E7**), Bull Trout (*Salvelinus confluentus*), and Cutthroat (*O. clarkii*) (WDFW, 2011). Of these eight, only the first six mentioned will be the focus of this thesis.

According to data downloaded from EDDMapS, there have been 600 total locations where the top four invasive species have been observed throughout the 19 Western Washington counties (see **Table 1** and **Appendix E8**) (University of Georgia Center for Invasive Species and Ecosystem Health [UGCISEH], 2020). When search parameters are limited to a 200-foot buffer between IVS and salmon stream segments, all four of the IVS appear within 120 locations across 17 of the 19 counties; which are further detailed in **Chapter 4**. EDDMapS is further explained in **Chapter 3.4**.

Table 1: Top invasive species detections by county
Unfiltered county populations of knotweed, reedcanary grass, yellow flag iris, and Brazilian elodea (Data generated from EDDMapS). Table 1 is sorted by highest to lowest totals per county.



		Number of Detections				
	County Name	**Knotweed Sp.**	Reed Canary Grass	**Yellow Flag Iris**	Brazilian Elodea	**Total**
1	King	**16**	9	**85**	21	**131**
2	Pierce	**12**	4	**48**	7	**71**
3	Skamania	**5**	23	**24**	0	**52**
4	Mason	**4**	20	**8**	9	**41**
5	Jefferson	**8**	8	**2**	19	**37**
6	Clallam	**3**	23	**9**	0	**35**
7	Skagit	**2**	0	**21**	12	**35**
8	Whatcom	**2**	6	**20**	2	**30**
9	Clark	**11**	3	**9**	0	**23**
10	Snohomish	**3**	2	**12**	3	**20**
11	Grays Harbor	**7**	3	**4**	5	**19**
12	Lewis	**10**	1	**5**	3	**19**
13	Thurston	**6**	3	**8**	1	**18**
14	Kitsap	**1**	0	**7**	9	**17**
15	Cowlitz	**0**	1	**10**	4	**15**
16	Island	**4**	1	**3**	5	**13**
17	Pacific	**1**	0	**2**	7	**10**
18	Wahkiakum	**0**	0	**5**	3	**8**
19	San Juan	**0**	1	**2**	3	**6**
	Total	**95**	108	**284**	113	**600**

1.4 Salmon History

With salmon populations on the decline, any effort to protect salmon requires immediate implementation. Today, 14 salmon species groups have been listed under the Endangered Species Act (Governor's Salmon Recovery Office [GSRO] et al., 2021). Of these 14, five salmon species groups remain in crisis; including: three Chinook (Puget Sound, Upper Columbia River Spring, and Snake River Spring/Summer), one Sockeye (Lake Ozette), and one Steelhead (Puget Sound) (GSRO et al., 2021). Also, five species groups continually struggle to recover; such as: one Coho (Lower Columbia), one

Chinook (Lower Columbia River), two Steelhead (Upper and Middle Columbia River), and one Chum (Columbia River) (GSRO et al., 2021). However, four groups have been making progress and approaching the recovery goals set in place by The National Oceanic Atmospheric Administration (NOAA); these consist of: two Steelhead (Snake River Basin and Lower Columbia River), one Chum (Hood Canal Summer Run), and one Chinook (Snake River Fall Run) (GSRO et al., 2021). The information on these species has been established based on adult "wild" stocks, lacks complete data, and that is not meant to replace NOAA's status review.

Salmon act as a keystone species and are known to play an important role in the trophic web, both as predator and prey. Salmon also provide many ecosystem services as illustrated in **Figure 2** (Bottom et al., 2009). Additionally, after returning to natal streams, their carcasses deliver important marine nutrients (such as nitrogen, sulfur, and carbon) as well as salinity into forestlands, prairies, and other ecosystems that would otherwise be deprived of these nutrients (Rahr, 2019). Moreover, salmon continue to be vital to our economy. According to the Washington Department of Fish and Wildlife (WDFW) Conservation website, Salmon fishing contributes approximately $175 million yearly to Washington State's economy while it provides recreational activities to 150,000 anglers and enables the continuation of several crucial tribal traditions (Washington Department of Fish and Wildlife [WDFW], n.d.). Furthermore, salmon persist as a major food source for another endangered species, the Southern Resident Orca. Thus, improving essential salmon habitat could have positive effects on the survival of many species.

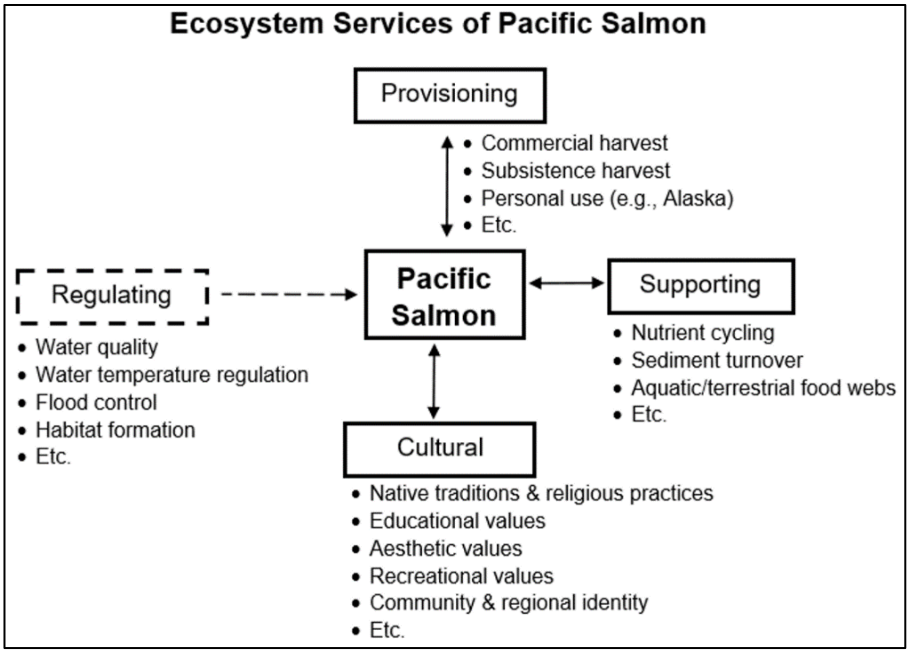


Figure 2: Ecosystem services of Pacific salmon

"Local salmon populations provide provisioning, cultural, and supporting ecosystem services that benefit people. These services often involve two-way interactions with feedbacks to salmon. Because salmon populations are sensitive to changes in environmental quality and habitat structure, they also are indicators of important regulating services that people derive from resilient salmon ecosystems." (redrawn from Bottom et al., 2009, Figure 2). The quote was taken directly from Bottom et al., 2009, Figure 2.

1.5 Invasive Vegetation History

Starting around 1845, Charles Darwin made the first mention to the potential awareness of invasive species (Henderson et al., 2006). The first weed law, according to the Noxious Weed Control Board (NWCB), passed in 1881 to combat the establishment of Canada thistle (*Cirsium arvense*) (Washington State Noxious Weed Control Board [NWCB], n.d.). In the late 1960's legislature established the Washington Noxious Weed Control Board (NWCB, n.d.). Later, the Global Invasive Species Programme (GISP) of 1997 (Henderson et al., 2006) formed. Then, in 1999, former President Bill Clinton passed Executive Order 13112, which created the National Invasive Species Council (NISC) and further promoted a need for management and control.

Invasive vegetative species (IVS) have been a substantial element of the anthropogenic changes to the natural systems of this planet. As of 2004, across the United

States, invasive plants covered roughly 133 million acres and persist with an estimated 1.7 million-acre spread per year (US Forest Service [USFS], 2004). Moreover, IVS can be seen just about anywhere. They remain present in and around cities and along highway corridors, such as where the frequency of soil disturbance becomes higher (Hansen & Clevenger, 2005) and where the density of humans increases (Spear et al., 2013). IVS cause varying levels of damage, such as reduction in local biodiversity, infiltration of municipal water systems, damage to infrastructure, reduced productivity of agricultural land, and depreciation of property value. IVS also require significant financial resources to manage as well as to maintain recovered areas; for instance, both rush skeletonweed (*Chondrilla juncea*) and Scotch broom (*Cytisus scoparius*) each cost Washington over $140 million annually to manage (Community Attributes Inc. [CAI], 2017). These costs only increase over time, as the species becomes more established in an area, as illustrated in **Figure 5**.

Invasive vegetation has the potential to dramatically affect salmon habitat, due to the biological sensitivity of salmonids to environmental changes, which become compounded by climate change and human influences (Bisson et al., 2009). By understanding the impact of invasive noxious weeds on salmon habitat, various conservation and ecological organizations/agencies/etc. will be able to better collaborate management efforts with salmon conservationists. This collaboration will allow for these various groups to combine efforts, time, money, and resources in a way that will lead to possible eradication of high priority invasive species. Eradicating the most impactful species will also increase the salmon recovery and enhancement efforts.

To best investigate such a thesis topic, an extensive literature review assessing each invasive species based on various environmental criteria will be needed (**Chapter 2**). This literature review will be used to assess the framework as well as history of both IVS and salmon. The review will also provide a deeper look into the relationships between each of the stakeholders. Stakeholders include Pacific salmon species, Western WA tribal nations, private landowners, businesses, environmental conservationists, invasive vegetation, and the ecosystem. Although the non-human stakeholders do not communicate in the traditional sense, their rights to a healthy environment are no less important and thus need to be advocated for.

1.6 Partnerships

The range of stakeholders regarding salmon habitat conservation is essentially limitless. The interconnectedness that human society shares with Pacific salmon is significantly widespread, and applies to all social positions, demographics, and professional affiliations. For instance, private landowners are concerned with property value, which may decrease as a result of poor land management policies regarding salmon habitat, i.e., water quality, local ecosystem health, environmental regulations, etc. Business entities may be impacted by restrictions imposed on their operational capacity due to legislative mandates involving salmon habitat conservation. Environmental activists see the need to protect salmon as a means to preserve the natural function of the ecosystem. Some individuals derive a sense of cultural identity from Pacific salmon, such as indigenous peoples, and feel that the fight for these iconic fish species has been a fight for their history. This topic gets covered in more depth in **Chapter 2.4**.

Chapter 2: Literature Review

This literature review serves as the first step in determining the top four most impactful Invasive Vegetative Species (IVS) in freshwater salmon habitat within Western Washington. Presented from the viewpoint of a western science ecologist, this review takes on a broad approach to answer the question: *Which invasive vegetative species (IVS) have the most impact on freshwater salmon habitat in Western Washington from the perspective of current field professionals and literature during 2021?* Because managing for invasive vegetation can be a controversial topic, this literature review will present a wide range of stances on that subject matter.

This literature review will address four main topics: 1) Pacific salmon species, while sensitive to environmental factors, play a key role in Western Washington's ecosystem and within society, due to their environmental, cultural, and economic importance; 2) invasive vegetation, despite any potential benefits, has become a serious concern in Western Washington; 3) invasive vegetation affects salmon habitat, contributing further to the decline of salmon populations; as well as 4) interagency communication and collaboration, though improving, still poses challenges to efficient management of freshwater systems.

2.1 Salmon Introduction

Pacific salmon, *Oncorhyncus* spp., belong to the salmonid family. Six commonly identified species of true anadromous Pacific salmon include: Sockeye (*O. nerka*), Coho (*O. kisutch*), Chum (*O. keta*), Chinook (*O. tshawytscha*), Pink (*O. gorbuscha*), and Steelhead (*O. mykiss*). Sub-populations of salmon[-;]' can reject the instinct to migrate to sea; some of these include kokanee trout, a non-migrating version of sockeye salmon;

rainbow trout, a non-migrating version of steelhead; and cutthroat trout. These resident populations spend all their life stages in freshwater environments. The focus of this thesis pertains to freshwater habitat.

All Pacific salmon start their life cycle as an egg that had been deposited in a gravel nest, also known as a ‘redd’, excavated by the female fish, and fertilized by a male in a freshwater stream. Two to three months after fertilization, it emerges as a hatchling, or ‘alevin’, with an external yolk sac (BiologyWise.com, 2010; Quinn, 2005). Once the alevin has fully metabolized the yolk sac, it exits the redd and begins the salmon life stage known as ‘fry’, colloquially referred to as fingerlings. Migration typically occurs when the salmon are one to two years old, though this varies by species and environmental cues (National Park Service, 2019). The anadromous fish will feed and mature at sea for several years (Quinn, 2005); however, this thesis does not focus on marine habitat. Once they have developed enough and assimilated the appropriate amount of nutrients, they begin the arduous migration back to their natal waters (Groot & Margolis, 1991). Salmon are semelparous, once they reach their natal spawning grounds, they reproduce and then die. Theoretically, certain species of noxious weeds may only affect distinct stages in a salmon’s life cycle. Knowing these various stages and the needs of salmon within each, can better determine the level and rate of effects by IVS.

2.1.1 Salmon Importance

The vital importance of Pacific salmon to Washington’s environment, cultural identity, economy, and public health has been well-established (Bottom et al., 2009; Close, 2015; Colombi, 2012; Cronin & Ostergren, 2007). Many of the freshwater streams in the Pacific Northwest exist as oligotrophic environments (Olympic National Park, 2015). The annual return, death, and subsequent decomposition of salmon contributes a rich nutrient dump on which many organisms depend (Dillon, 2020).

The salmon-derived nutrient pulse, especially N, plays such an important part in the trophic web (**Figure 3**), that environmental restorationists often place their carcasses within and around streams (Bisson et al., 2009). For instance, in their 2002 study, Hocking and Reimchen noted that many organisms depend on the salmon’s annual migration to meet their own protein and nutrient demands. After spawning, decaying salmon carcasses provide substantial nutrient inputs to riparian vegetation and larger food webs. Hocking and Reimchen also mentioned that research studies tended to focus on vegetational uses of salmon nutrients, suggesting that macro-invertebrates of coastal coniferous forests of the Pacific Northwest, such as spiders, insects, worms, etc., should be considered as highly important in this ecosystem process (2002).

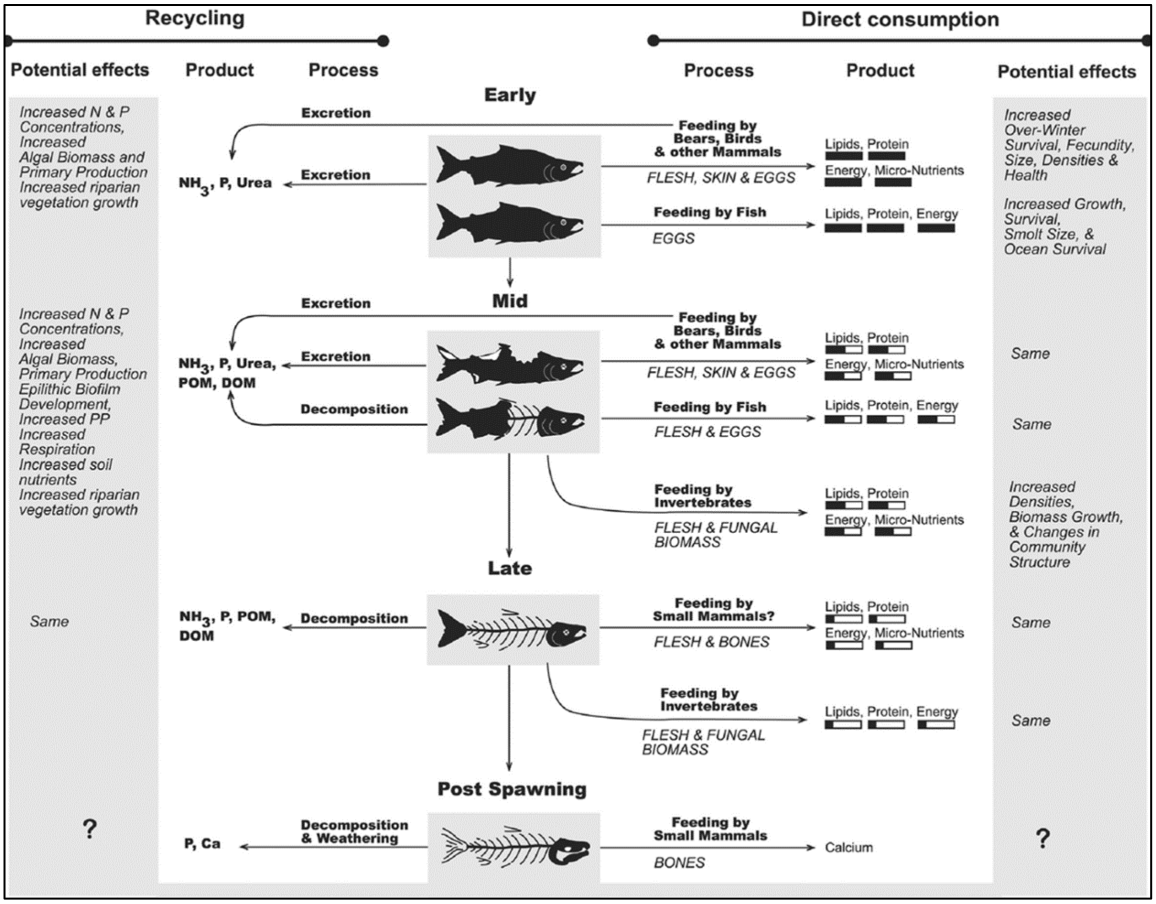


Figure 3: An example of the salmon nutrient pulse

"Schematic of major dispersal pathways for salmon-derived materials during the course of spawning. On the left is the "recycling" pathway and on the right is the "direct consumption" pathway. Boxes beneath the derived products of feeding pathways suggest changes in the importance of various components as spawning progresses and tissue chemistry and consumers change. Relative proportions are not to scale; they are simply suggestive of trends." (Gende et al., 2002, Figure 3).

Macroinvertebrate communities respond to salmon spawning and subsequent nutrient enrichment. During salmon spawning in the Snoqualmie River and Kennedy Creek in Washington State, aquatic invertebrate abundance declined; however, when salmon carcass decomposition began, invertebrate densities increased two-fold or greater compared to control reaches (Cederholm et al., 1999). Another 2002 study was conducted on six coastal watersheds in western British Columbia, in which the researchers correlated the presence of certain marine derived nutrients, C^{13} and N^{15}, within the riparian ecosystem with salmon abundance (Reimchen et al.). Several organic samples had been extracted from the riparian environments of each of the six locations, then processed and analyzed in a laboratory facility (Reimchen et al., 2002). The samples analyzed included tree tissue, vegetation foliage, invertebrates, and soil (Reimchen et al., 2002). Reimchen, Mathewson, Hocking, Moran, and Harris (2002) determined that concentrations of N^{15} were much higher in riparian areas with salmon presence when compared to riparian areas with an absence of salmon.

Furthermore, several large predatory fauna species derive a significant portion of their total annual nutritional requirements from the seasonal salmon runs. For instance, black (*Ursus americanus*), brown (*Ursus arctos*), and grizzly (*Ursus arctos horribilis*) bears often become primarily piscivorous during abundant salmon runs (Quinn, 2005), relying on the fish to supply them with adequate caloric mass to hibernate over winter. In British Columbia, foraging bears have been documented moving more than half to nearly all of the salmon biomass onto land, including as far inland as hundreds of meters, equivalent to multiple football fields, all the while redistributing vital nutrients through their urine and feces (Gende et al., 2002). The direct correlation of American Bald Eagle (*Haliaeetus leucocephalus*) populations to salmon migration has been well documented in the Pacific Northwest (Dillon, 2020). In fact, a 2018 study of the Skagit River showed that chum populations appeared to show parallelism with bald eagle populations (Rubenstein et al., 2019). Additionally, the orca (*Orcinus orca*), another iconic species of the Pacific Northwest, has a life-history intertwined with the fate of salmon. The current vulnerability of the resident orca population can be attributed to the depletion of wild salmon numbers (Lucas, 2009).

The indigenous peoples of the Pacific Northwest have relied heavily on wild salmon for subsistence, cultural purposes, and economic stability since time immemorial

(Blumm, 2017; Brown & Footen, 2010; Colombi, 2012). To indigenous tribes, salmon provide more than recreational activities and nutritious food. Tribal citizens celebrate salmon and sing about them in traditional ceremonies (Columbia River Inter-Tribal Fish Commission [CRITFC], 2016). Salmon have also been a primary food staple for more than 7,000 years (Cannon & Yang, 2006) and once acted as the source of a flourishing economy for the native peoples (CRITFC, 2016). Horace Axtell, a Nimiipuu elder tribesman, said this, "[t]he most important element we have in way of life is water. The next most important element is the fish…" (Colombi, 2012, p75).

2.1.2 Salmon Survival Needs

Knowing what key environmental factors influence healthy salmon populations at various life stages (**Figure 4**) will give insight into the criteria that could be used to assess the impacts of noxious weeds on freshwater salmon habitat. In his 2015 thesis, *Salmon Habitat Loss and Hatchery Dependence: A Case Study of Chambers Creek, Washington*, Julian Close explained the needs of salmon as they progress through their many stages towards adulthood (Close, 2015). For instance, rainbow trout/steelhead larvae prefer ambient temperatures near 19°C (66.2°F), and juveniles fair better in cooler temperatures around 13°C (55.4°F) (Sauter et al., 2001, P. 14). Furthermore, a 2009 study on coho, steelhead, chinook, and chum combined data on all four species from egg to fry stages and found that higher levels of very small sand/silt particles in the riverbed ("fines") decreased the odds of survival by about 17% (Jensen et al.). Once hatched, alevin retreat to the crevices of specific gravel substrate, unobstructed by fine sediment (Close, 2015). Anoxic conditions are fatal to salmon, but the more frequent sub-lethal effects of low DO concentrations can cause various biological impairments, such as impacts to growth and development, reduced nutritional intake, and a decrease in swimming performance and efficient upstream migration (Fellman et al., 2015).

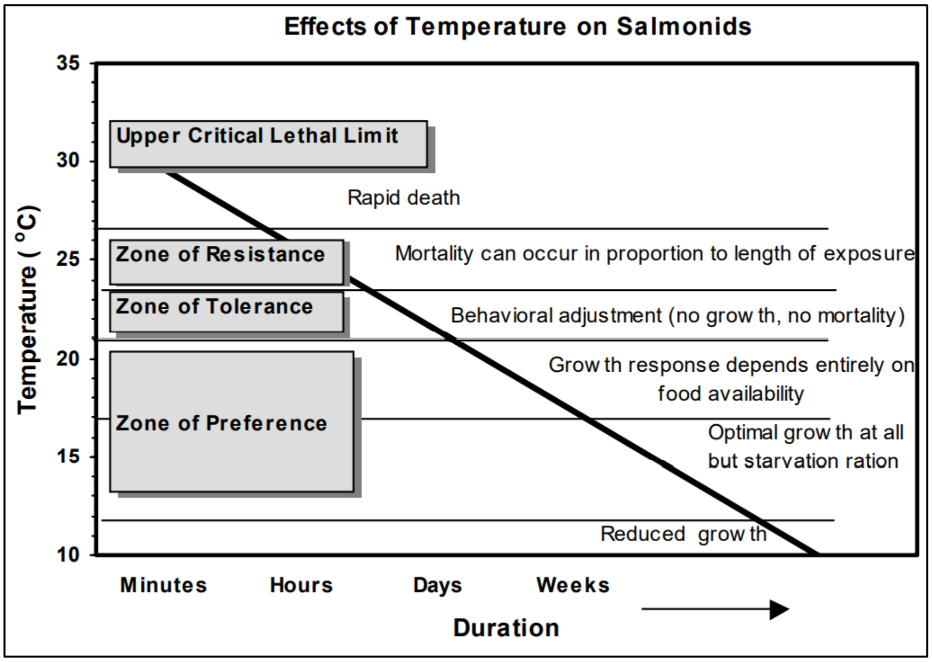
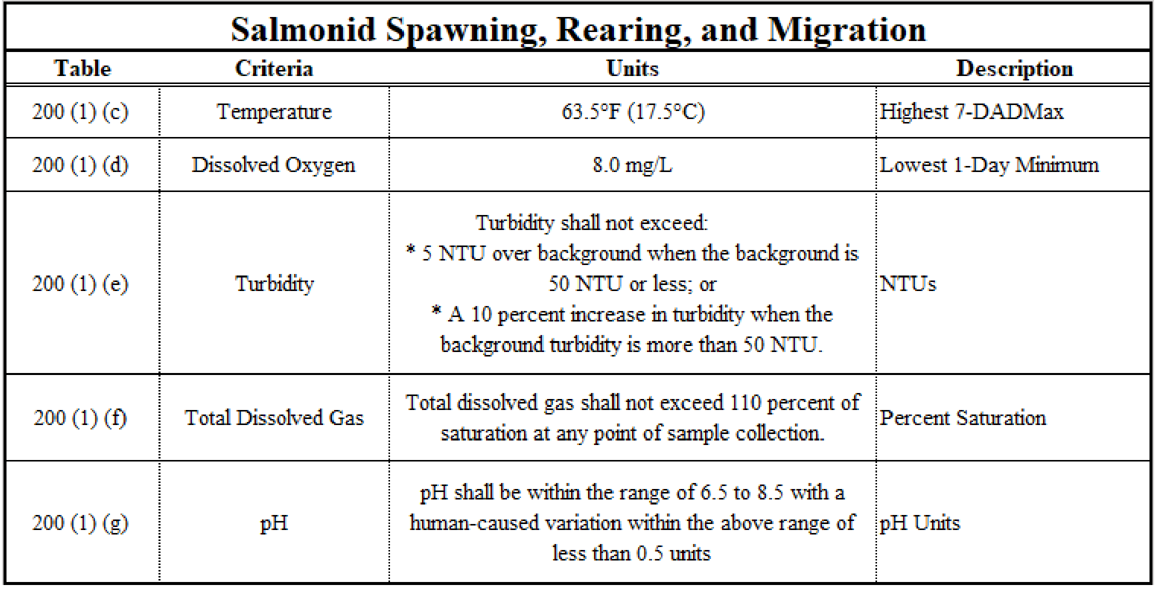


Figure 4: Effects of temperature on salmonids
"General biological effects of temperature on salmonids in relation to duration and magnitude of temperature" (Sullivan et al., 2000, Figure 2.1).

As salmon age into fry, they require a healthy supply of food, such as macro-invertebrates, and plenty of shelter from predators, which DWD provides (Close, 2015). The existence of DWD in streams creates low-velocity wakes behind structures and high velocity flow adjacent to the structures. This flow rate variation promotes a faster growth potential in juvenile salmon, as they minimize energy expenditure in low-velocity zones and have access to a greater invertebrate drift supply in the adjacent high velocity zones (Hafs, et al., 2014). All salmon species require clean freshwater habitat uncontaminated by chemical, biological, or industrial waste. Mcintyre et al. (2018) performed an extensive study on the effects of toxic stormwater runoff on coho and chum and determined that chemical pollutants contribute greatly to the decline of the species. Warming temperatures have been a contributing factor of salmon mortality during both sea-bound and homing runs and have possibly resulted in some straying patterns (Fellman et al., 2015; Keefer et al., 2019).

Based on the literature reviewed, the criteria used in this thesis to assess IVS effects on salmon survival needs will include impacts to overall biodiversity, sediment loads, stream chemistry, water flow regimes, stream temperatures, shelter abundance, migration route obstruction, and predator habitat. Many of these criteria will come from WAC 173-201A-200 for fresh water designated uses and criteria (**Table 2**) (Washington Administrative Code [WAC], 2020).

Table 2: Criteria for assessing IVS impacts on salmon in WA.
Various tables within WAC 173-201A-200 for fresh water designated uses and criteria and centered around the category for salmonid spawning, rearing, and migration (WAC, 2020).



Salmonid Spawning, Rearing, and Migration

Table	Criteria	Units	Description
200 (1) (c)	Temperature	63.5°F (17.5°C)	Highest 7-DADMax
200 (1) (d)	Dissolved Oxygen	8.0 mg/L	Lowest 1-Day Minimum
200 (1) (e)	Turbidity	Turbidity shall not exceed: * 5 NTU over background when the background is 50 NTU or less; or * A 10 percent increase in turbidity when the background turbidity is more than 50 NTU.	NTUs
200 (1) (f)	Total Dissolved Gas	Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.	Percent Saturation
200 (1) (g)	pH	pH shall be within the range of 6.5 to 8.5 with a human-caused variation within the above range of less than 0.5 units	pH Units

2.1.3 Salmon Resistance/Resilience

"Ecologists have often used resilience to refer to … the ability of a biological system to return to equilibrium after a perturbation" (Waples et al., 2009, p. 1). With regards to the habitat of Pacific salmon, resiliency reflects its ability to rebound from its current vulnerable state. Elements to be considered must include factors occurring outside of the historic context of Pacific salmon ecosystems, such as anthropogenic effects, climate change, and urbanization (Waples et al., 2009). Modern predictive climate models provide an invaluable tool in estimating the long-term resiliency of salmon habitat. Zhang et al. proposed that the effects of climate change on salmon might be better suited as a nonlinear response rather than classifying the effects as either suitable or lethal, as linear models might fail to fully capture the adaptive nature of living organisms to respond to their physical environment (2019). By comparing climate predictions, such as precipitation and temperature, to the suitable ranges of salmon species, an accurate assessment of species vulnerability can be established.

The success of Pacific salmon depends equally upon ecosystem resiliency and species resiliency. Resiliency at the ecosystem level allows for ecological process to reorganize, renew, and persist following a disturbance. Species resiliency then enables toleration of such changes in ecosystem conditions and promotes adaptations (Bottom et al., 2009). The adaptation of salmon habitat occurs across multiple scales, including shifts in climatic, economic, and geopolitical regimes.

In contrast, salmon adaptations on a species level, such as response diversity, occur on social, behavioral, or genetic levels (Bottom et al., 2009). Social adaptations in salmon may include the mating process, instinctually seeking genes within populations diverse from their own (Bottom et al., 2009). Behavioral adaptations in salmon could include homing and spawning behavior, which could be altered based on stress, such as changing stream temperatures, increased predation, lack of proper habitat, etc. (Schreck et al, 1997). Genetic adaptations in salmon consist of natural control responses, subject to continual modifications, which adjust the structure and abundance of their populations (Milner et al., 2003). Response diversity measures phenotypic plasticity – the ability of salmon species of one genotype to produce offspring with another genotype under changing environmental conditions (Waples et al., 2009). For example, the growth rate of salmon will vary between individuals depending on water temperature. In their 2009 paper, Bottom, Jones, Simenstad, and Smith explained the importance of response diversity of salmon in responding to warmer oceans or less productive ocean currents. They found that during periods of extreme climatic fluctuations, the growth rate and development of individuals became staggered within a particular population. Morphological heterogeneity of a population allows for differences in nutritional requirements, prey availability, position in the water column, and timing of migration. In this way, a population was able to occupy different levels of the trophic web and exploit separate resources. The researchers proposed that the evidence of response diversity occurs as a means of distributing the hardship of sudden environmental change across a population. Response diversity means that not all individuals occupy the same niches at any given point in time. Thus, it may be considered “an evolutionary strategy for spreading risk and avoiding brood failure in the presence of unpredictable watershed or ocean conditions” (Bottom et al., 2009, “Response diversity”).

Iverson (2008) uses the North of Falcon (NOF) monitoring process and looks at the Genetic Stock Identification (GSI) in the Genetic Analysis of Pacific Salmonids (GAPS) database using a Fishery Regulation Assessment Model (FRAM). While GSI data provides helpful insight in researching and understanding the temporal and spatial scale of salmon genetics/populations, the data has limitations. Kennedy (2008) studied the abundance of hatchery vs. non-hatchery chinook and found that hatchery salmon numbers far outweighed non-hatchery fish, which suggest that improving habitat may not be the only factor in trying to increase native fish populations.

In 1990, Waples and Teel discussed the rapid genetic change that occurs in hatchery salmon populations. They warned that “[a]ccelerated [genetic] change may compromise the long-term fitness of the species by reducing overall levels of variability and eliminating adaptive gene complexes…” (Waples & Teel, 1990, p. 145). Therefore, many of the genetic variations that occurred in hatchery populations might have been partially in response to artificially engineered conditions, which can often be less extreme when compared to wild environments. Thus, higher diversity of life histories translates to an increase in resilience of salmon populations (Waples et al., 2009). The Columbia River Basin has seen drastic decline in Pacific salmon populations, partly attributed to the overall reduction of life history diversity among the species (Gustafson et al., 2007). Compounded by the cumulative effects of dams, hatchery production, intensive harvest, and habitat degradation, reduced response diversity in the Columbia River populations may limit salmon resilience to future environmental changes (Bottom et al., 2009).

Lagasse et al. (2014) conducted a study of salmon habitat using a community-based assessment program which they hoped would successfully inform watershed management practices by integrating local and scientific knowledge. The program enabled the collaboration between the Coastal First Nations Regional Monitoring System (RMS) and the Canadian Provincial government. According to Lagasse et al., the RMS stream assessment program encouraged the development of crucial related data. The authors argue that the acquisition of such knowledge is necessary for learning about salmon conservation from the perspective of the First Nations community and thereby enhance restoration efforts by integrating local knowledge with western science. While Lagasse et al. focused on the Great Bear Rainforest in Canada, it may be possible to implement their study protocols in other salmon habitats; however, their study lacks any information regarding native versus non-native vegetation. This thesis seeks to cover that common information gap.

Larsen et al. (2004) examined trends in both spatial and temporal habitat changes over time, surveying 392 stream reaches for a duration between one and six years each. They agree with Lagasse et al. and added that to adequately gauge habitat changes, “research could focus on specific geographic subpopulations of streams [and] specific stream channel types within them[; additionally,]… it seems wise to begin monitoring programs that focus, at a minimum, on a core set of habitat elements, recognizing that complete agreement on the exact set, and the field procedures for their measurement, is unlikely” (Larsen et al., 2004, p. 289). Malick et al. (2017) attempted to take this one step further, examining a few specific challenges to ecosystem-based management (EBM) policies. The researchers found that the ability to make EBM policies for salmon species was largely affected by lingering scientific uncertainties about human impact and consequences, ecological processes occurring in too small or large an area to be widely applicable, spatial asymmetries in the distribution of costs and benefits associated with management decisions, and static management strategies that prevent timely action based on current science. Ultimately, since salmon migrate, management of habitats should account for their entire range. Furthermore, the impact human activities have on the ecosystem services provided by salmon should be considered. Equivalent management resources should be made available based at this scale level (Malick et al., 2017).

2.2 Invasive Vegetation Introduction

There remains some ambiguity surrounding the validity of invasive vegetation management. Mark Sagoff (2005) and Rejmánek et al. (2002) discussed the difficulty of defining terminology surrounding words and concepts related to ecology, such as ‘invasive/invasion’, ‘naturalized’, ‘native’, and ‘exotic’. Thus, more efficient management occurs when the various agencies share the same understanding of these definitions, allowing for deeper communication. Noxious weed research has advanced to the point at which it can now unequivocally quantify many environmental driving factors that contribute to a particular plant’s tendency to become invasive. These factors include: a greater phenotypic and genotypic plasticity (Walls, 2010), production of defensive compounds (allelopathy) (Inderjit, 2005), interspecific associations (i.e., mycorrhizal relationships) (Henderson et al., 2006), rapid evolutionary changes, and climate change (Sun et al., 2020).

One influential factor that promotes invasibility includes the plant species’ potential to propagate beyond a stable population. IVS dominate new territory based on traits which allow them to capitalize in ways the native species cannot. This can result in their population growing exponentially (Henderson et al., 2006). Allendorf and Lundquist (2003) discussed how invasive species go against the foundation of what we know about genetics in small populations. Initially brought over in isolated small populations, these invasive species can overcome the problems of inbreeding, reduced genetic variety, and the bottleneck effect; in addition to outcompeting already established native counterparts. Allendorf and Lundquist (2003) explain some of these anomalies, such as how a lack of predators could allow the IVS to divert energy it would have used in defending itself to energy used for creating more offspring. This energy surplus could translate to a greater success towards outcompeting the natives (Allendorf and Lundquist, 2003). However, more research needs to be conducted before fully understanding the phenomenon behind the concepts that allow IVS to overcome such obstacles and become aggressive competitors.

This section helps to illustrate the commonalities of IVS, but does not comprehensively explain their characteristics, traits, and behaviors. The subject of invasive species science continues to be nuanced in high complexity and interspecific relationships which have only recently been explored. Nonetheless, the need for noxious weed mitigation on behalf of Pacific salmon habitat restoration has a foundation in strong scientific research and supportive evidence.

2.2.1 A Growing Problem

Only recently have we begun to fully acknowledge that humans play a major part in the distribution, spread, and management of invasive plants. Similarly, the impacts of such species to various ecosystems have been a more recent topic of study (Ewel et al., 1999; Henderson et al., 2006). Henderson et al. (2006) also goes further into theoretical explanations for invasion success by plants. For instance, a greater genotypic/phenotypic plasticity of a species may allow it to adapt more readily to a novel environment (Henderson et al. 2006). The mechanisms which promote invasiveness in non-native plant species can vary greatly between situations and circumstances. Several current hypotheses attempt to explain the possible processes which may enable invasion by a species. Often labeled by catchy names, such as ‘biotic resistance’, ‘resource fluctuation’, ‘superior competitor’, ‘enemy release’, and ‘invasion meltdown’, these concepts provide theoretical frameworks which describe how certain plant species may achieve success and abundance in a novel ecosystem (Inderjit, 2004). This thesis will not go in-depth to the characteristics that promote invasion, instead it will elucidate the harmful effects that currently established IVS have on Pacific salmon habitat.

The presence of invasive vegetative species constitutes a growing concern for the health of ecosystems (Delach, 2006; Simberloff, 2003; Stuart, 2015) in Washington State (Smith, 2018). The current management strategy regarding IVS thus far has been inadequate, and the problem continues to progress. In a 2005 article in the *Ecological Society of America*, Simberloff, Parker, and Windle described this failure as a resulting combination from insufficient policies and research, partially due to a lack of appropriate funding as well as gaps in the scientific knowledge. These shortcomings only exacerbate the rapid spread of IVS in Washington State (Simberloff et al., 2005). Although Washington has taken a proactive stance on IVS management, the problem persists. A brief explanation of the state's IVS prioritization will be necessary to describe the current circumstances and severity of the issue. IVS have been categorized into three designations based on their current distribution status. These classifications range from Class A to Class C. Class A has the smallest population sizes and Washington mandates control for each of these species, while Class C includes recommended control due to having such a large population that control becomes too costly or timely, and Class B lies between them in prevalence and priority of control. These classifications are further explained in **Chapter 2.3.3**.

2.2.2 Anthropogenic Impacts

Numerous causes of IVS proliferation exist, but the most significant among those includes human activities. In fact, *homo sapiens* owe much of their success to the deliberate redistribution of plant species (Henderson et al., 2006). This began with the advent of agriculture, in which humans selectively cultivated certain beneficial plants and subsequently translocated those species outside of their geographical barriers (Henderson et al., 2006). As a common side effect of human activity and development, "invasive species can cause dramatic changes to ecosystems, including shifts in species composition, species mortality, biodiversity, disturbance regimes, and ecosystem-level nutrient dynamics" (Reo et al., 2017, p. 201).

Human-caused introductions of invasive species occurs by a wide array of mechanisms including agricultural practices, forestry, inadvertent dispersal of seeds or propagules, importation of contaminated foreign products, and deliberate cultivation. Typically, anthropochory of invasive vegetation most often occurs unintentionally. Some species easily adhere to clothing, pets, or car tires and are transported in that manner. IVS can also escape from nearby gardens or can be deposited as yard waste in natural areas. Furthermore, modern advances in efficient transportation technologies and development of intercontinental shipping logistics only exacerbates the spread of invasive plants by increasing their rate of distribution (Smith, 2018).

2.2.3 Benefits of IVS

Invasive vegetation can provide benefits as well as the widely understood negative impacts. As mentioned previously, the first attempts at translocation of vegetative species occurred for the benefit of human livelihood and society (Sagoff, 2005). Humans have depended on non-indigenous plant species throughout much of their history. The reason for this dependence ranges from "…food, shelter, medicine, ecosystem services, aesthetic enjoyment, and cultural identity" (Ewel et al., 1999, p. 619). Quantifying the impact of a particular vegetative species in terms of a cost-benefit analysis can be complicated. This complication becomes evident in the many documented cases of an IVS being deliberately propagated; often, such a species will be provided to consumers as a beneficial organism (Coelho, 2018; Chace, 2013). For example, the most notorious noxious weeds within North America includes Himalayan blackberry (Hays, 2012). Yet, this species of blackberry remains revered for its many benefits. Humans commonly harvest the large nutritious fruit, while inadvertently spreading its seeds across landscapes (Soll, 2004). Additionally, many people use the thorny thicket of Himalayan blackberry to act as a 'barrier', this same concept forms in the wild, where the barrier prevents the movement of wildlife, especially fauna such as deer (Soll, 2004). Beekeepers appreciate the benefits of Himalayan blackberry and another highly invasive species, purple loosestrife (*Lythrum salicaria*), due to the belief that it improves the palatability of honey (Chace, 2013, p. 13).

Another reason for fondness of IVS includes aesthetic value. Several species of ornamental plants cause severe impacts to the ecosystem, economy, and human health (Aronson et al., 2016; Pejchar & Mooney, 2009; Simberloff, 1996). English ivy (*Hedera helix*) and Morning Glory (*Convolvulus arvensis*) have long been admired for their beauty. Often seen adorning the sides of old buildings or growing over garden trellises, these plants can efficiently overcrowd and smother native species (Western Washington University, 2019). English ivy has been known to grow to a height of ninety feet as a vine

(Chace, 2013, p. 218). Yellow archangel (*Lamiastrum galeobdolon*) commonly escapes gardens and forms dense root-mats while outcompeting the native vegetation and displacing wildlife food as well as habitat. Additionally, the moment of initial observation of an invasive vegetative species happens long after the species has had time to establish itself, thus leaving management always ‘a step behind’; which can vary depending on each species’ or locale’s circumstances (Ewel et al., 1999).

In his book, *Invasive Plant Medicine,* Timothy Lee Scott describes the numerous ways in which various invasive plant species can be utilized in homeopathic and clinical medicines (Scott, 2010). For instance, Japanese knotweed (*Fallopia japonica*) can be used to treat Lyme disease, West Nile disease, the flu, *Staphylococcus aureus*, *Streptococcus pneumonia*, *E. coli*, and Salmonella (Scott, 2010, pp.142-149). Also, both English ivy and the tree of heaven (*Ailanthus altissima*) have been used to treat malaria as well as dysentery (Scott, 2010, pp.142-149). The tree of heaven has further been used to also treat giardia (Scott, 2010, p. 147). Although there have been many benefits derived from invasive vegetation, by definition, the harm caused by IVS outweighs any potential benefit.

2.2.4 Disadvantages of IVS

To address any ambiguity concerning the classification of IVS, the essential nature and characteristics of IVS must be examined more thoroughly. Invasive vegetation includes those plants whose current traits and behaviors have been widely regarded as more harmful than beneficial (RCW 77.135, 2017). Often, when left unchecked, these plants can multiply at exponential rates (USFS, 2004). Many IVS reproduce so vigorously that they form a monoculture in the area of proliferation (Poland et al., 2021;

Polster et al., 2006). By doing so, that species could reduce local biodiversity to negligible amounts. When monoculture proliferation of IVS occurs, the native ecosystem can suffer catastrophic results (Ainouche, & Gray, 2016; Byun et al., 2018; Godfree et al., 2017; USFS, 2004). In extreme cases, the entire trophic web collapses. Without substantial mitigation efforts, desertification becomes a possible outcome. Ravi et al. wrote a paper, titled *Can Biological Invasion Induce Desertification,* and explored the function of invasive exotic grass species in extreme desertification events (2009). They concluded that IVS can contribute to complete sterilization of localized areas by chemically altering the environment, increasing erosion, providing fuel to wildfires, and depleting soil nutrients (Ravi et al., 2009). Instances of IVS concentrations rarely reach this level of severity, which could be mostly attributed to the many agencies/organizations/etc. which have taken a serious interest in IVS management practices.

Observing secondary effects of IVS on freshwater environments, such as impacts to invertebrate populations (Going & Dudley, 2008), alterations to water chemistry (Hladyz et al., 2011), changes to stream structure, and decrease in DO (Kuehne et al., 2016) can be apparent. A 2020 thesis by Angela Dillon demonstrated the dysfunction of IVS on salmon habitat by statistically correlating the presence of invasive plants to the reduction of macroinvertebrate populations within the Puyallup-White watershed in Western Washington. In her study, Dillon compared taxa concentration of salmon habitat restoration sites managed for IVS with unrestored areas. She found that after three years, higher biodiversity existed within restored sites when compared to unrestored areas (Dillon, 2020).

In this ecologically dynamic world, it has become increasingly apparent that humans must intervene in the diminishing function of natural systems to preserve Pacific salmon habitat (Bottom et al., 2009); especially, when humans and numerous other species greatly benefit from healthy salmon populations (Garibaldi & Turner, 2004; Helfield & Naiman, 2006; Hyatt & Godbout, 2000). IVS undoubtably play a role in the decline of salmon numbers, and the content within this thesis will attempt to clearly illustrate the extent of that role.

2.2.5 Economic Impact of IVS

Invasive species have a national impact cost measured in billions of U.S. dollars annually (Jardine & Sanchirico, 2018; Reo et al., 2017; USFWS, 2012); a portion of that total goes towards IVS management. The cost of noxious weed control to business, commerce, and citizens in Washington State continues to be of great interest in recent years. Furthermore, the costs of managing individual species only increases over time as its presence becomes more established (**Figure 5**). This increasing management cost shows how important prevention can be when managing for invasive species.

A coalition of environmental agencies, including the Washington State Noxious Weed Control Board (NWCB), the Washington Invasive Species Council (WISC), and the Washington State Department of Agriculture (WSDA), contracted the firm Community Attributes Inc. (CAI) to run an analytical model predicting the potential impact cost of 23 selected high-priority invasive species to Washington State (2017). This high-priority species list includes plants, animals, and invertebrates.

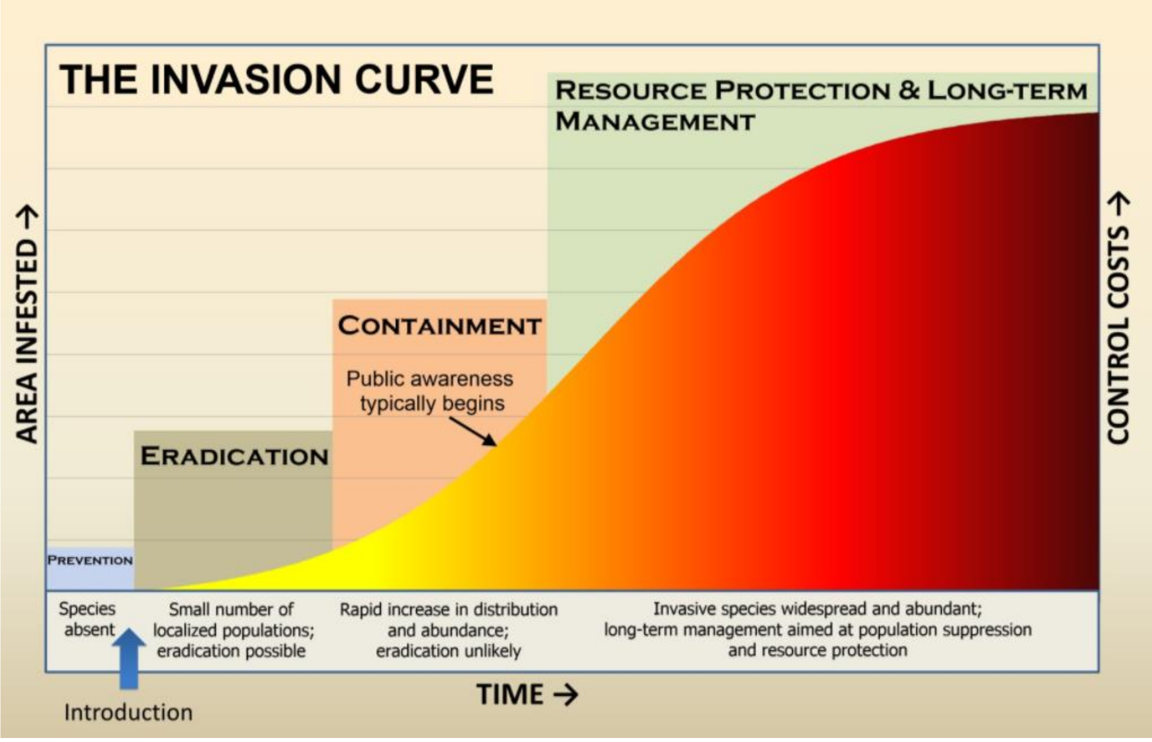


Figure 5: The invasion curve
The invasion curve demonstrates how management costs increase over time as the area becomes more infested by an invasive species (Adapted from the Victorian Department of Primary Industries, 2010).

In 2018, the Washington Noxious Weed Control Board published the results of that analysis and found that those 23 species, if left unchecked, could cost the state upwards of $1.3 billion in economic losses to agriculture, infrastructure, navigable waterways, property value, recreational activities, etc., each year (Washington Noxious Weed Control Board [NWCB], 2018). This analysis excludes estimates from the dozens of additional economically detrimental ‘mid-priority’ invasive species. Yet, when comparing the potential cost of a ‘do nothing’ approach to that of the current Washington State budget for IVS management, the mitigation efforts become the fiscally responsible option.

Washington State maintains a flourishing recreation industry which supports 248,000 jobs and contributes over $40 billion yearly in total economic contributions, according to a 2020 report by the Recreation and Conservation Office (RCO). This same report indicates that ecosystem services provided by Washington state recreational lands, such as “climate stability, disaster risk reduction, soil retention, … water supply, and carbon sequestration” ranges between $216 billion to $264 billion in yearly value (RCO report, 2020). Therefore, the threat from IVS demonstrates a clear and present danger to Washington State’s economy and environment.

The biennial amount of support from the Washington State general fund for the Noxious Weed Program in 2017 was $864,367 (NWCB, 2018). According to Washington State Citizen's Guide to the Budget – 2019 (Staff of the Senate Ways and Means Committee & Legislative Evaluation and Accountability Program (LEAP) Committee [SWM & LEAP], 2019), Natural Resources departments gets a combined total of about 2% of the biennium budget for 2017-19; this includes the Department of Ecology, Fish & Wildlife, State Parks and Recreation, etc. Other state agencies and universities spend more than $25 million a biennium to control invasive species in Washington ([2]Washington Invasive Species Council [WISC], 2016).

Washington State has a thriving forestry industry deeply invested in Invasive plant management (NWCB, 2018). The 2017 CAI report estimates the economic loss from the twenty-three high priority species for the Washington timber industry to be approximately $124.8 million annually. Scotch broom (*C. scoparius*), a ubiquitous class C noxious weed in Washington State, has a marked effect on conifer suppression (Jetter, 2000); thereby, posing potential negative impacts on growth rates to commercial forests (Slesak et al., 2016). Daniel Simberloff, a consummate authority on invasive species science, states that “Several introduced plant species simultaneously affect many native species by drastically modifying existing fire regimes” (Simberloff, 2013, p.14). This modification can translate to timber resource vulnerability and potential economic loss during a severe wildfire event.

The agricultural industry, remaining tightly bound to the salmon habitat restoration debate, has shown a strong negative correlation between IVS presence and profitability. The 2017 CAI report indicates that the twenty-three invasive species analyzed had a total potential economic impact of $239.5 million yearly for Washington’s agricultural industry. IVS impacts all agricultural sectors, costing millions of dollars to control, and reducing operational productivity (NWCB, 2018). Attempts to manage IVS on cropland ecosystems can be costly and very complicated. The cost of invasive plant management to farmers and agricultural workers eclipses the total combined cost of insects, rodents, and pathogen management (Mullin et al., 2000).

Livestock ranchers also suffer effects of IVS spread. Approximately three quarters of all domestic animals depend on rangelands for sustenance (Mullin et al., 2000); these ecosystems are uniquely susceptible to IVS. Increased instances of drought can promote non-native species that adapt more readily than native vegetative species to such arid conditions (Skaggs, 2008). As such, rangeland ecosystems suffer from low resilience, changing climate conditions, and competition from non-native vegetation (Skaggs, 2008). The authors of the 2017 CAI report claim that potential economic losses from the 23 priority invasive species to livestock ranchers in Washington State totals approximately $120 million each year. Some noxious weeds, such as the various knapweed species and yellow star-thistle (*Centaurea solstitialis*), have become a problem to Washington ranchers in recent years because of their unpalatability to livestock and tendency to outcompete forage species that herds depend on (NWCB, 2018). Many other

IVS, such as poison and water hemlock (*Conium maculatum* & *Cicuta douglasii*), kochia (*Bassia scoparia*), common groundsel (*Senecio vulgaris*), tansy ragwort (*Senecio jacobaea*), and many others can cause problems in multiple species of livestock ranging from sickness to death (NWCB, 2017). These examples help to illustrate the interconnectedness of invasive vegetation and the economics in Washington State. This thesis will attempt to clearly relate the topics mentioned in this section to the salmon population crisis and the ways in which humans, salmon, and the economy may mutually benefit.

2.3 Restoring Salmon Habitat

The benefits of restoring Pacific salmon habitat transcend any economic, cultural, or environmental reasons. The obligation falls upon humans to do everything possible to ensure the survival of this species. Indigenous peoples have had a relationship with these animals much longer than any other culture/ethnic group, and they understand the urgency to preserve and protect them. While he was serving as the Chairman of the Northwest Indian Fisheries Commission, Billy Frank jr. expressed this responsibility as follows, “It is our inherent duty to protect them, and to the degree that we fail to do so, we fail as human beings” (Frank & Neumeyer, 2015, p. 26).

2.3.1 Habitat Requirements

Put into the simplest terms possible, the habitat of Pacific salmon includes the Pacific Ocean and its constituent streams, rivers, lakes, and inlets. The native range of Pacific salmon spans from Northern Mexico to the Arctic Ocean on the North American continent and from Southern Japan and Korea to the Arctic Ocean on the Asian continent (Quinn, 2005). These anadromous fish can regularly travel hundreds of kilometers inland during homing migrations (Quinn, 2005, pp. 37-52). For the purposes of this thesis, oceanic populations of salmon species will largely be omitted from discussion. Further examination of the freshwater system will be necessary to fully grasp the environmental conditions which support healthy salmon populations. Glacial meltwater from the high elevation ranges of the Cascade and Olympic mountains feed the rivers, streams, and lakes of Washington. These spring glacial melts provide salmon with enough clean cool water to navigate their way upstream to spawning sites (Close, 2015). Furthermore, the glacial till and lithology of these streams provide proper gravel substrate for egg deposition and embryonic development (Quinn, 2005).

Climatic fluctuations have caused instability in natural systems, which adds to the difficulty of predicting future conditions of Pacific salmon habitat. For example, the general atmospheric warming trend observed in recent years has caused earlier snowmelt which altered seasonal flow regimes in many Washington rivers (Zhang et al., 2019). Evidence of this change can be observed in Washington’s Columbia River Basin, a major salmon migration route. A 2009 study of the effects of climate change on freshwater salmon habitat in Washington State provided strong evidence that the prolonged duration of low summertime flow is problematic for many salmon populations that migrate, spawn, or rear in the interior Columbia River Basin (Mantua et al., 2009). Though the primary focus of this thesis does not include climate variability, future research would benefit greatly from linking IVS and salmon habitat to climate change.

Aquatic environments must contain adequate concentrations of DO in order to support populations of salmonid species. DO regulates metabolic activity and permits strenuous exertion during migration, making it essential to salmon health and survival

(Fellman et al., 2015). Thus, oxygen depleted environments pose lethal risks to salmon. Low DO levels deprive salmon of oxygen required to breathe, feed, or swim upstream to spawn. Even if adults can migrate upstream, anoxic levels deprive salmon eggs, fry, and juveniles of the oxygen required for their growth and development. This can seriously affect the vitality of future generations.

The oxygen requirements for salmonids vary according to several factors including, season, life stage, stream temperature, metabolic activity level, time of day, and species. A study conducted in 1989, using respirometric analysis and a simulated natural light cycle, indicated that rainbow trout oxygen intake fluctuated between 100 and 360 milligrams of O^2 per kilogram of fish weight per hour during an eighteen-hour period. The highest levels of oxygen consumption by the fish were recorded during the greatest intensity of light exposure, while the lowest respiration occurred in darkness (Steffensen, 1989). Most diurnal ectothermic fish species, including salmon, commonly adhere to circadian respiratory cycles (Eliason & Farrell, 2016). Furthermore, the respiratory rate of salmon varies relative to their digestive activity; oxygen requirements are higher during active food consumption and lower during periods of homing starvation (Van Leeuwen et al., 2012). Not only does DO concentration directly affect the faunal species that inhabit an aquatic ecosystem, but it also enables populations of invertebrates, plants, and microbes, thereby influencing the composition of the entire local biome (Doke et al., 1995).

Varying levels of DO concentration can have either a positive or negative correlation to organism abundance depending on the species involved. For instance, anaerobic microbial colonies can thrive in low DO environments, further altering the chemistry of the local ecosystem by their metabolic processes. Many of these organisms can be extremely harmful to the health of fish and humans alike. For example, the notorious anaerobic bacteria *Clostridium botulinum* type E causes considerable mortality in juvenile salmon reared in earth bottom ponds (Abdelsalam, 2017).

Conversely, aquatic macroinvertebrates with tracheal gills or submergent respiratory mechanisms depend on DO much the same way that fish do, and there exists a positive relationship between species abundance and DO levels (Jacob et al., 1984). Much of a juvenile Pacific salmon's diet consists of such macroinvertebrates which spend all or some of their life stages in the aquatic ecosystem. The larval stage of some salmon prey species, such as mayflies (Ephemeroptera), caddisflies (Trichoptera), and stoneflies (Plecoptera), possess gill adaptations which require constant oxygenation in order to survive (Dillon, 2020).

Water temperature has a direct control on DO levels; see **Table 3**. Thermally stratified bodies of water have marked variations of oxygenated water layers due to this temperature control function. In 2002, researchers for the University of Thessaloniki, Greece proposed a model to simulate oxygen distribution in stratified lakes, in which the thermocline prevents oxygen transfer between the epilimnion and hypolimnion. The researchers determined that in these situations, oxygen sources are restricted primarily to the epilimnion (Antonopolous & Gianniou, 2003). Examination and analysis of aquatic biology in lentic ecosystems revealed that primary respiration of the organisms that resided in the hypolimnion, as well as seasonal deposition of reduced material, accounted for the depletion of DO in that water layer (Antonopolous & Gianniou, 2003). These findings have relevant implications for lacustrine habitats of salmon in Western

Washington due to salmonid’s biological sensitivity to temperature and aqueous DO concentrations.

Table 3: Physical Parameters of Lotic Waters
This table illustrates various environmental factors associated with dissolved oxygen in riverine ecosystems (Adapted from Fellman et al., 2015, Table 1).

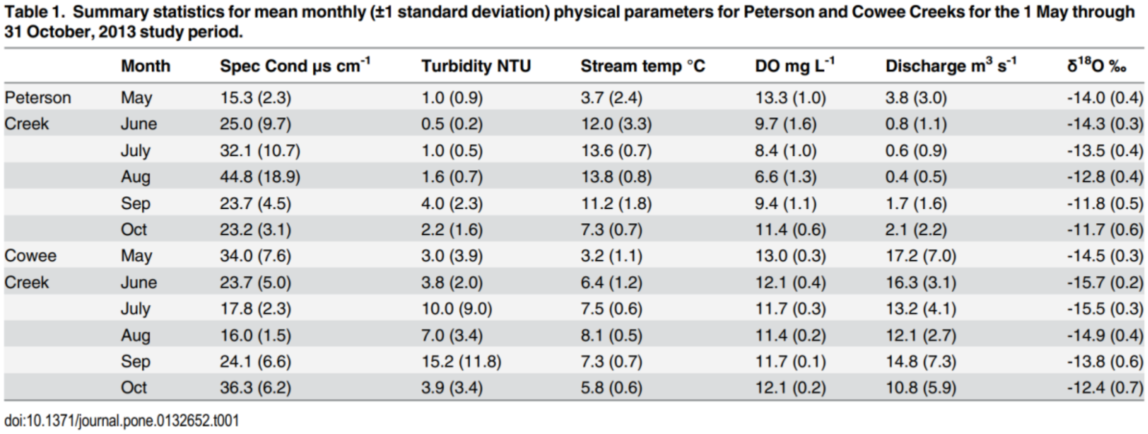


Table 1. Summary statistics for mean monthly (±1 standard deviation) physical parameters for Peterson and Cowee Creeks for the 1 May through 31 October, 2013 study period.

	Month	Spec Cond μs cm^{-1}	Turbidity NTU	Stream temp °C	DO mg L^{-1}	Discharge m^{3} s^{-1}	δ^{18}O ‰
Peterson Creek	May	15.3 (2.3)	1.0 (0.9)	3.7 (2.4)	13.3 (1.0)	3.8 (3.0)	-14.0 (0.4)
	June	25.0 (9.7)	0.5 (0.2)	12.0 (3.3)	9.7 (1.6)	0.8 (1.1)	-14.3 (0.3)
	July	32.1 (10.7)	1.0 (0.5)	13.6 (0.7)	8.4 (1.0)	0.6 (0.9)	-13.5 (0.4)
	Aug	44.8 (18.9)	1.6 (0.7)	13.8 (0.8)	6.6 (1.3)	0.4 (0.5)	-12.8 (0.4)
	Sep	23.7 (4.5)	4.0 (2.3)	11.2 (1.8)	9.4 (1.1)	1.7 (1.6)	-11.8 (0.5)
	Oct	23.2 (3.1)	2.2 (1.6)	7.3 (0.7)	11.4 (0.6)	2.1 (2.2)	-11.7 (0.6)
Cowee Creek	May	34.0 (7.6)	3.0 (3.9)	3.2 (1.1)	13.0 (0.3)	17.2 (7.0)	-14.5 (0.3)
	June	23.7 (5.0)	3.8 (2.0)	6.4 (1.2)	12.1 (0.4)	16.3 (3.1)	-15.7 (0.2)
	July	17.8 (2.3)	10.0 (9.0)	7.5 (0.6)	11.7 (0.3)	13.2 (4.1)	-15.5 (0.3)
	Aug	16.0 (1.5)	7.0 (3.4)	8.1 (0.5)	11.4 (0.2)	12.1 (2.7)	-14.9 (0.4)
	Sep	24.1 (6.6)	15.2 (11.8)	7.3 (0.7)	11.7 (0.1)	14.8 (7.3)	-13.8 (0.6)
	Oct	36.3 (6.2)	3.9 (3.4)	5.8 (0.6)	12.1 (0.2)	10.8 (5.9)	-12.4 (0.7)

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Lotic environments also have a direct temperature-oxygen relationship, similar to lacustrine environments, in addition to several factors of DO control unique to riverine ecosystems (see **Table 3**). These factors include flow regime, turbidity, sedimentary inputs and bank erosion, salmon spawning processes, as well as decomposition of salmon carcasses (Fellman et al., 2019) An in-depth examination of the various ways in which the top IVS alter the environmental factors that affect water flow, turbidity, and allochthonous inputs will be covered throughout **Chapter 4**.

Habitat temperature variations outside optimal ranges can create complications in salmon species (Zhang et al., 2019). Pacific salmon require cool water temperatures around 13°C (~ 55°F) for optimal healthy function (Zhang et al., 2019), but not in excess of around 23°C (~ 73°F) (Mantua et al., 2009). Fellman et al. conducted a field study which analyzed the stream conditions in two Alaskan watersheds over the course of a six-month period, and determined that DO concentration peaked around May, when water temperature was between approximately 2 - 4°C (~ 36 - 39°F) (2015). Temperature affects many water quality parameters, including nutrient cycling, biological productivity (Antonopolous & Gianniou, 2003), metabolic activity of salmon, and the solubility of dissolved gasses, such as carbon dioxide and oxygen (Fellman et al., 2015). The Washington Department of Ecology (Ecology), with approval from the Environmental Protection Agency (EPA), established water temperature standards for Pacific salmon habitat in Chapter 173-201A of the Washington Administrative Code (WAC, 2020). Therein, contains a water temperature range going from healthy function to life threatening. Such temperature ranges include a healthy temperature at less than 14°C (~ 57°F), while temperatures above 14 °C increases disease and stress, and temperatures over 23°C (~ 73°F) can be lethal (Mantua et al., 2009). Regular temperature readings conducted on the Columbia and Snake Rivers in Washington showed that some sections of these crucial salmon habitats regularly reached 20 - 23°C (~ 68 - 74°F) (Beechie et al., 2013; Mantua et al., 2009; Zhang et al., 2019).

A necessary component of stream structure in salmon habitat includes DWD (May et al., 1998; Nelson et al., 2015), as it provides shelter to salmon, creates pools and side channels, as well as houses macroinvertebrates (Close, 2015). Juvenile salmon are especially dependent on shelter for many reasons. Not only does the existence of shelter decrease the risk of predation but it may also provide metabolic benefits to young fish and thereby improves growth potential and development. For example, a 2006 study provided measurable evidence that adequate shelter abundance translated to a reduction in energy budget of juvenile salmon, due primarily to the fact that increased vigilance of predators equated to greater physiological stress and energy expenditure (Millidine et al., 2006). Furthermore, the ability of drift-feeding fish, such as juvenile Pacific salmon, to effectively consume prey items depends on the availability of low-velocity zones created by DWD (Hafs, et al., 2014). In their 2015 study, Nelson et al. analyzed the ten separate habitat characteristics that they hypothesized would affect the density of spawning chum and pink salmon. Their research indicated that, out of those ten considerations, the most significant characteristic correlating to spawning pink salmon densities had been the presence of large woody debris; for chum, it appeared to be water pH.

Several professional and academic projects in recent decades have provided insight into the importance of DWD inclusion in salmon habitat. The 2011 Chehalis Basin Salmon Habitat Restoration Strategy included a comprehensive long-term management plan in which DWD installation projects remain a high priority. This strategy illustrated the several ways in which DWD features enable a wide range of habitat benefits. For instance, juvenile salmon prefer to over-winter in the deep pools created by DWD (Kliem & Holden, 2011). A 2014 paper, titled *Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon,* utilized hydrodynamic and bioenergetic models to simulate the effects of DWD components on several stream characteristics, including flow, velocity, and turbidity (Hafs et al., 2014). The models included simulations for six different configurations ranging from sparse placement to excessive placement of DWD as illustrated in **Figure 6**. The authors used linear regression models to predict the favorable juvenile salmon habitat. The findings of this study showed that in the absence of DWD, there was not adequate juvenile salmon habitat. Conversely, the models indicated that high abundance of DWD reduced stream velocity by as much as 5% - 19%, and juvenile salmon habitat area increased by a factor of four (Hafs et al., 2014).

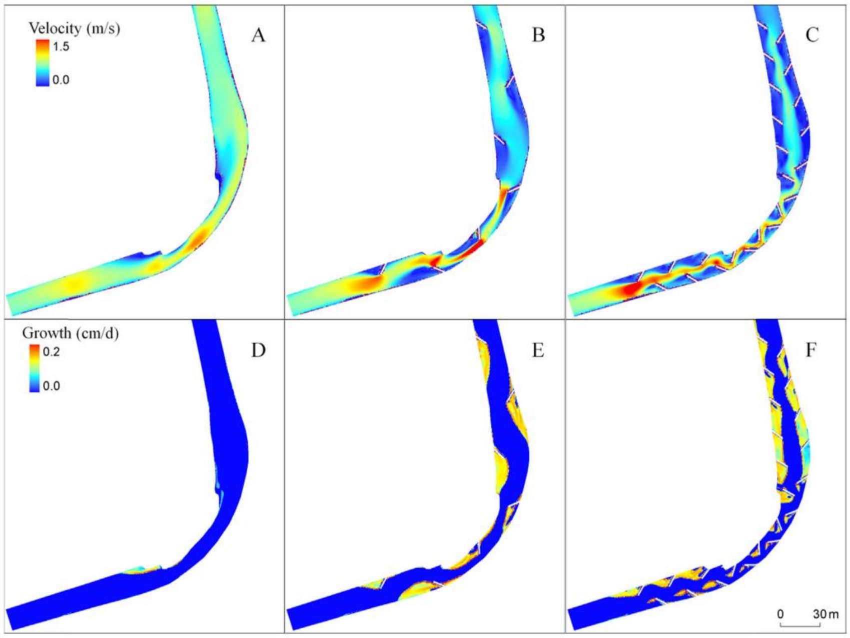


Fig. 1. Flow field and growth potential maps produced from simulations with no structures (Graphs A and D), a low density (41 m spacing, Graphs B and E), and a high density (12.3 m spacing, Graphs C and F) of 10 m long structures added.

Figure 6: DWD placement simulation
Correlation of Down Woody Debris (DWD) to stream velocity and juvenile salmon growth potential. This simulation shows how potential salmon growth occurs at a positive correlation to the addition of DWD placement within a reach of stream (Hafs et al., 2014, Figure 1).

This section summarizes the basic requirements of optimal Pacific salmon habitat but does not delineate conditions for individual species or populations of fish. The minimum target range for each of the vital environmental criteria for Pacific salmon habitat covered in this thesis will be assessed partially on the requirements for the WAC standards concerning the ‘salmonid spawning, rearing, and migration’ category set by the EPA (**Table 2**) (WAC, 2020). The remaining criteria, not addressed within these standards, will be based on cumulative data gathered from various comprehensive scientific studies; with the understanding that many of the criteria examined is site specific and should be reassessed accordingly. The impacts on salmon species habitat based on these criteria ranges will be further examined in **Chapter 4**.

2.3.1.1 WAC Standards. The WAC water quality standards have been designated for fresh surface waters to protect aquatic life, with a focus on salmon species.

These WAC standards provide detailed information about temperature, dissolved oxygen (DO), turbidity, and pH. These standards have been established in accordance with Washington State Department of Ecology guidelines for water quality and approved by the EPA.

WAC water temperature criteria has been designed with consideration of Pacific salmon biological responses, as a way to limit potential harmful effects, such as reduced feeding or starvation, thermoregulative stresses, and decrease in spawning activity and reproduction; which can contribute to lower survivability (Sauter et al., 2001). Water temperature remains an important factor for salmon survival and is directly linked to the available DO content in a water source. Washington standards for stream temperatures over a seven-day average of the daily maximum are suggested to not exceed 17.5°C (~ 63.5°F) (WAC, 2020).

DO is a measure of the amount of aqueous oxygen in the water and is essential for the respiratory function of aerobic life (Finch & Brown, 2020). Low DO concentrations can cause negative impacts to growth and development of salmon at all life stages, and can affect swimming, feeding, and reproductive behaviors of both juveniles and adults (Carter, 2005). Washington standards for spawning, rearing, and migrating salmon range between 8.0 to 9.5 milligrams per liter as the minimum range during a 24-hour period (Finch & Brown, 2020).

Fine sediment generally consists of particles less than 2 millimeters (~ 0.08 inches) and can block water flow and oxygen, increase fish mortality, reduce habitat, and lessen the success of hatching embryos (Finch & Brown, 2020). One measurement for suspended fine sediment concentrations includes turbidity, which can be expressed in "nephelometric turbidity units" (NTUs) (WAC, 2020). The higher the NTU number, the more turbid and murkier the water appears. It is recommended to consult WAC 173-201A-200 directly for each case to reference the appropriate use of NTUs. NTU values are unclear as they have been based on information compiled from a particular stream's history, which varies by stream, instead of by salmon requirements. Currently, these measurements are used in reference to NTU values previously collected for that particular waterbody, which may not depict a clear long-term profile of local turbidity. However, it has been suggested by some Washington ecologists that this method of turbidity assessment be revised in respect to salmon needs (A. Dillon, personal communication, May 10, 2021; Finch & Brown, 2020).

The pH of a stream needs to remain within 6.5 to 8.5, with an allowance of 0.5 units of deviation for human-caused variables (WAC, 2020). As deviation from these pH standards increases, the worse the physiological effects can be for the fish inhabiting that water body, ranging from diminished growth rates to mortality (Robertson-Bryan, Inc. [RBI], 2004). Severe effects of high pH on fish include "hypertrophy of mucus cells at the base of the gill filaments and destruction of gill and skin epithelium, with effects on the eye lens and cornea" (Alabaster & Lloyd, 1980, and Boyd, 1990, as cited in RBI, 2004). Effects of acidic water conditions, or low pH levels, manifest in respiratory distress and osmotic imbalances in salmon species, which translates to a reduction in growth rates and survivability (RBI, 2004).

2.3.2 Human Impacts

Freshwater habitat loss and degradation remain among chief factors contributing to the decline of Pacific salmon populations (Bisson et al., 2009; Hill et al., 2010).

Anthropogenic alterations to the environment advance this destruction (Lackey, 2003), and nearly every aspect of urban development promotes changes to salmon habitat. Human activities of notable concern include excessive commercial and recreational fishing, dam building and operation, flood control, municipal or commercial components, hatchery culture, as well as certain farming and ranching practices (Lackey, 2003).

A primary consideration in the salmon habitat conservation debate includes mankind’s use of water. In the last hundred years, half of the world’s wetlands have been drained, 48,000 large scale dam construction projects have been completed, and approximately 80% of the Earth’s large rivers have been diverted for human purposes (Vince, 2014, p.72). According to a dam inventory report in September of 2020, the Washington Department of Ecology regulated 1,226 separate dams in the state (Washington Department of Ecology [Ecology], 2020). Dam building and operation fundamentally changes natural salmon habitat in Washington State.

Numerous other methods of water diversion used by humans also cause impacts to natural systems. Take for instance, the ways in which water has been redirected to facilitate Washington’s public road construction. The high court determined these methods to be detrimental to salmon; therefore, remediation has been mandated (Brown & Footen, 2010, Blumm, 2017; Donovan, 2016). Water use and redirection by humans may have a profound effect on the distribution and spread of certain IVS species. Although hydraulic systems are not the focus of this thesis, they must be taken into consideration as a potential vector for IVS dispersal.

Hydrochory, a process of long-distance passive vegetative propagule dispersal along a waterway, may increase the spread of invasive species (Nilsson, et al., 2009).

Several high priority invasive plants in Washington State, such as Scotch broom, reed canarygrass (*Phalaris arundinacea*), and Himalayan blackberry commonly propagate by hydrochoric means (Woodward et al., 2011). Knotweed species often infest large areas of riparian zones and reproduce predominately by aquatic transport of rhizome fragments (Arnold & Toran, 2018). Brazilian elodea (*Egeria densa*), a class B noxious weed in Washington State, propagates strictly by clonal fragmentation instead of sexual reproduction, due to the lack of female individuals existing in the state (King County Noxious Weed Control Program [KCNWCP], 2014).

Properly maintained riparian buffer zones around streams within developed areas drastically improve stream quality. These vegetative margins offer several functions for improving stream quality, increasing biodiversity, and enhancing ecosystem resiliency (Stutter et al., 2019). Suitable salmon habitat has a narrow range of water quality standards, and any deviation outside of that range may threaten the health of fish and increase mortality. Neglecting the necessity of including adequate riparian buffers around streams allows toxic stormwater runoff, excess sediment, and potential biological contaminants to easily enter freshwater environments that house populations of salmon (Mooney & Eisgruber, 2001; Wilhere & Quinn, 2018). Conversely, a densely vegetated wide riparian zone acts as a natural filter for water flowing through it, thereby limiting any toxic runoff from entering the stream. In addition to water filtration, riparian buffer zones with substantial canopy cover regulate stream temperature by blocking solar radiation from reaching the surface of the water (Mooney & Eisgruber, 2001; Wilhere & Quinn, 2018).

A study conducted by Mcintyre et al. (2018) found increasing evidence that toxic stormwater runoff caused premature mortality to adult transitional salmon. The study also points out other non-fatal symptoms of water toxicity on salmon, such as loss of orientation, surface swimming and gaping, and loss of equilibrium (Mcintyre et al., 2018). A recent analysis of PNW stream water composition by Tian et al. (2020) indicated that stormwater runoff in developed areas commonly contained a toxic compound from car tires and has been directly linked to salmon mortality. A previous study in 2006 shows the strong correlation between urbanization and aquatic ecosystem degradation in a region of Western Washington. In their paper, titled *The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowlands Ecoregion*, University of Washington researchers showed the impacts of urbanization on Pacific salmon habitat and the role that riparian buffer zones play in mitigating non-point source pollution in Washington streams. Furthermore, this study demonstrated the implications of riparian buffer zones for stream quality and biotic integrity in the Puget Sound Lowlands region (May et al., 1998); see **Figure 7**. May et al. (1998) found that riparian buffers must maintain a general minimum width of 30 meters (~ 98 feet), or 100 meters (~ 328 feet) in more sensitive areas, in order to mitigate the effects of urbanization. The data collected in this study indicated that at least 70% of the corridor’s length must be maintained as a healthy riparian margin to promote optimal stream conditions (May et al., 1998). These riparian buffers are just one factor in ecological integrity that is best used when combined with other natural functions (May et al., 1998).

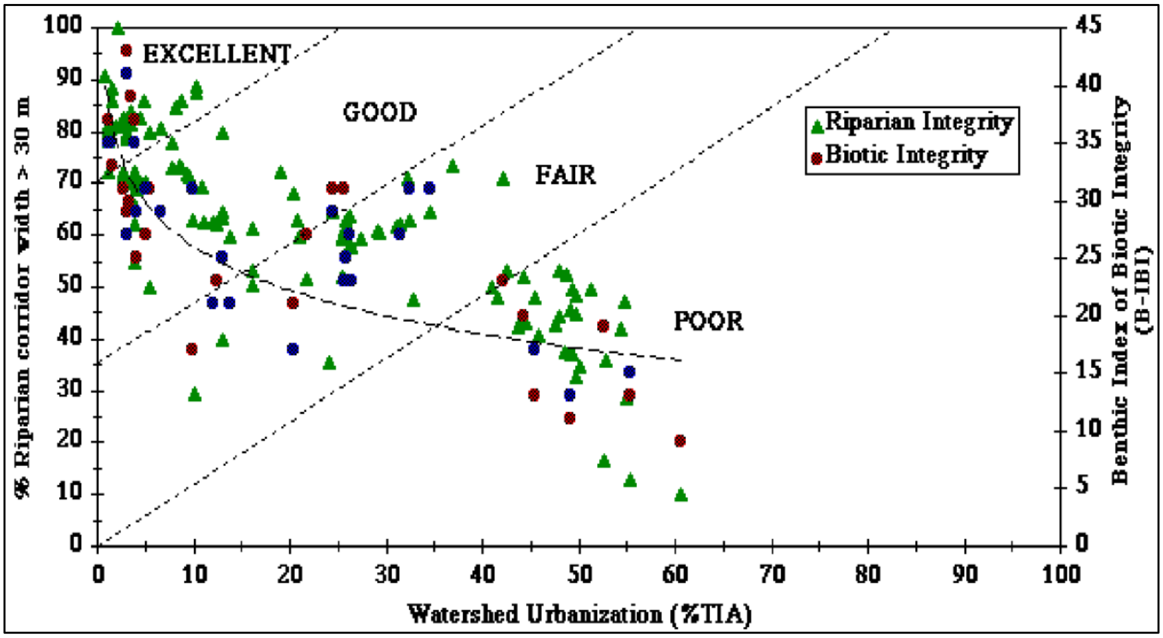


Figure 7: Riparian zone quality at various urbanization levels
Model depicting the relationships between riparian buffer widths, biological integrity, and watershed development (taken from May et al., 1998, Figure 16)

The agricultural industry strongly supports Washington State's economy and society. Recently, there has been increased attention brought to this necessary practice, and the ways in which farming and ranching activities influence the conditions of the environment. Although there remains much controversy over which farming practices pose the most significant harm to salmon habitat (Breslow, 2014), many have been widely identified as undeniably detrimental. Fertilizer use (Seiter, 2008), pesticide application (Seiter, 2008), riparian canopy reduction (Chapman & Knudsen, 1980), water capture and irrigation (Essaid & Caldwell, 2017), nutrient inputs from animal waste (Seiter, 2008), as well as excessive soil tillage (Fu et al., 2006) have been documented to be among the most notorious dangers to salmon habitat currently in use by Washington farmers. For instance, Gerald Whittaker, in a 2005 paper titled *Application of SWAT in the Evaluation of Salmon Habitat Remediation Policy*, detailed an analytical model used by the United States Department of Agriculture (USDA) to assess non-point source water pollutants which contributed to the environmental distress of salmon runs in the Pacific Northwest (2005). Whittaker pointed out that agricultural practices, which include the heavy application of fertilizers and pesticides, were directly responsible for habitat degradation from non-point sources (2005). He goes on to describe the cascading effects that fertilizer can have on lotic systems,

> Nutrient loading is thought to be responsible for ‘increased primary and secondary production, possible oxygen depletion during extreme algal blooms, lower survival and productivity, increased eutrophication rate of standing waters, certain nutrients (e.g., non-ionized ammonia, some metals) possibly toxic to eggs and juveniles at high concentrations’ (2005, p. 841).

Agricultural activities can have a profound effect on aquatic organisms. Soil tillage can contribute small particulate matter to streams at unnatural rates, which may adversely affect aquatic organisms. This fine sediment (<2mm) fills spaces between larger particles, thus reducing the flow of oxygen to salmon eggs, fry, and other benthic dwelling organisms (Larsen et al., 2004). Average stream temperature can also be influenced by local farming activities. If the cleared land of an agricultural site abuts a fish bearing water body, then an adequate riparian buffer zone must be maintained to regulate stream temperature sufficiently in order to promote optimal conditions for salmon habitat. The research conducted by Larsen et al. (2004) found that tree canopies were essential to the cool conditions required for salmon reproduction and growth.

Many commercial farmers have a profit driven perspective concerning their use of land. In that sense, a common farming practice has been to dedicate all possible land area to the goal of maximizing production. A case in Skagit Valley, Washington illustrates this mentality well. From 1996-2008 the Swinomish Tribe pursued legal action against the local farmers to include a riparian buffer zone of 50-180ft for salmon habitat recovery (Breslow, 2014). The case eventually made its way to the Washington Supreme Court. In the proceedings, the “Skagit farmers argued that habitat restoration on farmland would undermine an already dwindling land base to the point that arable acreage would slip below a "critical mass" necessary to maintain the economic viability of the local agricultural industry” (Breslow, 2014, p. 739). This paper features numerous instances which allude to a much-needed reformation of the agricultural industry and its degree of environmental responsibility (Breslow, 2014). Yet, there remains resistance from agricultural landowners to meet this challenge, which this thesis expands upon in **Chapter 2.4.1**. Anthropogenic changes to the habitat of salmon are extensive and will be a recurring theme throughout this thesis.

2.3.3 Ownership Boundaries

Like all U.S. territories, Washington has been divided into legislative/congressional districts and counties, and further sub-divided into municipalities. Each of these distinct areas have designated governing bodies and legal jurisdictions. These jurisdictions determine allocation of federal and state funding and legislative function. Municipalities include cities and towns, which have been separated into public and private land parcels. Often there exists discrepancies between federal and state laws, much like the differences between county ordinances. This convolution often causes much discourse regarding environmental law.

Regulatory standards have become a ‘hotbed issue’ for interjurisdictional cases involving salmon habitat recovery (Bisson et al., 2009; Breslow, 2014; Donovan, 2016). Difficulties often arise between stakeholders of differing perspectives, conflicting goals, or interpretations of information regarding policy and regulations. This can be especially true where an unclear jurisdictional boundary exists. Some of the cases in this thesis will feature such instances, and offer areas of ‘common ground’, in which conflicting stakeholders may mutually reach amenable solutions to their individual challenges.

> The Washington State Noxious Weed Control Board updates the Washington State Noxious Weed List annually. This includes adding any new species [as well as] re-classifying any existing species. Noxious weeds are defined in RCW 17.10 as non-native highly invasive plant species. The weed list is divided into three classifications, A, B, and C. Class A noxious weeds are very limited in distribution and eradication is required for infestations. Class B noxious weeds are limited in some parts of the state and more prevalent in other parts. Class B noxious weeds can be designated by the state noxious weed board for required control within a county or selected by the county for required control. Class C noxious weed species are found throughout the state. County noxious weed boards may select class C species for required control within their county. RCW 17.10 and 17.04 are the [legislative] statutes that require noxious weed control throughout the state. RCW 17.10 requires that the noxious weed list be updated annually by the State Noxious Weed Control Board and gives the authority to the county noxious weed boards to require control of noxious weeds. It also mandates that [property] owners have the duty to control noxious weed species [on their lands]. RCW 17.04 is a very similar law governing noxious weed districts rather than noxious weed boards. Both noxious weed boards and districts have the authority to enforce noxious weed control on all private, county, and state landowners within their jurisdiction. Only federal lands are exempt from noxious weed districts and boards jurisdiction. However, cooperative weed management is strongly encouraged between state, federal, and local agencies [as well as] private landowners (M. Fee, personal communication, April 15, 2019).

2.3.4 Habitat Availability

Current predictions claim that salmon habitat loss will be 5% to 22% in Washington State, by the year 2090 (Mantua et al., 2009). This loss of habitat will be precipitated mainly by increasing water temperatures and disappearance of glacial ice due to anthropogenic climate change (Zhang et al., 2019). In their 2002 *Roadmap for Salmon Habitat Conservation at the Watershed Level,* The State of Washington Joint Natural Resources Cabinet proposed that reduced flow, water quality, streambank erosion and sediment inputs, riparian degradation, habitat accessibility, as well as channel complexity pose significant risks to Pacific salmon habitat (Washington Joint Natural Resources

Cabinet [WJNRC], 2002). Furthermore, future atmospheric warming may render much of Western Washington's freshwater environments uninhabitable to Pacific salmon (Zhang et al.,2019; Rubenstein et al., 2019; Sullivan et al., 2000).

A paper published in 2013 by Beechie et al., used a two-step modelling analysis to predict future conditions in the Pacific Northwest in regard to salmon habitat suitability. By using the variation in global climate (VIC) model, which incorporated dynamic runoff routing, stream flow, and stream temperature simulations, they predicted that minimum monthly summertime flow rate in the region will decrease by 10% to 70% by the year 2100. They forecasted a stream temperature increase between 1 to 4°C (~ 34 - 39°F) during the period of 2030 to 2069, and an increase between 2 to 6°C (~ 36 - 43°F) by the year 2100 (Beechie et al., 2013). The findings of this study indicate that future stream conditions may be incapable of supporting Pacific salmon populations.

Many high priority critical salmon habitats fall within regions which are especially susceptible to erosional risks. The Columbia River Basin has experienced drastic changes in hydrologic function since the late nineteenth century. These changes frequently manifest in ways that have led to the degradation of Pacific salmon habitat. For example, the 2013 *ESA Recovery Plan for Lower Columbia River Coho Salmon, Lower Columbia River Chinook Salmon, Columbia River Chum Salmon, and Lower Columbia River Steelhead*, cited evidence that sediment deposition from the interior Columbia Basin to the Columbia River estuary has been reduced to around 40% of the late nineteenth century volumes (National Marine Fisheries Service [NMFS], 2013).This has occurred not because of a decrease in bank erosion throughout the Columbia River watersheds, but as a result of reduced flow throughout the system. This reduction in discharge due to agricultural water usage and municipal hydraulic systems in the region allows for sediment particles to fall out of solution sooner than they would if flow rates were higher. This limitation of estuarine deposition has translated to an approximate 60% increase in sediment loads to the interior Columbia watershed, which includes WRIAs 24 through 29 (Brannon et al., 2004).

The Chehalis Basin Salmon Recovery Plan indicates that riparian degradation, water temperature increase, low discharge, low DO concentrations, poor water quality, and bank erosion pose a substantial threat to salmon habitat within WRIAs 22 and 23 (Kliem & Holden, 2011). The main stem of the Chehalis River, a critical Salmon habitat in Southwestern Washington, experiences high sediment loading from several of its tributaries including, Satsop River, Wynoochee River, Newaukum, South Fork Chehalis River, and the mainstem above the town of Doty, WA. (Kliem & Holden, 2011). Lack of riparian vegetation, inadequate quantities of woody debris, agricultural practices, and urbanization have contributed to the salmon habitat destruction observed in the Chehalis River Basin (Kliem & Holden, 2011).

These examples highlight some of the current and future problems facing Pacific salmon populations in Western Washington and demonstrate a crucial need for habitat restoration as a means to preserve the species. The conditions detailed above are commonplace throughout freshwater ecosystems in developed areas of Western Washington, and salmon habitat availability continues to decline. The following section will illustrate some of the detrimental effects that IVS have been documented to cause on Pacific salmon habitat and the related ecological harms to the environment.

2.3.5 IVS Potential

This section will synthesize concepts taken from previous research and scientific studies by incorporating those findings into a framework that forms connections between salmon habitat degradation and IVS proliferation in Western Washington. There have been rigorous studies conducted on some invasive plant species and their ecological effects on natural systems, but there currently exists substantial knowledge gaps regarding the ways in which IVS impact Pacific salmon habitat. Noxious weeds that cause direct alterations to overall biodiversity, sediment loads, stream chemistry, water flow regimes, stream temperatures, shelter abundance, migration route obstruction, and predator habitat should be species of concern for Pacific salmon habitat conservation.

A common error in attempting to quantifying the detrimental effects that IVS have on local ecology often occurs when comparing a single invasive plant species to its native counterpart. Two separate vegetative species which may fill the same particular ecological niche typically provide similar ecosystem services, regardless of their respective nativity (Sagoff, 2005). The complete truth may only be revealed by conducting a long-term critical study of the effects that the non-native species has on the whole ecosystem.

It may also be tempting to assume that a positive correlation between a non-native species and ecosystem health equates to a low impact assessment of said plant, but this would be an incomplete analysis. For instance, although the class C noxious weed reed canarygrass has shown promise as a suitable bank stabilizer in erosion prone areas (Martinez, 2013), this single metric is insufficient to deem it as ecologically beneficial in all circumstances. Reed canarygrass has also been documented to reduce the growth potential of juvenile salmon by altering the diversity of macroinvertebrate populations and limiting accessible lateral stream area (Klopfensein, 2016). Similarly, knotweed has been shown as an adequate food source substitute of native leaf litter for many aquatic detritivorous invertebrates (Braatne, et al., 2007), which salmon regularly prey upon, but it is also notorious regarding stream bank erosion (Arnold & Toran, 2018). These examples simply highlight some of the pitfalls which may occur in the risk assessment of IVS regarding Pacific salmon habitat. Many other IVS in Western Washington may provide some ecosystem services that are equivalent to, or even superior to, their native counterparts. Therefore, it is imperative to analyze the overall effects of the species to a comprehensive list of environmental response metrics in order to quantify its inherent impact level.

The biological or environmental conditions which enable a particular vegetative species to become invasive may not always be recognized during its early introduction to a novel ecosystem. Sometimes, the mechanisms of invasion are only understood after years of prolonged study. Take knotweed for example, recent genetic analysis indicates that species within this genus propagate primarily through clonal replication rather than sexual reproduction; previously, science was unable to explain its rapid mode of dispersal (Engler et al., 2011). Japanese knotweed, often seen growing along the banks of salmon bearing streams, has become widespread in all but one county within WA (NWCB, 2018). Molecular analysis of this knotweed revealed that only a single male-sterile clone of the plant introduced into the environment generated its subsequent invasion (Rotherham & Lambert, 2012). These examples show how long-term observation may be the best way to determine the true impact of IVS in Western WA.

Modern science has yet to adopt a unified system for classification and prioritization of IVS. As a result, invasion ecology features a wide spectrum of opinion and bias concerning the environmental harm of invasives. The impacts from most invasive plant species have not been fully quantified, and those that have, are frequently analyzed by such a limited set of response metrics that their ecological impact may be considered inconclusive (Barney et al., 2013). This inadequacy can be especially problematic concerning newly introduced non-native plant species in which risks to the environment, economy, or public health may not be obvious.

In contrast, other instances of IVS include impacts to the health of humans and livestock, which can manifest so severely that they become almost immediately apparent. Poison Hemlock, for example, can arguably be considered the most well-known invasive plant in the world and has a substantial presence throughout North America. This plant can cause illness and death when ingested by animals and humans (NWCB, 2017). Yellow flag iris (*Iris pseudacorus),* a class C noxious weed in Washington, contains dangerous toxins harmful to animals and contact with its resin causes skin irritations in humans (NWCB, 2018). Giant hogweed *(Heracleum mantegazzianum)*, found in 15 western Washington counties, exudes an extremely caustic sap that causes skin blisters and sensitivity to ultraviolet radiation, exposure symptoms to this plant can last for years (NWCB, 2018).

The effects that IVS have on salmon habitat can be difficult to quantify because of the intrinsic complexity of ecosystems and the extensive interspecific relationships between organisms. The burgeoning field of invasion biology remained ambiguous until around turn of the 21st century, when the scientific community recognized that more advanced research would greatly benefit this newly founded branch of ecology (Simberloff et al., 2005). Bisson et al. summarized this inadequacy in regard to salmon habitat:

> Very little is known of the effects of invasive riparian plants on the water quality and physical habitat of streams inhabited by Pacific salmon. Moreover, the effects of exotic riparian plants on the contribution of terrestrial organic materials to aquatic ecosystems have rarely been studied (2009, *Climate change* section).

Riparian zones of the Pacific Northwest typically have a composition of heterogeneous sedimentary soils that have been deposited by the influence of water flow and associated erosional effects (Mikkelsen & Vesho, 2000). The combination of this type of soil composition, active geology, and moderate to heavy precipitation makes erosion a frequent occurrence in Western Washington. Native tree species such as Douglas-fir (*Pseudotsuga menziesii*) (Sakals & Sidle, 2004), western redcedar (*Thuja plicata*) (Bennett et al., 2002), western hemlock (*Tsuga heterophylla*) (Bennett et al., 2002), and big-leaf maple (*Acer macrophyllum*) (Purewal, 2004) have deep extensive root systems that provide bank stability along water bodies; thereby, regulating soil erosion regimes.

A plant's root system has a profound effect on its ability to stabilize stream banks in riparian zones. Root cohesion is a measure of a plant's ability to bind soil mechanically and hydrologically. Mechanical reinforcement by roots contributes to a higher shear strength of a sloped soil mass, while hydrological resistance of roots decreases soil pore water pressure; thereby, reducing sub-surface stress loads. (Mickovski & Gonzalez, 2017). Several root characteristics, such as depth and total underground root volume (Gyssels, et al., 2005), fiber tensile strength (Roering, et al., 2003), and quantity of fine-root material (Martinez, 2013), contribute to a plant species' overall root cohesion value.

Root strength is often quantified as a function of root diameter, in which fine roots maintain a higher tensile strength per unit area than those with larger diameters (Martinez, 2013). In fact, studies have indicated that there exists an exponential increase in root soil cohesion as fine root mass increases (Gyssels, et al., 2005).

Many IVS, like knotweed (Arnold & Toran, 2018), giant reed (*Arundo donax)* (Stover et al., 2018), reed canarygrass (Martinez, 2013), or Himalayan blackberry (United States Department of Agriculture [USDA], 2015) possess relatively shallow root systems which do not bind soil as well as their native counterparts. Unbound soils can increase the frequency of large-scale erosion events, translate to sediment inputs many magnitudes greater than the maximum threshold permitted for freshwater salmon habitat, and reduce salmon survival in a local area for up to several years (Waples et al., 2009). Severe monocultures of IVS in areas of steep topography have even been linked to landslides (Malik et al., 2016; Al Mahmud et al., 2018), which can render a stream impassible by fish. Increased sediment loads to salmon bearing streams can limit available nesting habitat, clogs gills, and lower survivability of fish (Close, 2015). A study published in 2014, in *Access International Journal of Agriculture*, found that native plants have most often been the best option for slope stabilization and a feasible remediation method in landslide prone areas (Lu, 2014).

As reiterated many times throughout this thesis, DO in Pacific salmon habitat must exists in adequate concentrations in order to permit several necessary biological functions in this species and enable the perpetuation of vital ecosystem services. The ways in which vegetation may affect aqueous DO concentrations varies by species and can be the result of biotic or abiotic processes. As previously explained in **Chapter 2.3.2**, Washington standards for DO in spawning, rearing, and migrating salmon range between 8.0 to 9.5 milligrams per liter for a one-day minimum (Finch & Brown, 2020). The following section addresses some potential effects that vegetation can have on DO in aquatic ecosystems and attempts to correlate IVS occurrence in Western Washington and salmon habitat degradation.

Some emergent macrophyte species deplete oxygen in water by venting oxygen produced during photosynthesis directly above of the water-air barrier, rather than into the water column (Kuehne, 2016). A 2016 study indicated that the invasive emergent macrophyte parrotfeather (*Myriophyllum aquaticum*) within the Chehalis River system reduced DO concentrations to hypoxic levels in areas dominated by the plant; “The lowest DO concentrations were observed in quadrats dominated by parrotfeather” (Kuehne, 2016, p. 1853). An early study on Eurasian watermilfoil indicated that it reduced DO during seasonal periods of senescence and subsequent decomposition (Aiken et al., 1979). Other invasive plants, such as reed canarygrass, (Klopfenstein, 2016), giant reed (Stein et al., 2000), and saltcedar (Stein et al., 2000), mechanically restrict water flow to the point at which available DO is consumed by aerobic aquatic organisms faster than it can be replenished (Mitchell-Holland et al., 2018). It has been established as scientific fact that there exists a negative correlation between the water temperature and solubility of DO (Fellman et al., 2018). Many IVS in Western Washington have the tendency to form monocultures in the area of proliferation, which can reduce native tree canopy cover and thereby increase solar radiation exposure to a water body.

It is possible for invasive plants to have a larger effect on an entire ecosystem, as their proliferation can alter the local hydrology quite drastically. In Washington State,

“…common cordgrass has transformed intertidal areas and gently sloping mudflats into poorly drained marshes” (Simberloff, 2013). Several well-studied invasive plants contribute allochthonous material to streams, rivers, and lakes which can alter many characteristics of the local environment. The addition of organic material to freshwater ecosystems by non-native plants can introduce novel chemicals that the native biology is ill-equipped to cope with (Bottollier-Curtet et al., 2015). In a paper published in 2008, Going and Dudley monitored and documented the laboratory growth and survival of the aquatic saprophagous caddisfly *(Lepidostoma unicolor)* upon feeding on a diet of plant litter native to the study site (white alder [*Alnus rhombifolia*], Frémont’s cottonwood [*Populus fremontii*], and willow [*Salix* spp.]) versus non-native invasive plant litter (saltcedar [*Tamarix ramosissima*] and giant reed). Going and Dudley concluded that giant reed promoted significant reduction in caddisfly colonization and even induce high mortality (~ 80%) in larvae, likely due to the plant’s production of alkaloid and sterol compounds (2008).

In 2015, Bottollier-Curtet et al. analyzed the effect of invasive plant litter, Japanese knotweed, in riparian areas on the diversity of detritivorous organisms, and found that “…native microorganisms and invertebrates may have to face unusual secondary compounds produced by exotic plants” (Ehrefeld as cited in Bottellier-Curtet et al., 2015, p.266). Although, the authors found no significant correlation between organism abundance/diversity and the particular exotic plant litter used (Bottollier-Curtet et al., 2015). A separate similar study performed in Clear Creek Idaho arrived at the same conclusion: “Japanese knotweed exhibited no differences from native leaf litter in either decomposition rate or macroinvertebrate colonisation dynamics” (Braatne et al. 2007, p. 664).

The native mixed conifer/deciduous forests of the Pacific Northwest provide shade to streams by their extensive canopy cover and decrease stream surface area exposed to solar radiation. One of the greatest threats posed by IVS in riparian zones along salmon habitat has been their tendency to outcompete and displace native tree species. By doing so, non-native plant species can reduce native canopy cover and expose large areas of salmon habitat to warming sunlight and predators (Zedler & Kercher, 2004). This reduction in canopy cover and increase in water temperature directly affects the solubility of aqueous DO and limits the respiratory capacity of aquatic aerobic organisms. This has crucial implications for Pacific salmon habitat as the species are sensitive to low DO concentrations. Healthy riparian zones are especially important within urbanized areas, particularly those which contain freshwater streams that support salmon populations (May et al., 1998).

DO concentrations in salmon habitat can be altered by IVS in other ways besides increased stream temperatures resulting from riparian canopy reduction. A paper published in the journal *Freshwater Biology* in 2016 shows the devastating effects of the notorious Pacific Northwest invader parrotfeather on local conditions of the Chehalis River, a major salmon migration route (Kuehne et al.). The authors asserted that areas proliferated by parrotfeather provide poor quality habitat for native species (Kuehne et al., 2016). Relative abundance of native fishes in the river, including Pacific salmon, were diminished around high concentrations of this invasive macrophyte, likely because “DO concentrations were significantly reduced and approached hypoxic levels in areas dominated by parrotfeather [when] compared with native vegetation" (Kuehne et al., 2016, p. 1846). The depleted DO concentrations in the Chehalis river system due to parrotfeather proliferation are believed to be caused by mechanisms associated with emergent floating-mat macrophytic species (Kuehne et al., 2016). These mechanisms include the minimal rate of photosynthesis and venting of oxygen directly into the air rather than the water column (Kuehne et al., 2016).

Invasive plants can affect the chemistry of a freshwater environment either directly or indirectly. Direct chemical inputs to an aquatic ecosystem by IVS can include contributing allochthonous materials during seasonal senescence (Urgenson, 2006), exudation of allelopathic compounds (Murrell et al., 2011), or by altering nutrient cycling regimes (Corbin & D'Antonio, 2012). The effect of natural plant toxicity, another aspect of chemical alteration to salmon habitat, warrants future research. Species such as poison and water hemlock have a notable presence in Washington state, can grow within riparian zones, and have been found to be toxic to both humans and animals (NWCB, 2017). Research conducted on the effects of toxic phytocompounds on Pacific salmon habitat is currently limited and wide knowledge gaps exist on this subject.

Indirect effects that IVS may have on the chemical composition of an ecosystem often manifest as a result of alterations to the physical structure of the local environment. Invasive plants that commonly establish severe monocultures have the capability of drastically changing the environmental foundation. IVS, such as Himalayan blackberry (Bennett, 2006), English ivy (Ingham, 2008), and knotweed (Urgenson, 2006), regularly form monotypic stands in Western Washington and can effectively suppress the growth and development of native vegetative species. By suppressing native vegetation, either through allelopathy, hyper competitiveness, or nutrient appropriation, these IVS may reduce the native tree abundance in a riparian zone and limit the efficiency of several riparian ecosystem functions which are beneficial to salmon species.

Natural riparian zones exist as considerably diverse ecosystems which provide several services, including filtering of surface and ground water, bank stabilization by vegetation, as well as buffering a stream from toxic stormwater runoff and aerosol drift pollutants (Everest & Reeves, 2007). Riparian ecosystems are efficient at trapping, binding, degrading many common types of pollutants, including phosphoric and nitrogenous chemicals, hydrocarbons, heavy metals, polychlorinated-biphenyl compounds, as well as agricultural chemicals (Desbonnet et al., 1994). Severe degradation to riparian zones may further compromise the health of the local aquatic ecosystem which they envelop by allowing excess toxins and contaminated particulate matter to easily enter the water column. May et al. (1998) submitted a comprehensive analysis on the ecological benefits of riparian zones in urban settings in the Pacific Northwest region. By performing extensive multi-parametric analyses on water samples in the Puget Sound ecoregion and taking comprehensive riparian zone vegetative inventories, the researchers of this study provided substantial unequivocal data that demonstrated the function of healthy riparian zones in providing suitable Pacific salmon habitat (May et al., 1998).

Aside from the previously mentioned ability of some IVS to suppress native vegetation, there remains a concern of alterations to species composition, diversity, and abundance of an ecosystem. Introduced vegetative species tend to support different dependent organisms than those of native vegetative species. There have been several recent studies that indicate there is often a negative correlation of IVS and species diversity at the ecosystem level (Colleran & Goodall, 2013; Going & Dudley, 2008; Simberloff et al., 2005; Weilhoefer et al., 2017).

One example, is a 2008 study by Going and Dudley which examined the colonization characteristics of an aquatic detritivorous invertebrate shredder-species on native leaf litter versus non-native leaf litter. This study found that the aquatic caddisfly (*Lepidostoma*) larvae showed preferential feeding habits towards the native vegetation litter, such as white alder and willow. The larvae selectively fed on leaf margins of the non-native vegetation, giant reed, and avoided other parts altogether. Whereas the invertebrate indiscriminately consumed all portions of the native vegetation.

Similarly, Klopfenstein (2016) conducted research on salmon habitat in partially and fully restored sites within the Lower Columbia River floodplain. By taking surveys of vegetation types and performing feeding experiments in artificial enclosures, the researchers determined that an invasion of reed canarygrass in the Columbia River estuary altered the abundance and diversity of many species of energy-rich invertebrates which juvenile salmon depend on for growth and development (**Figure 8**) (Klopfenstein, 2016). The IVS-induced change to invertebrate diversity and abundance translated to a seasonal growth variance, between juvenile salmon feeding in enclosures dominated by reed canarygrass and native vegetative cover, by as much as approximately 29% (Klopfenstein, 2016).

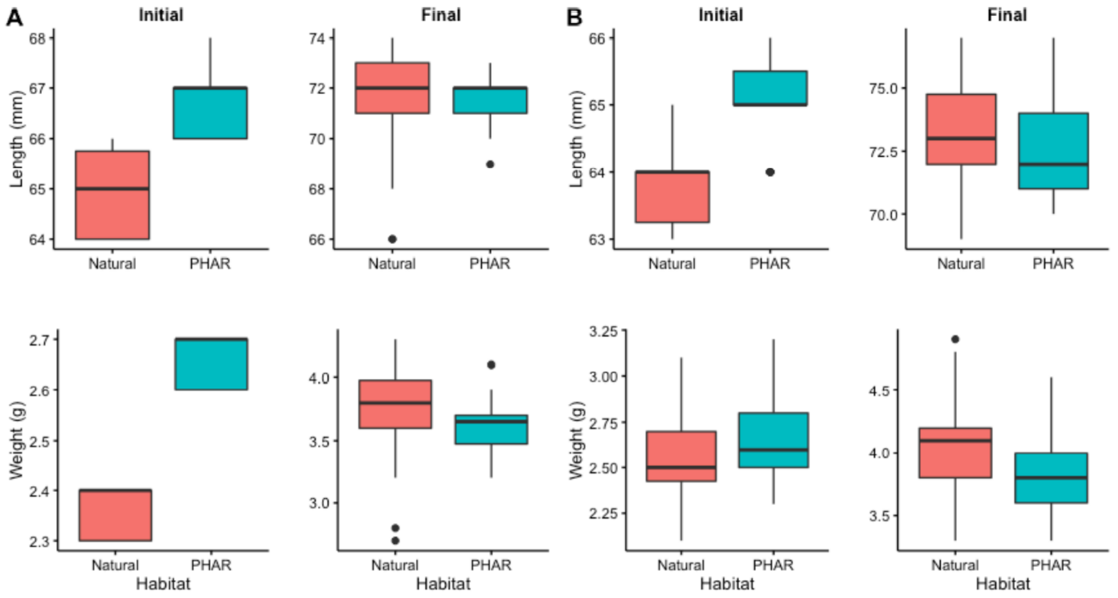


Figure 9. Mean juvenile Chinook Salmon growth (change in length and in weight) during the experimental net pen deployments at MCM in A) 2015 and B) 2016. Initial length and weight was calculated as the average size for fish in each pen. Individual final measurements were recovered upon retrieval of fish reared in either PHAR or natural emergent vegetation across all deployments.

Figure 8: Chinook size variances across two habitat types

This two-year study was conducted on the Columbia River just northwest of Portland, OR in the Multnomah Channel Marsh Natural Area (MCM) and compares salmon growth and diets in areas dominated by reed canarygrass (referred to as PHAR in this study) to areas dominated by native vegetation. This figure displays those growth characteristics in both habitat types across two years, 2015 and 2016; illustrating that the chinook displayed more growth in areas dominated with native vegetation than in reed canarygrass infested areas (Klopfenstein, 2016, Figure 9).

There exists a wealth of research regarding knotweed and its effects on invertebrate populations. Yet, the determination on whether or not the invasive plant diminishes biodiversity differs widely between studies. While some studies indicate that knotweed may contribute organic material that fulfills a detrital function similar to native vegetation (Braatne et al., 2007), other studies indicate a pronounced negative correlation of invertebrate biodiversity and knotweed presence (Claeson et al., 2014; Gerber et al., 2008). Knotweed presence has even been linked to a reduced growth potential of a green frog species (*Rana clamitans*) native to New York State (Maerz et al., 2005). Based on the literature gathered in this thesis, knotweed related impacts to native vegetation diversity and abundance appear to be more common than the invasive plant's effects on invertebrate, amphibian, or faunal populations. Pacific salmon habitat restoration efforts would benefit greatly from future research into knotweed's effects on invertebrate species that salmon rely on for growth and development.

The potential of IVS to significantly impact Pacific salmon habitat has been well established through previous research efforts. The available literature on the subject has demonstrated a great need for natural habitat restoration as the first step to preserving this iconic species. The role of invasive plants in the destruction of salmon habitat in Western Washington must be addressed as a high priority element of future management plans.

2.4 Stakeholder Relationships

The degree of efficiency in which entities cooperate to accomplish mutual goals can determine the ultimate outcome of a particular situation. Good working relationships are based on trust, equality, and respect. For interrelated parties to work effectively together in achieving common objectives, there needs to be transparency of information, alignment of values, dedicated individuals, and flexibility. Each constituent of the partnership must keep the group's interests at the forefront of their agenda and be able to make compromises when needed, in order to accomplish the greater good. The following section will feature some of the challenges of interagency relationships, as well as provide examples of good stakeholder relationships, in the practice of land management and Pacific salmon conservation.

2.4.1 Communication/Collaboration

A major challenge when managing invasive species and protecting riparian habitats has long included the inability to effectively communicate across stakeholders. Lackey postulates key points in his 2003 article about forecasting Pacific Northwest salmon populations into the year 2100, claiming that serious changes in society must occur if wild salmon runs are to be restored. He articulates his belief that society's failure to effectively manage salmon habitat derives from policy conundrum, by stating that even though a strong majority is in favor of taking action to preserve the species, preexisting deeply entrenched policy stances by established bureaucracies convolute and obstruct the process (Lackey, 2003). Furthermore, Lackey believes that the salmon conservation debate has been politicized to the point of which policy preferences and political affiliation have become more of a focus than scientific fact and objective reasoning (2003). Lackey's (2003) statements exemplify many of the difficulties experienced between concerned parties regarding the importance of salmon preservation.

Various groups/agencies have conflicting perspectives about the priority of their interests. Although, each party has valid arguments, compromises must be made for salmon populations to survive. Malick et al. have identified other difficulties in the interdisciplinary approach to salmon habitat management; stating that "Ecosystem openness presents a [challenge] to integrating highly migratory species into [ecosystem-based management (EBM)] policies because these species frequently move across ecosystem and jurisdictional boundaries" (2017, p. 123). Because of this fact, there can be ambiguity with understanding which local agency/department has operational status. For example, a salmon migration route which spans private, public, and tribal lands is often the topic of policy disagreements between stakeholders. In these instances, it can be common to see fragmentary or partial restoration sites.

In 2014, Sara Breslow wrote an insightful article for *Anthropological Quarterly* in which she describes many of the incongruities between private landowners and environmental advocates surrounding the topic of salmon habitat restoration. In her submission, Breslow focusses on a case study which occurred in the Skagit River Valley of Washington State, where various state agencies, two state-supported salmon habitat restoration groups, and other environmental organizations worked in concert with local tribes to persuade farmers to convert part of their land to suitable salmon habitat. The tribes "…produce[d] scientific research in support of fisheries management and salmon recovery by hiring teams largely comprised of non-native biologists…" (Breslow, 2014). The restoration strategies proposed by the project developers include planting of trees along streams, removing and setting back dikes, removing and modifying culverts and tide gates, recreating spawning channels, and adding stream structure by anchoring logs into riverbanks. Most of the farmers approached with this proposition had demonstrated significant resistance, stating that the project failed to consider "…ecological processes, such as invasive species and local drainage and flooding patterns…" (Breslow, 2014, p. 728). Some landowners have even expressed outrage and claimed that the scientific data tends to be biased towards abstract anti-farming assumptions. Although ample evidence remains for the need to restore salmon habitat, some of these landowners adopted a defensive stance when asked for their cooperation. Interviews conducted by Breslow revealed that the farmers' defiance seems more to do with the perceived feeling of disrespect rather than disagreements with the scientific methods employed in the project (2014). Farmers coalesced around a defensive position and opposed this project proposal by writing letters to the editor of a local paper, bringing their arguments to the courts, and successfully lobbying against changes to the state's hydraulics code. By employing social, economic, and cultural counter-arguments, the farmers gained the full support of county officials. To date, this project effort has gained little traction in the local farming culture, and the breadth and scope of its aspirations have not yet materialized. Though, this study highlights some of the difficulties experienced when pleading the case for salmon habitat restoration.

2.4.2 Relationships with Salmon

It is feasible to claim, based on the information covered in this literature review, that stakeholders of salmon habitat restoration fall into one of four groups: economic, tribal, environmental, private. Each of those constituents hold their own unique perspective on the topic. A substantial portion of Washington State fisheries businesses have an inextricable dependance on Pacific salmon. In fact, all levels of fishermen/women, from Washington businesses to individuals, are affected by Pacific salmon conservation legislation on some level. Businesses operating in the state are required to adhere to strict environmental regulations, many of which have been strongly influenced by salmon restoration efforts, such as the water quality standards, and land use restrictions set by the Washington State Department of Ecology (see **Table 2**). Many of the indigenous tribal organizations of Washington State are interconnected with salmon, and rely on them for cultural, subsistence, and economic reasons (Colombi, 2012; Cronin & Ostergren, 2007; Dillon, 2020). The U.S. Supreme Court upheld the Boldt Decision to grant Pacific Northwest indigenous people legal rights to fifty percent of harvestable fish (Blumm, 2017; Brown & Footen, 2010; Donovan, 2016). Several federally recognized state tribes still practice cultural ceremonies during the major seasonal salmon runs and regard these animals as sacred. In addition to providing a food staple to indigenous peoples, salmon have been a major part of tribal economy for thousands of years (CRITFC, 2016).

2.4.3 Stakeholders and IVS

Concerned parties of noxious weed invasion exist in all sectors of Washington State society. IVS impact private landowners by damaging infrastructure, posing a risk to health, and decreasing property value (NWCB, 2018). Industries such as forestry and farming are commonly impacted by IVS. Timber lands can become particularly vulnerable to IVS as they are often the site of soil disturbance from logging practices, which non-native plants can readily establish. A study by Slesak et al. provides statistically significant evidence of suppression by Scotch broom on Douglas-fir forests of the Pacific Northwest (2016). As previously stated in this literature review, agriculturists experience impacts due to IVS in a direct effect on profitability and reduced crop production (NWCB, 2018).

2.4.4 Perceptions and Controversies

Invasive Vegetative Species (IVS) management suffers from a lack of clearly defined terms. Lackey (2003) explained how certain terms prevent management from progressing; for example, different groups have different ideas for what constitutes ‘ecosystem health’, so they continue to debate the terms’ definition. Lackey also provided evidence of backlash to the Endangered Species Act concerning salmon populations, specifically regarding the inability to protect salmon without impacting humans or changing human behavior, as well as the inability to protect salmon when completely ignoring human needs (Lackey, 2003). This debate can lead to bias on the part of some agendas.

Drs. Mark Sagoff and Daniel Simberloff have had a long rivalry and debated the terms and the management of IVS. One of the recurring themes of their debates concerns the term, ‘environmental harm’. Dr. Simberloff has advocated for invasive species control whereas Sagoff states that management based on this concept typically remains a waste of time and resources (Sagoff, 2009). While Sagoff (2009) stated that he agrees that controlling invasive vegetation is warranted when it causes ‘economic harm’ or ‘harm to human health’, he also states that ‘environmental harm’ exists as an imaginary concept (Sagoff, 2005 & 2009), that it cannot be used in science, and even considers it to be ‘diktat’ and ‘diatribe’. Thus, Sagoff argued that management cannot be justified for a species based on this concept. Sagoff (2009) also proposed that ‘environmental harm’ is based solely on opinion set by those who are ‘offended’ or ‘do not like’ the species. According to Sagoff, “Science on occasion may be able to tell us what is false or true[,] but it can never tell us what is bad or good” (2009, p.84). Sagoff added that a biodiversity increase may result from the invasive species adding pressure to the native counterparts (Sagoff, 2009); while there is always the ‘exception to the rule’, IVS tend to establish towards creating a monoculture of the species – the very opposite from being bio-diverse.

Sagoff (2018) made a claim that when differentiating between the terms of ‘invasive’ or ‘colonizing’ species as well as between ‘established alien’ and ‘native’ species that we need to remove the human component and the time of arrival in the definition; however, humans are very much a part of the ecosystem and thus must be included. Also, the time of arrival certainly makes a difference in determining specific terms of a species nativity. Sagoff held his position about an invasive species posing ‘ecological damage’ as something that “cannot possibly be tested because [it] is a normative idea that can mean almost anything” (2018, p. 28). On the contrary, each of Simberloff’s articles supported management and control of invasive species without any terminological confusion. This can be especially evident when Simberloff, Parker, & Windle (2005) stated that with more research, better technologies, and innovative approaches IVS have a real chance at being detected early, managed quickly and efficiently, as well as eradicated in many instances. Simberloff, Parker, & Windle (2005) insisted that all this potential success for management does not fall within the realm of fiction.

Allendorf and Lundquist (2003) discussed the long-standing controversy in invasion biology, typically referring to a debate over the need to manage for such species. Proponents of invasive species management have often relied on terminology which has been deemed by some scientists as confusing or vague to support their position. Allendorf and Lundquist also argue that non-native species have invaded throughout history and that natural systems adapt to the invaders. The statement “There are many unknowns, but [a] lack of information should not stop scientists from influencing such decisions” (Allendorf & Lundquist, 2003, p.26) provided a strong argument for the advancement of invasive species management. Ruckelshaus et al. simplified interagency disputes by stating that, “our charge as scientists is to respond to the intense pressure for biologically defensible answers in a way that clearly distinguishes scientific conclusions from policy choices” (2002, p. 667).

The literature featured within this thesis provided a wealth of knowledge concerning the relationship between Pacific salmon and the occurrence of invasive vegetation in the Pacific Northwest. Through the investigation of previous scientific endeavors and in-depth research studies, this project has shown the importance of effective IVS management for protecting and maintaining salmon habitat. The information established the prominence of salmon in Western Washington's environment, society, indigenous cultures, and economy. It also provided an extensive background of Western Washington's invasive plant species and their role in natural systems. Furthermore, the effect of IVS on freshwater habitat has been established to contribute significantly to the decline of salmon populations. Knowledge gaps do exist, specifically related to the impacts of noxious weeds, which can only be satisfied through future scientific research. As science gains more understanding into the subject, various agencies invested in salmon conservation and land management may be better equipped to address the problem of an iconic Pacific Northwest fish species' declining population.

Chapter 3: Methods

This methods section has been broken up into various sub-sections and organized chronologically by the order of completion for this thesis project. These sections include the creation of the support team as well as methods for the survey creation and distribution, survey analysis, and post-survey literature review and analysis.

3.1 Team

I initially met with Justin Bush, the Executive Coordinator for the Washington Invasive Species Council (WISC), who suggested this thesis topic and later began introducing me to those who would ultimately become part of my team of field experts. This team was designed to provide professional support, maintain proper focus, and supplement my research with data and resources. Those who initially joined the group include Justin Bush with WISC, Mary Fee with the Washington State Noxious Weed

Control Board (NWCB), Chad Phillips with the Washington State Department of Agriculture (WSDA): Pest Program, Alice Rubin with the Salmon Grants Section of the Recreation and Conservation Office (RCO), as well as Lizbeth Seebacher and Jenifer Parsons with the Washington Department of Ecology (Ecology). This team was later joined by Irene Weber as a Vegetation Ecologist with the Washington State Department of Natural Resources (DNR), as well as Angela Dillon and Caleb Graham with the Puyallup Tribe Fisheries (PTF). Once the survey was collected, new additions to this team included: Danny Najera, PhD, biology instructor at Green River College (GRC); Patricia Grover, Mason County NWCB; Gavin Nishiyori, West Fork Environmental; Susan Bird, Yakima County NWCB; Jennifer Mendoza, Cowlitz County NWCB; Sarah Zaniewski, Squaxin Island Tribe; Jeff Nesbitt, Pacific County NWCB; Marty Hudson, Klickitat County NWCB; Kiley Smith, Grays Harbor NWCB; and David Heimer, Washington Department of Fish and Wildlife (WDFW).

3.2 Survey

This survey involved a multi-step process requiring approval for implementation. As a first step in the process for this research, I completed a Human Subjects Review (HSR), detailing the purpose and objective of this study. The HSR was approved on July 15th, 2020 by The Evergreen MES Human Subjects Review committee. Once the HSR was approved, the creation, distribution, and analysis of the survey followed.

The survey (see **Appendix A, C, & D**) consisted of three parts: Part 1 (**Appendix A**) provided the introduction to the survey, Confidentiality Agreement, Letter of Interest, and optional demographic information; Part 2 (**Appendix C**) consisted of the survey body which will soon be discussed in more detail; and Part 3 (**Appendix D**) included feedback on the survey itself.

After completing Part 1 of the survey, respondents were asked to select a single invasive vegetative species from a list of 52 possible species within Washington (**Appendix B**). This list was generated from a broad list of candidates using the NWCB website for Class A, B, and C invasive weeds. Once a species had been chosen, the respondent was directed to Part 2 of the survey; a page for that specific species and asked a series of questions relating to its location, extent/abundance, potential future impact/spread, and current level of control for that plant, as well as research availability. Respondents also had the option to provide any additional comments, concerns, or suggestions for that species (such as any Water Resource Inventory Area (WRIA) information or information about multiple county locations for that species).

I chose to group the data by county because the majority of respondents were more familiar with county level operations than on the WRIA level. Making the questions more relatable to the group majority allowed for more respondents to finish the survey. However, salmon information may be more relevant to watershed boundaries than at the county level. This sacrifice of WRIA data, which could potentially provide for more appropriate data to the study, is justified by the possibility of a larger sample size. However, a follow up email to those who received the survey was issued shortly after the distribution, as the questions regarding infestation, impact, and control (see Questions 10, 11, & 12 in **Appendix C**) had referenced the previously designed watershed format instead of county distributions. This email was intended to inform the recipient of the survey to disregard the word ‘watershed’ in the relevant questions and substitute it for ‘county’ instead.

3.3 Survey Distribution

This survey was distributed as a judgement sample. A judgement sample is when the researcher decides who the survey is distributed to and based on their own judgement (businessjargons.com, 2016). The justification for this type of sampling was to narrow the respondents to those with invested interest in the subject matter in order to create more accurate results since the survey focused on a very narrow field of study.

With the help of the NWCB Executive Secretary, Mary Fee, I used the NWCB Survey Monkey account to administer the initial survey. I sent the original email to my team members in January of 2021. The Team each had a copy of the SurveyMonkey link and then forwarded the email to various professionals within their agency/professional listservs; for instance, Mary Fee was able to send the link to each of the County NWCBs. Each of the pre-survey team members were able to choose recipients at their own discretion based on who they determined to be a “best fit” candidate for taking the survey. They were also encouraged to ask their recipients to redistribute the survey where applicable. I too included the same SurveyMonkey link in emails from my personal account which were distributed to my undergrad professors, who spend many hours in the field collecting data with students, fellow alumni from my undergraduate institution, who currently work in the field at various agencies, and other professional contacts which I felt were appropriate for this study.

The initial distribution occurred between January 13th and 15th of 2021; the respondents were given until February 1st, approximately two weeks, to complete and submit their responses. Initially, there were very few returns on the survey, thus limiting the sample size and making it very hard to draw any conclusions about a top number of IVS. As a result, the deadline became extended into late-March and new recipients were included to take the survey.

3.4 Survey Analysis

The purpose of the survey was to narrow down the list of 52 potential invasive vegetative species found in Western Washington (**Appendix B**) to a more manageable number of approximately five species (**Table 4**). The narrowing down of the list was achieved by focusing on the species mentioned most often by the respondents. In essence, the species selected by respondents may not represent their true abundance. It is possible that respondents based their choices on their familiarity with them, visual abundance, or for more scientific reasons. Nonetheless, this thesis is designed to value the perspective of field experts, assuming a certain degree of professional integrity and individual competency relating to their respective disciplines. To understand the choice of species, a question was included asking the respondents for reasoning behind their choice. To further account for the bias, I examined literature pertaining to each of the top species and discuss this further in **Ch 4**.

The literature review explored various criteria and environmental conditions proven to be important for salmon survival needs. These criteria, also briefly explained in **Chapter 2.1.2** and **Chapter 2.3.1**, includes overall biodiversity, sediment loads, stream chemistry, water flow regimes, stream temperatures, shelter abundance, migration route obstruction, and predator habitat.

Once the post-survey literature review was completed, a comparison between survey results was analyzed and examined in **Ch 4**. Information gaps, created by the lack of available scientific literature, on the impact an IVS has on salmon habitat were also noted (**Table 5**). The results on the impact these invasive species have on salmon survival is detailed in **Chapter 4**. Each of the top species has its own dedicated sub-section, where the survey results are compared with relevant scientific literature.

3.5 Mapping

Multiple data layers were created in ArcGIS Pro and uploaded to ArcGIS Online for further analysis. County shapefiles were collected from Washington Department of Natural Resources GIS Open Data Portal. There are 19 counties selected from this shapefile and used to represent the study area as well as to analyze the locations of salmon streams and IVS presence within Western Washington (**Appendix E1**).

Salmon-bearing streams were downloaded from SalmonScape's website (Washington Department of Fish and Wildlife [WDFW], 2020). Salmon streams were filtered by species and represented with unique colors to each species as it pertains to their spawning (darkest tint), rearing (middle tint), and migration/presence (lightest tint) (**Appendices 2 – 7 & 9 – 14**). It is important to note that there is a disclaimer with this data; for instance, the data represented may not be complete due to insufficient staff availability, funding constraints, and changes in populations which may occur over time (WDFW, 2020).

The top four IVS species were selected from EDDMapS website and downloaded as specific points for estimating each species locations (**Appendices E8 – E14**) (UGCISEH, 2020). The IVS points are represented as a flag with a unique color value to each species. EDDMapS is a software application created by members of the Center for Invasive Species and Ecosystem Health at the University of Georgia (UGCISEH, 2020). This application can be downloaded to a smartphone or tablet allowing the general public to find, map, and track invasive species in their area, which becomes verified by professionals in the field before becoming available for access to view and/or download (UGCISEH, 2020). While this can be a great tool for early detection and rapid response (EDRR) of invasives in an area, there remain limitations. Some of these limitations, similar to the SalmonScape data, include the lack of available resources for verifying species (such as available personnel, time, or funding), a lack of public awareness and/or knowledge in identifying certain species, a lack of awareness to the application itself (not everybody knows this app exists), or limitations in mobility (not all areas where IVS prevail are easily accessed by the public) (UGCISEH, 2020). Thus, this data serves as starting points for restoration projects, but do not necessarily reflect the true population of invasive species.

After the collection of each of these types of data (county, salmon streams, invasive vegetation location), they were analyzed in various maps that show their approximate locations (salmon are represented in **Appendices E2-E7** and IVS in **Appendix E8**) and relations to one another (**Appendices E9-E14**). The proximity analysis was based on a 61-meter (200-foot) buffer between IVS locations and salmon stream segments. This buffer was selected in accordance with the Forest Practices Illustrated manual for Washington’s riparian buffers (Washington Department of Natural Resources [WA DNR], 2021).

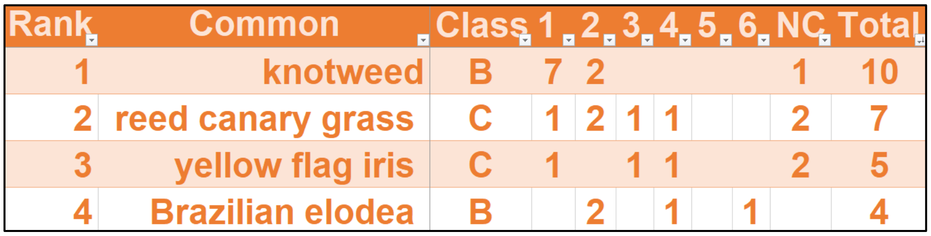
Chapter 4: Results & Discussion

Based on the survey results, the four most frequently mentioned for highest priority of noxious weeds within Western Washington included knotweed (all four knotweed species in general but with preference for Japanese knotweed), reed canarygrass, yellow flag iris, and Brazilian elodea (**Table 4**). According to surveyed individuals, knotweed appears to have the most research available for sufficiently meeting the needs of their agencies/organizations/etc. Responses concerning reed canarygrass research availability fluctuated widely. Both yellow flag iris and Brazilian elodea were suggested as understudied (**Table 5**).

Table 4: Survey Results and Ranking of top IVS

This table displays the number of votes for each of the highest ranked species. These counts are generated from the survey. The columns are defined below:

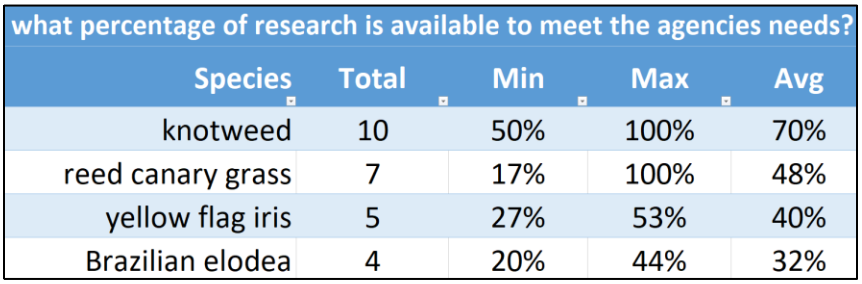
- *"Rank" shows which species was counted the most times within the survey*
- *"Common" displays the common name for the species on the survey*
- *"'Class" depicts the invasive species' national classification system based on abundance*
- *#'s "1" - "6" illustrate whether an individual noted the species first through sixth as the respondents ranked them within their survey, and the count within those columns is based on how many individuals chose that ranking for the correlating species.*
- *"NC" is the 'no-count' column is for individuals that picked a species in the survey but did not include them in the ranking process.*
- *"Total" was then sorted from most to least allowing for a ranking of the top (including the NC's).*



Rank	Common	Class	1	2	3	4	5	6	NC	Total
1	knotweed	B	7	2					1	10
2	reed canary grass	C	1	2	1	1			2	7
3	yellow flag iris	C	1		1	1			2	5
4	Brazilian elodea	B		2		1		1		4

Table 5: Percentage of available research by species

This table illustrates how much research on each IVS is perceived to be available to various agencies/organizations/groups/etc. This question is based on "Question 13" from the survey as shown in ***Appendix C: Survey Part II****.*



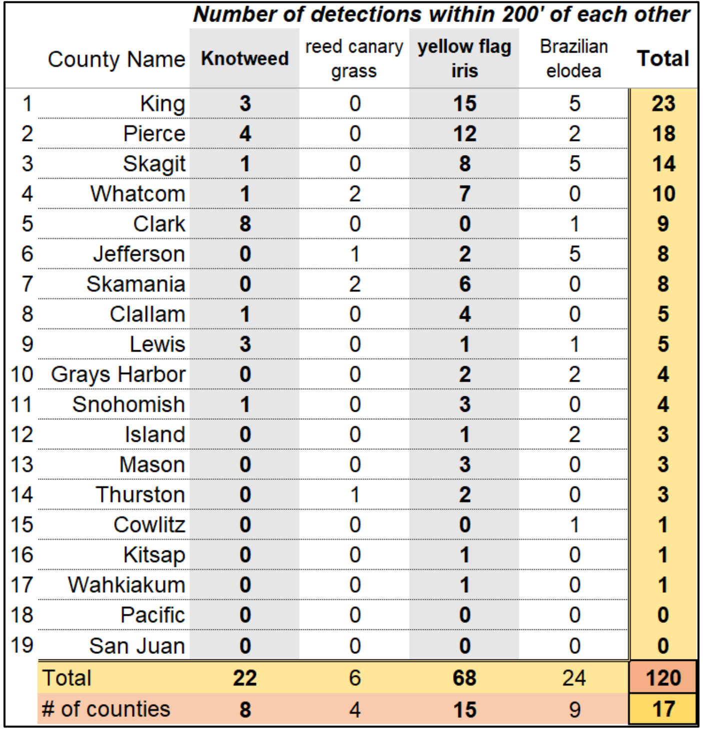
what percentage of research is available to meet the agencies needs?

Species	Total	Min	Max	Avg
knotweed	10	50%	100%	70%
reed canary grass	7	17%	100%	48%
yellow flag iris	5	27%	53%	40%
Brazilian elodea	4	20%	44%	32%

Japanese knotweed, a class B noxious weed, appears in 95 total locations (**Table 1** and **Appendix E8**). When search parameters are limited to a an approximate 61-meter (200-feet) buffer of each other, knotweed appears within 22 locations across eight of the counties (**Table 6** and **Appendices E9-E14**). Reed canarygrass, a class C noxious weed, has been documented in 108 total locations (**Table 1** and **Appendix E8**). When search parameters are limited to the same buffer amount, reed canarygrass appears within six locations across four of the counties (**Table 6** and **Appendices E9-E14**). Another class C noxious weed, Yellow flag iris has been found in 284 total locations (**Table 1** and **Appendix E8**). When search parameters are limited to the buffer amount, yellow flag iris appears within 68 locations across 15 of the counties (**Table 6** and **Appendices E9-E14**). Furthermore, Brazilian elodea, a class B noxious weed, has 113 total documented locations (**Table 1** and **Appendix E8**). When search parameters are limited to the buffer amount, Brazilian elodea appears within 24 locations across nine of the counties (**Table 6** and **Appendices E9-E14**).

Table 6: Top IVS within 200 feet of salmon streams

Table illustrating the number of IVS found within 200-feet of salmon streams within Western Washington. These amounts have been mapped and can be seen in ***Appendices 9-14****.*

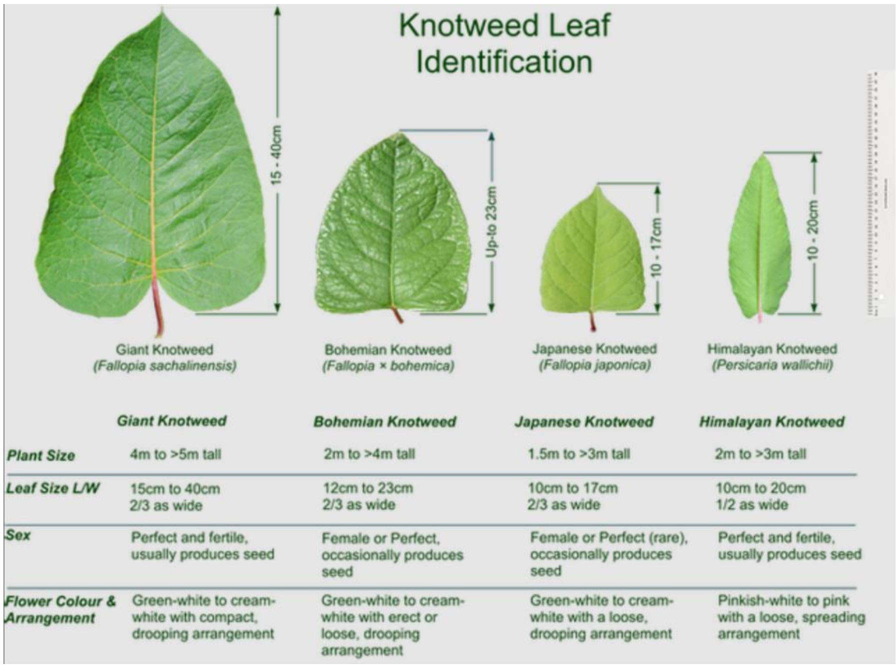


		Number of detections within 200' of each other				
	County Name	**Knotweed**	reed canary grass	**yellow flag iris**	Brazilian elodea	**Total**
1	King	**3**	0	**15**	5	**23**
2	Pierce	**4**	0	**12**	2	**18**
3	Skagit	**1**	0	**8**	5	**14**
4	Whatcom	**1**	2	**7**	0	**10**
5	Clark	**8**	0	**0**	1	**9**
6	Jefferson	**0**	1	**2**	5	**8**
7	Skamania	**0**	2	**6**	0	**8**
8	Clallam	**1**	0	**4**	0	**5**
9	Lewis	**3**	0	**1**	1	**5**
10	Grays Harbor	**0**	0	**2**	2	**4**
11	Snohomish	**1**	0	**3**	0	**4**
12	Island	**0**	0	**1**	2	**3**
13	Mason	**0**	0	**3**	0	**3**
14	Thurston	**0**	1	**2**	0	**3**
15	Cowlitz	**0**	0	**0**	1	**1**
16	Kitsap	**0**	0	**1**	0	**1**
17	Wahkiakum	**0**	0	**1**	0	**1**
18	Pacific	**0**	0	**0**	0	**0**
19	San Juan	**0**	0	**0**	0	**0**
	Total	**22**	6	**68**	24	**120**
	# of counties	**8**	4	**15**	9	**17**

Many studies have documented the direct biodiversity impacts of knotweed and reed canary grass. The direct impacts of Brazilian elodea and yellow flag iris on overall biodiversity are understudied, but there remains a vast amount of literature on indirect impacts, such as specific traits that could make them better competitors. Sediment is also well studied in knotweed and reed canarygrass while understudied in yellow flag iris and does not apply to Brazilian elodea. Impacts on stream chemistry is well studied in knotweed and Brazilian elodea, but underrepresented in reed canarygrass, mostly inconclusive in yellow flag iris. Disruption of water flow is typically a widely accepted trait among all four of the IVS but appears to be very underrepresented in quantitative data. Shelter abundance effects are a tricky category to synthesize in available literature since they are mostly an indirect effect caused by IVS outcompeting any native vegetation that would normally provide DWD or cover. Migration route obstruction is better studied in reed canarygrass and yellow flag iris and largely unexplored in knotweed or Brazilian elodea. Promotion of salmon predator habitat is not applicable to knotweed or yellow flag iris but has been observed in literature for reed canarygrass and Brazilian elodea. There was difficulty in exploring information regarding IVS as salmon predator habitat, because it requires preexisting knowledge of salmon predator species in freshwater stream environments in order to do a complete investigation.

4.1 Knotweed (*Fallopia* spp.)

The four species of invasive Knotweed found in Washington include: Japanese (*F. japonica*), giant (*F. sachalinensis*), Himalayan (*Persicaria wallichii*), and Bohemian (*F.* x *bohemicum*). The total allotted budget for Washington State's knotweed management program was $950,484 over the course of two years (2017-2019). That funding was spent managing 835.2 miles of riparian ecosystems, of which 469.2 miles were located in Western Washington counties (Washington State Department of Agriculture [WSDA], 2017). The taxonomic designation of knotweeds has often been the subject of debate, as they are categorized within several genera (i.e., *Fallopia*, *Reynoutria*, *Polygonum*, and others). This thesis will use the most recent North American nomenclature associated with knotweed, *Fallopia*. These rhizomatous, herbaceous perennial plants range in size from 1.5 meters (~ 5 feet) to 5 meters (~ 16.5 feet) in height (Parkinson & Mangold, 2010). Due to the climate of the Pacific Northwest region, knotweed experiences accelerated growth in early spring, usually around April, with its first flowers appearing in late summer, and a complete dieback of the plant occurs soon after the first frost. (McHugh, 2006). The four species can be easily distinguished from one another by their different leaf sizes (**Figure 9**).



	Giant Knotweed	**Bohemian Knotweed**	**Japanese Knotweed**	**Himalayan Knotweed**
Plant Size	4m to >5m tall	2m to >4m tall	1.5m to >3m tall	2m to >3m tall
Leaf Size L/W	15cm to 40cm 2/3 as wide	12cm to 23cm 2/3 as wide	10cm to 17cm 2/3 as wide	10cm to 20cm 1/2 as wide
Sex	Perfect and fertile, usually produces seed	Female or Perfect, occasionally produces seed	Female or Perfect (rare), occasionally produces seed	Perfect and fertile, usually produces seed
Flower Colour & Arrangement	Green-white to cream-white with compact, drooping arrangement	Green-white to cream-white with erect or loose, drooping arrangement	Green-white to cream-white with a loose, drooping arrangement	Pinkish-white to pink with a loose, spreading arrangement

Figure 9: [photo] Knotweed leaf identification
Differences in knotweed leaf sizes compared between species (Knotweedkillers.com, n.d.).

The biological traits inherent to this aggressive plant promote its ability to harm local ecosystems by degrading riparian ecology, causing stream bank erosion, as well as negatively affecting native vegetation, wildlife, and salmon habitat (Andreas & DesCamp, 2015). The ability of knotweed to hybridize with similar knotweed congeners may provide it with a competitive edge over native vegetation. Japanese and giant knotweed have cross bred to create a successful hybrid, Bohemian knotweed, commonly found in Washington State. In a controlled greenhouse experiment, Parepa et al. (2014) compared the competitive behaviors of Japanese and giant knotweed to their hybrid, Bohemian knotweed. The researchers discovered that the hybrid generally outperformed either parent plant in terms of growth and development, fragment regeneration, competitive behaviors, and overall success (Parepa et al., 2014).

The rhizome network of knotweed, which can extend to a depth of 4.5-meters and laterally by 20 meters (approximately 15 by 65 feet), possesses characteristics that have enabled its aggressive clonal reproduction and hyper competitiveness (Jones et al., 2018). These invasive plants can easily reproduce from root and stem fragments less than 2.5 centimeters (1 inch) in size (McHugh, 2006; Urgenson, 2006; Harbaugh, 2017). Research conducted by Colleran & Goodall (2014) indicated that approximately 70% of the Japanese knotweed clones observed in natural settings had sprouted from rhizome fragments, and their subsequent laboratory experiments confirmed this regeneration rate. Knotweed has been observed sprouting from rhizome fragments 20 years after the complete removal of its surface material (Stuart, 2015). While all four knotweed species listed will be discussed, Japanese knotweed will be given priority as it has the most research associated with it (**Figure 10**).

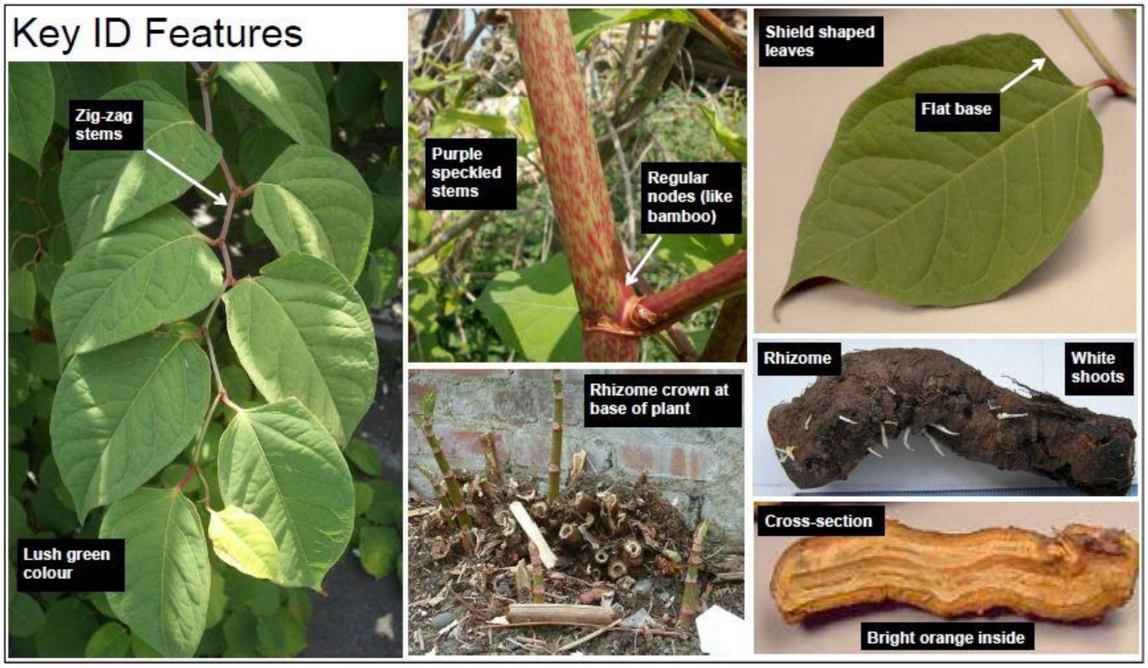


Figure 10: [photo] Japanese knotweed identifiers
Identifying characteristics of Japanese knotweed (Olaf B. et al., n.d.).

Knotweed ranked the highest from the survey results, with 67% of respondents mentioning this genus as having a high impact on freshwater ecosystems. When asked why this plant was specifically a priority, respondents mentioned that knotweed:

1) outcompetes native species thus reducing biodiversity as well as preventing species that would otherwise provide better canopy cover and shelter (80% of knotweed respondents),
2) grows rapidly as a highly aggressive invader (60%),
3) causes soil instability which increases erosion rates and sediment (50%),
4) is common along streams (40%),
5) has roots that can alter stream morphology (30%),
6) is difficult to remove (20%),
7) can be costly to manage with limited and intensive options (20%),
8) increases water turbidity (10%),
9) increases flooding events (10%), and
10) reduces food availability for macroinvertebrates (10%).

The survey responses indicate that this highly invasive species drastically degrades natural riparian conditions to the point which management becomes a top priority.

4.1.1 Dichotomy

The following dichotomy is taken directly from the second edition of the book, *Flora of the Pacific Northwest* (2018), in which the genus *Fallopia* for giant, Bohemian, and Japanese knotweeds begin on page 330, and the genus *Persicaria* for Himalayan knotweed begins on page 331 (Hitchcock & Conquist, 2018). This dichotomous breakdown of the plants allows for a deeper look into the plants 'personality'.

> ***Fallopia*** (p. 330)
> Flowers perfect or some to all pistillate or staminate, inflorescence spikelike, panicle, or racemose; pedicels not jointed at tip; perianth 5-parted most of length or only near tip, greenish, white, or pink, outer tepals winged or keeled, largest; stamens 6-8; pistil 3-carpellate; stigmas capitate, fimbriate, or peltate; fruit 3-

angled; annual or large perennial herbs, some twining, or woody climbing vines; stipules light to dark brown; leaves alternate, cauline, never jointed at base. Many noxious weeds.

1b. Stems erect; stigmas fimbriate

  3a. Veins of leaf underside with multicellular hairs (15x); mid-stem leaf bases deeply cordate; inflorescence much lower than subtending leaf; riparian zones, roadsides, meadows, ditches; aggressive Asian intro, escaped from cultivation; both sides Cascades, Alaska to California, east to Atlantic coast; giant knotweed (*P.s.*)

  3. ***F. sachalinensis*** (F. Schmidt) Ronse Decr.

  3b. Veins of leaf underside scabrous or with simple hairs (15x); mid-stem leaf bases slightly cordate to truncate or slightly cuneate; inflorescence above or below subtending leaf

    4a. Veins of leaf underside with scattered, simple, stout-based hairs; mid-branching leaf base usually slightly cordate; well-developed mid-stem leaves usually greater than 20 centimeters long; riparian zones, roadsides, wastelots; aggressive Asian intro, escaped from cultivation; Alaska to Oregon, east to Montana and scattered east to Atlantic coast; hybrid knotweed [aka Bohemian knotweed] hybrid of 3 [giant k.] x 5 [Japanese k.]

    4. ***F.*** x***bohemica*** (Chrtek & Chrtova) J.P. Bailey

    4b. Veins of leaf underside minutely scabrous with scattered swollen cells or knobs; mid-branching leaf base truncate (rarely slightly cuneate); largest mid-stem leaves over 18 centimeters long; aggressive Asian intro, escaped from cultivation, riparian zones, roadsides, wastelots; Alaska to California, east to Atlantic coast; Japanese knotweed

    5. ***F. japonica*** (Houtt.) Rouse decr.

Persicaria (p. 331)

Flowers perfect; inflorescence capitate, spikelike or panicle; pedicels not jointed at tip, or absent; perianth 4-5-parted about 1/5-2/3 length, greenish, white, pink, red, or purple, outer tepals unkeeled and largest; stamens 5-8; pistil 2-3 carpellate; stigmas capitate; fruit 2-3-angled; annual or perennial herbs, subshrubs; stipules green to brown; leaves alternate, mostly cauline, never jointed at base, often with a dark triangular mark. Plants of little or no grazing value; many noxious weeds.

1b. Stem smooth; leaf blade base usually truncate to tapered, rarely cordate but then not clasping stem.

  2b. Petioles unwinged; inflorescence usually more elongate in spikes or panicles; anthers pink to red or purple

    3a. Inflorescence a branched panicle; stigmas 3, achenes trigonous; tepals 5, spreading, white (rarely faint pink); rhizomatous perennial, 7-25 decimeters; leaf blades 9-22 centimeters; floodplains, roadsides, disturbed ground; Asian intro; west Cascades, Alaska to California, mostly near coast; Himalayan knotweed

3. ***P. wallichii*** (Greuter & Burdet)

4.1.2 Overall Biodiversity (Flora, Fauna, Invertebrates)

Knotweed species possess a host of evolutionary adaptations which may provide the plant with several environmental advantages over native flora. These biological traits and physical attributes converge to make this plant one of the most ecologically destructive organisms in Western Washington. Knotweed's rapid growth potential, efficient use of nutrients, tolerance for environmental stresses, and hyper-competitive nature enable this IVS to infest vast areas and drastically reduce native biodiversity. Knotweed demonstrates a considerably high growth rate when compared to competitor species, which allows it to grow taller, develop greater foliar surface area, and form underground tissues faster than most competitors at the same stage of development. Knotweed has been documented to grow as much as 15 centimeters (6 inches) per day in early spring (Urgenson et al., 2009; Bailey et al., 2009). By growing taller than its competitors, knotweed gains unobstructed access to sunlight and establishes photosynthetic dominance.

The biological functions which provide knotweed with a high growth potential reside in its rhizome network. The manner in which this plant utilizes carbon and nitrogen is vastly superior to most Pacific Northwest native species. Prior to leaf-fall, knotweed begins transferring the majority of their foliar nutrients to rhizome tissues for storage; in this way, the species utilizes carbohydrate reserves the following spring for instantaneous rapid growth. Confirmed observations of nutrient appropriation by knotweed demonstrates that the plant possesses specialized biology conducive to extreme invasiveness (Walls, 2010). A study by Urgenson (2006) indicated that knotweed can retain around 75% of its foliar nitrogen during seasonal senescence. By doing so, the plant limits the amount of nitrogenous nutrients available to competitor species. This aggressive tactic of reabsorbing its own nitrogen stores gives knotweed a significant advantage over most other plants (Urgenson, 2006).

There has been increased attention brought to knotweed's ability to exude allelopathic phytochemicals as a mechanism to suppress competitive native vegetation (Murrell et al., 2011; Vrchotová & Šerá, 2008; Bailey et al., 2009); although definitive evidence of effective allelopathy by knotweed remains inconclusive. A controlled greenhouse experiment by Murrell et al. (2011) tested the allelopathic potential of Bohemian knotweed on six separate plant species (Roberts geranium [*Geranium robertianum*]*;* spotted dead nettle [*Lamium maculatum*]; red campion [*Silene dioica*]; common comfrey [*Symphytum officinalis*]; perennial ryegrass [*Lolium perenne*]; and rough bluegrass [*Poa trivialis*]) native to the study region. The results of this study showed a significant indication of allelopathy by knotweed, though it was only effective on the native forbs used in this experiment. The plants that grew in pots with knotweed and absent of added activated carbon showed an average weight reduction of 57%, when compared to pots without knotweed and activated carbon. Adding carbon to the pots containing Bohemian knotweed and native plants provided a 35% reduction in the suppressive effects of knotweed. The cutting of the knotweed shoots also had a profound effect on all species in this study. For the single cutting treatment, biomass of knotweed rhizome was reduced by 75% and biomass of the natives increased an equal amount. In the pots where knotweed was cut three times, knotweed rhizome biomass was reduced by 94% and native plant biomass increased by 177% (Murrell et al., 2011).

Knotweed can alter the composition of invertebrate taxa in areas where the plant establishes a substantial presence (Claeson et al., 2014). Research shows knotweed may support different assemblages of detritivores than native Pacific Northwest riparian plants (Claeson et al., 2014). For example, Claeson et al. (2014) conducted a study in Washington State which demonstrated that a variety of native aquatic invertebrate detritivores prefer to feed on native leaf litter over knotweed. The results of this study indicated that knotweed litter packs hosted considerably different invertebrate assemblages than either the alder or cottonwood litter packs (Claeson et al., 2014). Shredder invertebrate species, primarily stoneflies *Zapada* sp., *Malenka* sp., and *Capnia* sp., were recorded in lower abundance in knotweed packs than on alder packs; "…these results suggest that the influence of native species replacement by knotweed on stream ecosystem function may be exacerbated by the loss of benthic invertebrate shredders" (Claeson et al., 2014, p. 1540).

Gerber et al (2008) performed a similar study of invertebrate diversity in Swiss knotweed infestations. The researchers in this project used pitfall and window traps to collect indigenous invertebrates in native vegetation and Japanese knotweed infestations, and then analyze the abundance, richness, and diversity of species (**Figure 11**). Through the two-year duration of this study, the researchers documented around 40% less invertebrate abundance collected in pitfall traps from knotweed infestations when compared to native vegetation. The diversity of invertebrates was also affected by knotweed presence, with fewer herbivorous invertebrates found in knotweed; predatory and detritivorous invertebrate reductions were less pronounced but still significantly reduced. Furthermore, the researchers noted that morphospecies richness was 20% to 30% lower in knotweed plots than in native vegetation (Gerber et al., 2008).

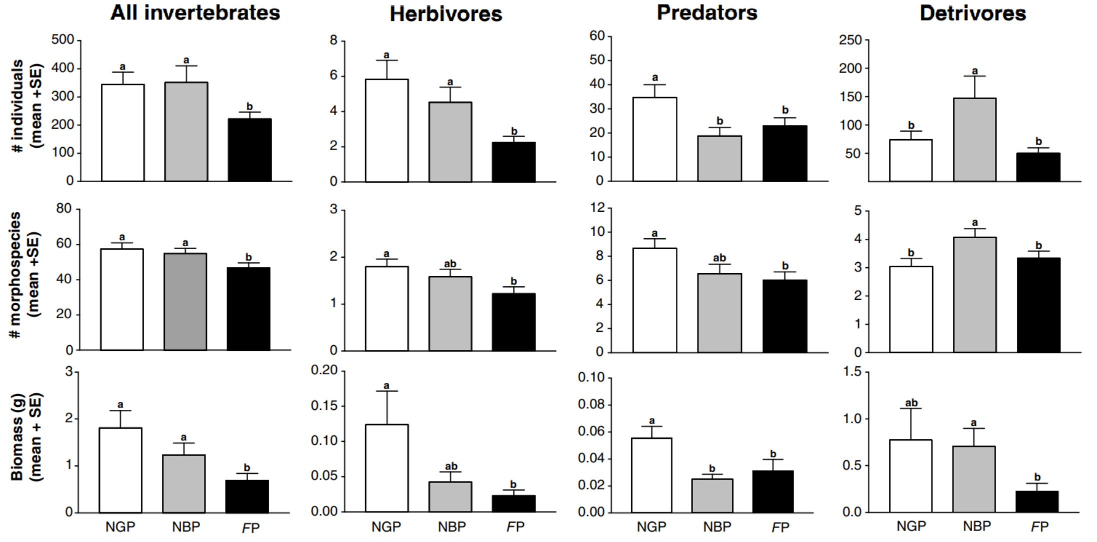


Fig. 2 – Numbers, morphospecies richness and biomass of invertebrate recorded in pitfall traps in the three different vegetation types in 2005. Individual figures are shown for all invertebrates, herbivores, predators (spiders) and detrivores (isopods). NGP = native grassland plots; NBP = native bush plots; FP = *Fallopia* plots. Given are means ± SE per plot; different letters indicate significant differences among vegetation types ($P < 0.05$; Tukey test).

Figure 11: Knotweed influences on the food web

There is an overall declining pattern of invertebrates, herbivores, predators, and detritivores in plots dominated by knotweed than by native grasses or bushes in all three categories, total population, richness of morphospecies, and biomass.

Research studies such as the ones mentioned above indicate the severity of knotweed alterations to the local biodiversity in areas of its substantial presence. The data collected in these rigorous scientific projects contribute invaluable knowledge for Pacific salmon habitat restoration; the goal of restoring this iconic species is contingent on providing them with an environment that maintains native biodiversity and natural ecological functions. The aggressive invader knotweed presents a substantial obstacle in Pacific salmon habitat restoration efforts.

4.1.3 Sediment Loads

Knotweed is well-known for its devastating ability to erode streambanks. Less well known are the particular mechanisms by which these species degrade fluvial geomorphology. Anecdotal accounts describe the dangers to streambank erosion by knotweed and subsequent sedimentary deposition but fail to quantify the processes. Researchers have acknowledged this gap and call for more research on the subject (Lavoie, 2017). Thoroughly analyzing factors, such as the plant's root cohesion value and tensile strength, fine root material, as well as water pore pressure resistance, will lead to a better understanding of knotweed's effect on riparian zones and salmon habitat.

Much of the literature featured in this thesis suggest that the physical characteristics of the plant may hold the key to understanding its erosional capabilities. Several research studies allude to the rhizome network as a chief facilitator in knotweed's erosional rates. These species utilize a reproductive strategy primarily dependent on the fragmentation of its rhizome structure rather than sexual propagation. "Rhizome fragments have been found to sprout even when buried up to 1 [meter (around 3.3 feet)] deep" (Seiger, 1993 as cited in Talmage & Kiviat, 2004, p. 5). These rhizomes are relatively weak and are not suitable for binding sloped soil masses effectively (Mummigatti, 2008).

When compared to many native tree species, knotweed has shallow underground biomass which lacks substantial fine root material. Additionally, the seasonal growth cycle of the invasive includes a complete die back of its aboveground biomass upon exposure to freezing temperatures, leaving the local area unable to attenuate the erosional effects of precipitation and stormwater runoff during winter months (personal communication with D. Ross as cited in Van Oorschot et al., 2017). In areas of knotweed monoculture, there may be no available surface vegetation to dampen the effects of extreme precipitation that accompanies Pacific Northwest winters.

In his 2003 doctoral dissertation, Richard Keim proposed that conifer species may decrease the occurrence of erosion events in Pacific Northwest forests, not only by anchoring the soil with deep extensive root systems, but also intercepting rainfall with their dense wide canopies. He asserted that conifer forests may decrease soil saturation and water pore pressure by, temporarily storing large volumes of water in their canopies, and then slowly releasing that water over a prolonged duration (Keim, 2003). The results of this study indicated that peak instantaneous rainfall intensities were diminished by 31% to 83% in old growth conifer stands (Keim, 2003). However, in the wintertime, knotweed monocultures have negligible vegetation cover to intercept Pacific Northwest rain. In fact, erosion rates in knotweed dominated areas remains consistently higher during the fall-winter rainy season than in spring and summer (Arnold & Toran, 2018; Van Oorschot et al., 2017; Urgenson, 2006).

Additional research needs to be conducted on knotweed and its impacts to streambank erosion. A critical analysis of knotweed's rhizome characteristics – primarily belowground architecture, rhizome tensile strength, amount of fine material, and overall cohesion value – may shed light on its inferior nature in stabilizing soil masses. By methodically analyzing the physical and biological characteristics of the plant, science may gain a clearer understanding of what unique mechanisms knotweed may employ that exacerbate geomorphological riparian degradation. Any knowledge gained from such investigations would provide ecological conservationists with invaluable tools to apply to Pacific salmon conservation efforts.

4.1.4 Stream Chemistry

Knotweed alters water chemistry by reducing biodiversity in the areas where it proliferates. By suppressing native vegetation, knotweed reduces ecosystem services provided by healthy riparian zones and negatively impacts water quality. Natural riparian zones serve multiple functions in providing suitable habitat to Pacific salmon, including filtering inflowing surface and groundwater, buffering streams from airborne pollutants, and regulating nutrient cycling regimes (May et al., 1998; Everest & Reeves, 2007).

Monotypic stands of knotweed can reduce native plant abundance to negligible levels, through out-competing, allelopathy, and nutrient appropriation. Riparian conditions devoid of healthy vegetative layers, including tree canopies as well as understory plants, may allow contaminants to enter a stream with minimal restrictions. May et al. (1998) provided unequivocal evidence that adequate riparian buffer zones around Pacific salmon habitat significantly improved the survival rate of the species. By mitigating the effects of transitional pollutants in urbanized areas, healthy vegetated riparian zones provide a substantial ecosystem service in the form contaminant interception (May et al., 1998). Conversely, riparian areas lacking in adequate vegetation can contribute to biological dysfunction and mortality of salmon populations. Knotweed reduces native vegetation to critically low quantities if left uncontrolled. In winter months, after complete dieback of surface material, monocultures of knotweed may leave streambanks fully exposed to the inundation of chemical pollutants and toxic contaminants.

Additionally, Knotweed infestation can alter the nutrient cycling regime by its unique ability to reabsorb the majority of its foliar nitrogen during seasonal senescence, upwards of 70% (**Figure 12**) (Urgenson et al, 2009). This biologic function has a profound effect on the success of the invasive as well as a considerable disadvantage for all other proximal vegetation. Additionally, the minimal amount of nitrogen (N) contained in knotweed leaf litter may contribute significantly less soluble N to streams. By storing the nutrient reserves in its rhizome tissue, this plant can diminish available nutrients to many important native vegetative species that provide a greater benefit to Pacific salmon habitat (Urgenson et al, 2009). Knotweed essentially functions as a nitrogen sink, slowly extracting nitrogen from the local environment as it efficiently dominates the landscape. A European study by Parepa et al., (2019) found that Japanese knotweed was more effective at nitrogen uptake when compared with five other plants native to the geographic research area. The results of this study indicated that although the knotweed demonstrated a similar rate of nutrient uptake to its native competitors, it had a superior nitrogen-use efficiency (Parepa et al., 2019).

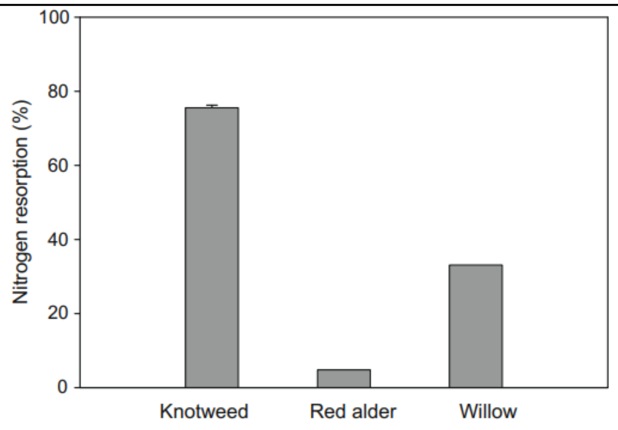


Fig. 3. Resorption (%) of leaf N during autumnal senescence of knotweed (*Polygonum sachalinense*) and the dominant native woody taxa, red alder and willow. The error bar for knotweed is 1 SE of the mean of five samples analyzed; for all other values, $n = 1$ (see Section 2.5).

Figure 12: Knotweed N resorption prior to litterfall.
Leaf litter sapped from nutrients contributes less to the stream input of N (Urgenson et al, 2009, p. 1540).

The research examples above allude to the biochemical nature of knotweed species' ability as a mechanism to alter the nutrient cycling regimes in areas of proliferation. Similar research studies are recommended for the Pacific Northwest region, in particular, to riparian areas that support populations of Pacific salmon. There also exist substantial knowledge gaps regarding knotweed's ability to alter several other water quality parameters, such as pH, DO concentration, and pathogen transmission. Future salmon conservation efforts would benefit greatly from further scientific investigation into the processes by which knotweed alters chemical composition of aquatic ecosystems.

4.1.5 Water Flow Regimes

The potential effects that knotweed species may have on hydrologic processes remains largely unexplored. The seasonal growth cycle of knotweed includes a complete dieback of aboveground biomass soon after the first frost and provides no resistance to water flow during that time. Anecdotal accounts claim that knotweed may obstruct waterways when its stem material separates from the plant, floats downstream to an accretion point, and concentrates in dense masses (McHugh, 2006). A few authors speculate that knotweed may be the cause of increased flood risk (Cygan, 2018; Michigan Department of Natural Resources [MIDNR], 2012), water flow reduction, and stream obstruction (Lavoie, 2017; McHugh, 2006), but the extensive literature review contained in this project did not uncover substantial quantifiable data on the subject.

4.1.6 Stream Temperatures

One prominent characteristic of knotweed infestation is a decrease in riparian canopy cover as a result of native tree suppression. This could arguably be considered this invasive plant's most harmful effect on salmon habitat since reductions in canopy cover equate to an increased amount of solar radiation able to reach the water's surface. Healthy native riparian forests exert a strong control on stream microclimates by absorbing the sunlight during photosynthesis. Knotweed does not possess an adequate foliar canopy to intercept a significant amount of solar radiation at any point during its growth cycle (Harbaugh, 2017). Substantial riparian vegetation also has a temperature control function on streams during the cold season, when it acts as an insulating layer and prevents radiant cooling of the water; thereby keeping water warmer than outlying temperatures (Everest & Reeves, 2007). Knotweed simply does not possess the physical structure necessary to regulate the temperature of riparian environments. The literature cited indicates that any negligible effect this invasive plant may have on blocking solar radiation or insulating stream water approaches the values associated with bare ground. Therefore, knotweed must be considered as an aggravating factor in high temperature stream conditions that are extremely detrimental to Pacific salmon habitat.

4.1.7 Shelter Abundance (Woody Debris)

Knotweed also limits woody debris recruitment into riverscapes, negatively impacting Pacific salmon habitat. By suppressing the establishment, growth, and development of large native tree species, knotweed renders large areas of riverine environments completely absent of DWD components. Since juvenile salmon rely so heavily on DWD for their survival, this aspect of knotweed ecology should be considered a high priority reason for mitigation and control of large infestations that occur around salmon bearing streams. The 2011 *Chehalis Basin Salmon Habitat Restoration and Preservation Strategy for WRIA 22 and 23* considers inclusion of DWD a necessity for effective salmon habitat restoration and mentions it a total of 387 separate times throughout the body of the document; coincidentally, all four of these knotweed species found in Western Washington are listed as invasive plants of concern for the implementation of that project. Since knotweed has a highly effective competitive ability to displace native tree species in riparian ecosystems, it must be considered a major threat to juvenile Pacific salmon.

4.1.8 Migration Route Obstruction

Knotweed can also cause blockages in waterways and obstruct the migration route of Pacific salmon. While the research for this project did not discover substantial quantitative data on the occurrence of knotweed related waterway obstruction, previous studies have indicated that the canes of this plant, when detached from their base, can be transported by flowing water as well as collect in tangled masses (McHugh, 2006). Hypothetically, any obstruction in a stream channel can accrete additional material and further increase the blockage; careful measurement of these occurrences was not uncovered in the literature reviewed.

Any significant knotweed related occurrence of salmon migration route obstruction most likely originates from the invasive plant’s ability to induce streambank erosion (**Figure 13**), an impact also explained previously in **Chapter 4.1.3**. Arnold and Toran (2018) asserted that the greatest risk of knotweed erosion occurs in areas of streambank that have been incised during periods of high discharge. Over their 9.5-month observation of knotweed infested streambanks, the researchers measured averages of 29 centimeters (~ 11 inches) of erosion on incised banks and nine centimeters (~ 3.5 inches) of erosion on banks with little incision (Arnold &Toran, 2018).

Figure 13: [photo] Knotweed-induced erosion
This is an image of a Japanese knotweed infestation and a streambank slump
(photograph by Jenn Grieser, New York City Department of Environmental Protection, Bugwood.org).
This image was cited as specified by the author.

These observations have implications for the plants' ability to trigger large soil mass displacement into salmon bearing waterways. Arnold and Toran's (2018) work suggest that knotweed induced erosion is more pronounced in streambanks that have a sharp vertical slope gradient or project horizontally over a waterbody than those with a gradual slope gradient. The modern universal soil loss equation, commonly used by geoscientists, considers the slope length factor and slope steepness factor in the overall prediction of soil loss quantity in a given area.

$$A = (R)(K)(L)(S)(C)(P)$$

> *Where: A is mean annual soil loss (metric tons per hectare per year), R is the rainfall and runoff factor or rainfall erosivity factor (megajoule millimetres per hectare per hour per year),* K^1 *is the soil erodibility factor (metric ton hours per megajoules per millimetre), L is the slope length factor (unitless), S is the slope steepness factor (unitless), C is the cover and management factor (unitless), and P is the support practice factor.* (Benavidez et al., 2018)

This equation expresses the probability of a greater volume of mass-wasting occurring with steeper slopes than with gentle slopes of the same length (Benavidez et al., 2018). Incised streambanks containing knotweed infestations can instantaneously deposit large volumes of material during the event of streambank collapse and possibly block passage of migrating Pacific salmon.

4.1.9 Predator Habitat

The literature reviewed for this thesis was insufficient on the topic of knotweed's influence on salmon predation. It is possible that a gap in scientific literature exists, warranting future research, or that because knotweed grows alongside water rather than within it, any possible predator habitat would be more terrestrial rather than aquatic in nature.

4.2 Reed canarygrass (*Phalaris arundinacea*)

Is reed canarygrass (*P. arundinacea*) native to Western Washington? Native populations of reed canarygrass may have hybridized with multiple European genotypes and thus they have become indistinguishable (Lavergne & Molofsky, 2007). As stated in **Chapter 4.2.1**, there have been *Phalaris* specimens collections by David Douglas, David Lyall, and others from before 1860 which are considered to be the native North American grass; however, the native genotype seems morphologically identical to the invasive European population (Hitchcock & Conquist, 2018). For the purpose of this thesis and because there is no good way to discern between the two, it will be assumed that all reed canarygrass in Washington State is the invasive European genotype.

A large rhizomatous wetland perennial, reed canarygrass, has been designated a class C noxious weed in Washington due to its tendency to dominate wetland areas, negatively impact local ecology, and alter hydrologic processes. In temperate regions, growth of reed canarygrass begins early in the spring, senescence occurs with summer drought, and limited vegetative growth resumes in autumn with increased precipitation (Stannard & Crowder, 2003). This cool-season C3 grass possesses sturdy rigid stems about 1 centimeter (less than half an inch) in diameter with a reddish hue at the top during the growing season (Seebacher, 2008) (**Figures 13 & 14**). Reaching an average mature height of 1 to 2 meters (~ 3 - 6.5 feet) tall, it produces dense crowns and extensive underground rhizome networks. This invasive propagates both by vigorous seed dispersal and rhizomatic regeneration (Barnes, 1999; Kim et al., 2006), as well as stem fragmentation (Wisconsin Reed Canary Grass Management Working Group [WRCGMWG], 2009).

Reed canarygrass has a considerable tolerance for environmental stress, such as cold temperatures, (Seebacher, 2008), hydrologic inundation, and anoxic soil conditions (Martinez, 2013; Lavergne & Molofsky, 2004) but less of a tolerance to shade (Kim et al., 2006). Reed canarygrass commonly forms highly productive monotypic stands that negatively impact many wetland ecosystems throughout Washington State (NWCB, 1995). This invasive grass has been documented to slow water velocities, increase sediment deposition rates, and affect local flood regimes in areas which it dominates (Seebacher, 2008). In fact, this ubiquitous species causes such significant damage that David Heimer with the Washington Department of Fish and Wildlife (WDFW) has cleverly deemed it the “plastic grocery bag of the weed world” (D. Heimer, personal communication, February 10, 2021). However, shade could be a limiting factor in its growth potential. Kim et al. examined multiple studies that indicated how reed canarygrass’ above ground biomass was not only stunted by 97% in shaded greenhouse experiments, but new seedlings did not show germination in the dark environments until a disturbance allowed a gap of light to penetrate through the canopy (Kim et al., 2006).

Reed canarygrass ranked the second highest in the survey results, with 47% of respondents mentioning this species as having a high impact on freshwater ecosystems. When asked why this plant was specifically a priority, respondents mentioned that reed canarygrass:

1) outcompetes other vegetative species (71% of reed canarygrass respondents),
2) is highly aggressive and spreads easily (71%),
3) is ubiquitous in both streams and upland areas (57%),
4) can be difficult to manage (57%),
5) chokes out freshwater systems (57%),
6) alters stream morphology (43%),
7) reduces available salmon habitat (14%),
8) reduces passageways for salmon (14%),
9) increases water temperatures (14%), and
10) creates dense matting (14%).

The survey responses indicated that reed canarygrass can quickly dominate an area, changing stream morphology, and reduces the survivability of Pacific salmon.

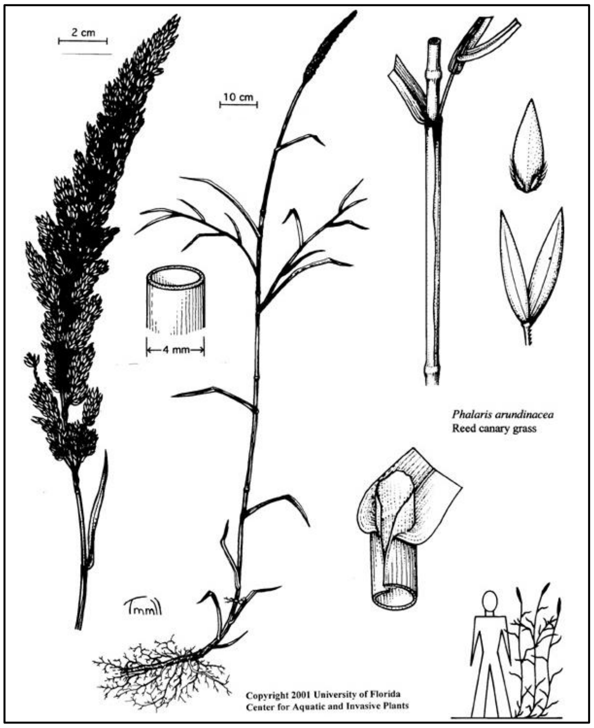


Figure 14: [photo] Reed canarygrass identification drawing
Drawing to identify reed canarygrass ([1]University of Florida Center for Aquatic and Invasive Plants, 2001). Cited with authors permission.

Figure 15: [photo] Reed canarygrass identifying photos
Photograph used to help identify reed canarygrass features (Michael D. C. & Daniel J. U., 2019).

4.2.1 Dichotomy

The following dichotomy is taken directly from the second edition of the Flora of the Pacific Northwest (2018), in which the genus *Phalaris* begin on page 809 (Hitchcock & Conquist, 2018).

> ***Phalaris*** (p. 809)
> Spikelets in congested, often spikelike panicles, articulated above the glumes, occasionally spikelets deciduous as a whole, strongly compressed, (1-)3 flowered, the uppermost floret generally perfect, the lower one(s) represented by a sterile, generally hairy, more or less linear lemmas, or lacking; glumes approximately equal, greatly compressed, often strongly keeled, generally 3-nerved; fertile lemma generally hardened, mostly appressed-hairy, rounded to acute, much lower than the glumes; stamens 3; annual or perennial with hollow culms, open sheaths, membranous ligules, and flat blades rolled in the bud.
>
> 1a. Plants long-rhizomatous, perennial; glumes broadest near base, lanceolate, the keels not winged, or wings less than or equal to 0.2 millimeters wide; inflorescence an elongate more or less oblong to lanceolate panicle, generally slightly lobed at base, with numerous ascending to spreading branches visible in flower, appressed in fruit; fertile lemma shiny; marshes, shores, swales, wet meadows, ditches, disturbed ground; collections by David Douglas (east Cascades along Columbia River), David Lyall (Washington Cascades), and others from before 1860 are apparently the native North American race, but inseparable morphologically from the invasive European introduced race in our area used for rangeland improvement by around 1885; Alaska southward, both sides Cascades, to California, east to Atlantic coast; reed canarygrass 1. ***P. arundinacea*** L.

4.2.2 Overall Biodiversity (Flora, Fauna, Invertebrates)

Many scientific studies have shown that reed canarygrass can reduce the abundance and diversity of local plant and invertebrate assemblages (Green & Galatowitsch, 2002; Lavergne & Molofsky, 2004; Spyreas et al., 2010). Several biological and evolutionary traits converge to provide this plant with advantages over competitors. Miller and Zedler (2003) indicated that reed canarygrass possesses a high degree of architectural plasticity when grown in high competition settings. This enables reed canarygrass to allocate nutrients to increase canopy volume, by altering its root length to biomass ratios, effectively shading out its competitors (Miller & Zedler, 2003). Coops et al. (1996) discovered that this grass has the ability to transfer nutrients from its roots to its shoots during periods of inundation, and from its shoots to its roots during drought, presumably developed as an evolutionary water management adaptation. In addition, when in proximity to competitors, reed canarygrass can preferentially distribute nutrients to increase its shoot length which intercepts sunlight more effectively than neighboring plants (Lavergne & Molofsky, 2004).

Tamura & Moriyama (2001) found that reed canarygrass is better equipped to survive harsh winters and may also have a stronger growth response in the early spring than other plant species. The authors performed a controlled experiment to study the nutrient storage capacity of reed canarygrass, orchard grass, timothy, and ryegrass roots during late summer to early spring (Tamura & Moriyama, 2001). After sampling the plants, once in November and once in March, the researchers measured the aboveground and belowground growth, then conducted high-performance liquid chromatography analysis on the foliage and root tissues (Tamura & Moriyama, 2001). The non-structural carbohydrates in the reed canarygrass roots were found to be three times higher than in its foliage, and significantly higher than any of the other plants in the study (Tamura & Moriyama, 2001). This early spring 'jump-start' could prove to be especially advantageous in the cold dark winters of the Pacific Northwest.

This domineering species has the strong propensity to exclude all other plant species from within areas it infests. A 2013 report for the U.S. Army Corps of Engineers, stated that reed canarygrass was the most prolific non-native plant found in the main stem Columbia River estuary, accounting for approximately 28% total cover of all vegetative species present (Diefenderfer et al., 2013). Spyreas et al. (2010) investigated the impacts on wetland ecosystems associated with reed canarygrass invasions and found that there existed a negative correlation between the plant's density and local biological integrity (Spyreas et al., 2010). They uncovered a diminishing effect of the invasive grass on multiple taxa, including plants, small mammals, birds, and arthropods (Spyreas et al., 2010).

Reed canarygrass has a strong positive growth response to eutrophic soils and when exposed to agricultural runoff it can surpass the development of most other native plant species. Green and Galatowitsch (2002) performed a field experiment using controlled quantities of a common form of agricultural fertilizer (NO3-N) in sedge meadows with occurrence of reed canarygrass. Native vegetation, primarily meadow sedge species, consistently demonstrated reduced growth rates when in proximity of reed canarygrass. This study indicated that, with the application of the fertilizer, the native sedges showed a growth reduction by as much as 50% (Green & Galatowitsch, 2002).

Klopfenstein (2016) conducted a study on the effects that reed canarygrass had on Pacific salmon habitat within the Columbia River estuary and found that the plant altered the composition of macroinvertebrate populations in areas of dense proliferation. Her research indicated reduced growth and development among juvenile salmon when confined to areas dominated by reed canarygrass. Klopfenstein insisted that this occurred as a result of a decrease in certain energy-rich invertebrate species that are supported by more diversely vegetated ecosystems, rather than the common assumption of a diminished abundance in invertebrate prey resources in response to invasive plant presence (Klopfenstein, 2016); as previously illustrated in **Figure 8**.

Reed canarygrass does support some native organisms in the Pacific Northwest. Holzer and Lawler (2015) conducted a study of native frog species of Oregon within 62 separate ponds, with varying densities of reed canarygrass, and the ecological benefits provided to the amphibians by the invasive grass. By taking an inventory of vegetation and amphibian populations within the ponds during summer months, the researchers determined that reed canarygrass hosted greater abundances of Pacific chorus frogs (*Pseudacris regilla*) than any other vegetation in the study area (Holzer & Lawler, 2015). The ponds that had an occurrence of reed canarygrass contained an average of five times the number of adult male Pacific frogs than ponds with other vegetation. Out of the 386 separate frog egg masses observed, 205 of them had been laid in ponds with reed canarygrass (Holzer & Lawler, 2015). Tadpoles showed a strong positive statistical correlation to reed canarygrass presence as well (Holzer & Lawler, 2015). The researchers also noted that approximately ten percent of the ponds surveyed contained four separate native amphibian species, including two frog species and two salamander species (Holzer & Lawler, 2015).

Reed canarygrass provided Pacific chorus frogs with conditions beneficial to its development and survival (Holzer & Lawler, 2015), by doing so it may also negatively impact any Pacific salmon which coincide with populations of the frog. Since salmon do not regularly choose to feed on amphibians (Richter & Azous, 1995), the contributions of these frogs to salmon habitat may be negligible. On the other hand, Pacific chorus frogs and salmon species may be competing for the same prey resources within their mutual range. Pacific chorus frogs have been documented with arachnids, such as those in the order Araneae in both female and male stomachs; insects in the order Coleoptera in both male and female stomachs, the Diptera, Hemiptera, and Hymenoptera order in male stomachs; the moth/butterfly order of Lepidoptera in female stomachs; and the woodlice order of Isopoda in both female and male stomachs (Hothem et al., 2009). Many of the invertebrate species mentioned above are also commonly preyed upon by Pacific salmon in Western Washington (Dillon, 2020).

4.2.3 Sediment Loads

Available scientific literature on reed canarygrass does not point to a direct relationship between this plant and streambank erosion. Conversely, it acts much like a natural sediment trap, building up the elevation in the areas it proliferates. Martinez (2013), performed an extensive analysis on the geomorphic effects of reed canarygrass on a Pacific Northwest river and determined that the invasive possessed high root cohesion values which indicated it as a suitable streambank stabilizing species (Martinez, 2013). Additionally, the tendency of reed canarygrass to form dense mats of above ground biomass may protect streambanks from erosional effects of high-water flow and scouring. In fact, the invasive plant's ability to build up layers of sediment may be so effective that it can clog waterways, potentially decreasing side channels accessible to salmon (Silver & Eyestone, 2012).

4.2.4 Stream Chemistry

Since reed canarygrass commonly dominates areas of intense stormwater runoff (Galatowitsch et al., 2000), it is presumed to have some effect on the chemistry flowing into the water body it encompasses. Although evaluations of this plant's ability to intercept toxic stormwater runoff or aerosol pollutants has not been thoroughly discussed by any of the literature discovered in this project, it may be inferred that reed canarygrass monocultures do not possess the physical attributes, such as those of native Pacific Northwest riparian forests, necessary to mitigate significant quantities of common stream contaminants. Pacific Northwest riparian integrity is characterized by wide buffers of mature conifer forests and well-developed morphologically complex floodplains (May et al., 1997).

Reed canarygrass can simplify the biological diversity of riparian zones and floodplains by forming dense monotypic stands along vast stretches of streambanks. Since this invasive grass grows to an average maximum height of two meters (~ 6.5 feet), it can be considered inferior, in its ability to intercept high elevation aerosol drift, to many of the large Pacific Northwest tree species which grow to heights in excess of 20 to 30 meters (~ 65 - 98 feet), respectively. Additionally, the grass' tendency to act as a sediment trap may impair the water filtration value of an area by reducing the soil percolation rate; thereby, limiting the subsurface water flow; though, studies on the subject remain inconclusive.

Quantitative data suggests that reed canarygrass may provide some value in removing heavy metal contamination (Marchand et al., 2014; Moschner et al., 2020). C. R. Owen (1999) used a piezometer, a device used to measure electrical conductivity of water, to determine that reed canarygrass dominated wetlands within the study area maintained higher average specific conductance's when compared to the other twelve vegetation dominated sites assessed. Future research on reed canarygrass' efficacy to intercept toxic compounds, pollutants, and agricultural chemicals should be conducted to gain a better understanding of its ecological impacts, specifically on Pacific salmon habitat.

This aggressive wetland plant has been documented to decrease DO concentration in streams that it envelops. By outcompeting native riparian plants and forming dense aboveground biomass, reed canarygrass can change the local hydrology so significantly that water quality is drastically reduced. Reed canarygrass can restrict water flow to the degree that it may absorb a greater to amount of solar radiation than if it were flowing at faster rates. This increase in water temperature negatively affects the solubility of DO and adversely impacts the survivability of salmonid species.

Questions remain about whether reed canarygrass contributes organic material to the environment that may be considered toxic to aquatic organisms. Due to the fact that reed canarygrass contains naturally high levels of several alkaloid compounds (Coulman et al., 1977; Østrem, 1987), it may have the potential to impact salmon species or their prey resources by chemical contamination. Further research into the effects of these alkaloids, primarily Phenols, Indoles, and β-carbolines, on Pacific salmon habitat should be conducted.

Although reed canarygrass has been successfully utilized in phytoremediation for extremely toxic environmental conditions, such as sewage sludge spills (Antonkiewicz et al., 2016; Rosikon et al., 2015), mining operations (Moschner et al., 2020), and industrial manufacturing sites (Chekol et al., 2002), its capacity for long-term phytoremediation remains inconclusive. Rosikon et al. (2015) compared the heavy metal (Cd, Ni, and Zn) contaminant removal by reed canarygrass and giant miscanthus from given inputs of municipal or industrial sewer sludge (Rosikon et al., 2015). After two years of study and analysis, the researchers concluded that reed canarygrass could provide effective removal of Zn and Ni during the initial growing season, with Zn retention considerably higher in the biomass of reed canarygrass when compared with miscanthus (Rosikon et al., 2015). Soil amendments did provide some significant increase in the absorption rate of heavy metals by reed canarygrass when compared to the control samples during the second year of the study, but this ability was significantly diminished compared to the first growing season; reed canarygrass showed little capacity to remove Cd in any of the experiments (Rosikon et al., 2015). Timing and the type of contaminant thus appear to be key factors in the phytoremediation capabilities of reed canarygrass.

Still, reed canarygrass can be effective in obscure applications of phytoremediation. An experiment by Moschner et al. (2020) shows that reed canarygrass can be used as an effective ‘phytomining’ method to extract precious metals from contaminated soils, though the researchers indicated that this wetland grass was most effective when provided with regular inputs of soil amendments or compost (Moschner et al., 2020). These researchers concluded that reed canarygrass could successfully extract Mn, Fe, Zn, As, Pb, Cd, and rare earth elements when provided with soil amendments (Moschner et al., 2020). This wetland perennial grass has even been confirmed to successfully mitigate the toxic effects of soil contamination by the widely used mining explosive trinitrotoluene (Chekol et al., 2002).

Although the examples provided in the studies referenced above indicate that reed canarygrass can be an effective phytoremediator in moderately to severely contaminated sites, studies focusing on the ability of this invasive plant to remove low levels of toxins common to riparian zones in Pacific salmon habitat remain underrepresented in scientific literature. Since Pacific salmon habitat must maintain high environmental quality standards, it may never reach a level of toxicity at which reed canarygrass could provide substantial detoxifying effects. Questions about the efficacy of reed canarygrass to extract low levels of environmental pollutants, chemical wastes, and toxic compounds may only be resolved by thorough investigation and scientific analysis.

4.2.5 Water Flow Regimes

Due to a combination of its physical characteristics, such as the high density of above ground material, stiff stems, and large foliar surface area, reed canarygrass can mechanically obstruct water flow to the point that it negatively impacts local ecology (Martinez, 2013). Gebauer et al. (2015), Owen (1999), and Schilling and Kiniry (2007) discussed the severe water loss associated with this invasive grass, but few have submitted quantifiable data or described the processes by which water loss occurs. It is widely accepted that reed canarygrass performs as a wetland sediment trap, has the tendency to partition water flow, and in extreme cases, even forms stagnant pools of isolated water. A combination of specialized biology and unique architecture enable this plant to drastically alter the hydro-morphology of a local area (Owen, 1999). In monotypic stands of reed canarygrass within floodplains, these biological traits can enable a positive feedback loop of reduced flow followed by sediment deposition and plant growth (Seebacher, 2008).

Previous studies have looked at the transpiration rates of reed canarygrass as a mechanism by which this plant may limit water availability (Gebauer et al., 2015; Schilling & Kiniry, 2007). A 2015 study on Eastern Washington wetlands infested with reed canarygrass provided detailed data that suggests this aggressive plant can greatly diminish water resources by foliar transpiration (Gebauer et al., 2015). By measuring leaf area transpiration with a Li-Cor® portable photosynthesis system, the researchers assessed the water use of several wetland species in the project area (Gebauer et al., 2015). They revealed that in the active main channel bank and floodplain the transpiration rate of reed canarygrass was many times greater than all of the other plants studied, except one. It was suggested that this high transpiration rate was likely due to reed canarygrass having three times the total average evaporative surface area per square meter of ground surface compared to other vegetation in the study (Gebauer et al., 2015). The measurements of reed canarygrass transpiration rate, based on mean leaf area, were not significantly different from other plants; yet, when the cumulative transpiration rate of its total canopy was measured, it surpassed all others. The researchers concluded that, because of its high transpiration rates, reed canarygrass may play a significant role in regional water loss within wetland ecosystems (Gebauer et al., 2015).

A 2007 project by Schilling and Kiniry attempted to quantify the average water use by reed canarygrass in an Iowa wetland ecosystem. By relying on proven predictive models for plant transpiration rates based on leaf area index, light absorption and photosynthesis, as well as biomass production among other parameters, Schilling and Kiniry were able to simulate the estimated water use of reed canarygrass (2007). The results of this study elucidated several insightful characteristics of this wetland invader. The researchers noted that nocturnal water use by reed canarygrass decline precipitously from daytime levels (Schilling & Kiniry, 2007). Furthermore, the grass' water consumption was relatively consistent from the months of May through September, but water use after October was nearly imperceptible (Schilling & Kiniry, 2007). Reed canarygrass had the greatest daily water table extraction rate during the month of July at around 3.3 millimeters (0.1 inch), May through September averaged 2.3 to 2.8

millimeters (Schilling & Kiniry, 2007). This study could be replicated, with a few adaptations for Pacific Northwest conditions, to determine reed canarygrass' water use effects on Pacific salmon habitat.

4.2.6 Stream Temperatures

Reed canarygrass can increase stream temperatures of a local area by impeding water flow, thereby extending the duration of solar radiation exposure to the water's surface. This prolonged exposure increases water temperature and evapotranspiration, and as a result, initiates a positive feedback loop of warming water temperatures, increasing rate of evaporation, and reduced water volume. These processes create a convergence of inhospitable environmental conditions for Pacific salmon species. Not only does this prolific wetland grass raise water temperatures to the point at which it may inhibit the biological function of salmon, but it also diminishes aqueous DO concentrations and reduces the volume of water available.

4.2.7 Shelter Abundance (Woody Debris)

Because reed canarygrass can reduce native tree species abundance in riparian areas, it can limit woody debris recruitment to aquatic environments. By forming dense monotypic stands over large areas, this invasive wetland perennial can establish sprawling 'grass deserts', devoid of substantial biodiversity. Reed canarygrass commonly covers 50% to 100% of invaded habitats in Washington (Lavergne & Molofsky, 2004). Furthermore, the physical structure of this invasive does not provide any substantial material which could serve as in-stream shelter for juvenile salmonids, as does DWD (Seebacher, 2008).

4.2.8 Migration Route Obstruction

Several features of reed canarygrass enable it to drastically alter channel morphology and stream embankments. Formation of dense impenetrable mats is a defining characteristic of this successful invader; few native plant species can produce such highly concentrated biomass as reed canarygrass. Vast quantities of sediment can then accumulate and increase the elevation directly below stands of the invasive. One year's sediment deposition becomes the growth substrate of reed canarygrass in the subsequent year. The cycle can perpetuate to the point of complete stream channel obstruction during part of the year, typically in late-summer and early fall (Seebacher, 2008). For example, in the Quinault River basin reed canarygrass remains a major concern of off-channel access for juvenile salmon (Silver & Eyestone, 2012). The Columbia River estuary contains a considerable presence of this high-risk grass (Diefenderfer et al., 2013), and it may pose a substantial threat to homing salmon populations. For these reasons, reed canarygrass must be considered harmful to salmon; it limits access to off-channel habitat and can totally obstruct passage routes.

4.2.9 Predator Habitat

Northern pike (*Esox lucius*) is a carnivorous fish with a voracious appetite known to prefer salmonid species (Carim et al., 2019) (**Figure 16**). This predator is also considered an invasive species in Washington (Washington Invasive Species Council [WISC], 2020) and has been documented in parts of the Columbia River (Carim et al., 2019) as well as other Eastern Washington rivers (WISC, 2020). In Wisconsin, Northern pike is an actively managed native species (Wisconsin Department of Natural Resources, n.d.). A 1977 technical bulletin for the Wisconsin Department of Natural Resources advocated for the dispersal of reed canarygrass seeds in marshes that were devoid of grasses in an effort to maintain northern pike habitat (Fago, 1977). Due to the age of this report, the reed canarygrass discussed was most likely a native genotype and not the invasive form that also currently plagues Wisconsin. However, if northern pike receives habitat benefits from reed canarygrass, then it will be beneficial to remove this grass from salmon habitat in order to better protect Western Washington's declining salmon population from such an aggressive invader.

Figure 16: [photo] Northern pike stomach contents
An image of northern pike stomach contents full of juvenile salmon (photo by Kristine Dunker).

4.3 Yellow flag iris (*Iris pseudacorus*)

Designated a class C noxious weed in Washington State, yellow flag iris (*Iris pseudacorus*) is easily distinguished by its vibrant yellow coloration with three upward pointing petals and three larger hanging sepals which are often streaked with brown or purple venation (**Figures 17 - 19**). Yellow flag iris is native to Eurasia (Morgan et al., 2018; Sutherland, 1990). Reaching an average mature height of 1.5 meters (5 feet), this invasive perennial flower is commonly found in wetlands throughout the temperate regions of the world (Sutherland, 1990). Single or multiple flowers with a diameter between 8 to 10 centimeters (3 - 4 inches) can form from seed pods attached to long round stems and surrounded by long blade-like leaves (Sutherland, 1990). This prolific invasive plant reproduces effectively by sexual and vegetative means, such as by seeds or clonally (Sutherland, 1990). Yellow flag iris develops seeds 6 to 7 millimeters (around a quarter of an inch) in diameter in three-sided capsulate pods around 3.5 to 8.5 centimeters (1.4 to 3.3 inches) long (Morgan et al., 2018). The rhizomes are 1 to 4 centimeters (0.4 - 1.5 inches) in diameter, up to 30 centimeters long (11.8 inches), prefer saturated substrate, and can withstand acidic soil conditions, pH around 3.6 (Sutherland, 1990; Yousefi & Mohseni-Bandpei, 2010).

Due to a substantial lack of literature describing this invasive plant's ecological effects in the Pacific Northwest, accumulation of relevant data has been fraught with difficulty. Many publications express field observations of yellow flag iris but do little to quantify its effects on cooccurring organisms. Speculations on the harms this aggressive wetland plant may have on Pacific salmon abound, yet most studies on the subject remain inconclusive. There exists a significant knowledge gap of how yellow flag iris impacts water quality standards, such as flow, chemistry, and turbidity. The effects this plant has on native biodiversity has not been adequately documented, and its impacts to salmon habitat require extensive future investigation. The following sections will attempt to form correlations between existing yellow flag iris data and Pacific Salmon habitat.

Yellow flag iris ranked the third out of the top four species from the survey results, with 33% of respondents mentioning this species as having a high impact as an invasive on freshwater ecosystems. When asked why this plant was specifically a priority, respondents mentioned that yellow flag iris:

1) is very widespread (60% of yellow flag iris respondents),

2) easily outcompetes other vegetation (40%),
3) lacks sufficient management (40%),
4) proliferates aggressively (40%),
5) changes hydrology (20%),
6) difficult to control (20%), and
7) the seeds have a high germination rate (20%).

The survey responses speak to the difficulty in managing such a prolific species.

Figure 17: [photo] yellow flag iris flower

Yellow flag iris flower photograph by Jonathan Billinger (Jonathan B., 2019).

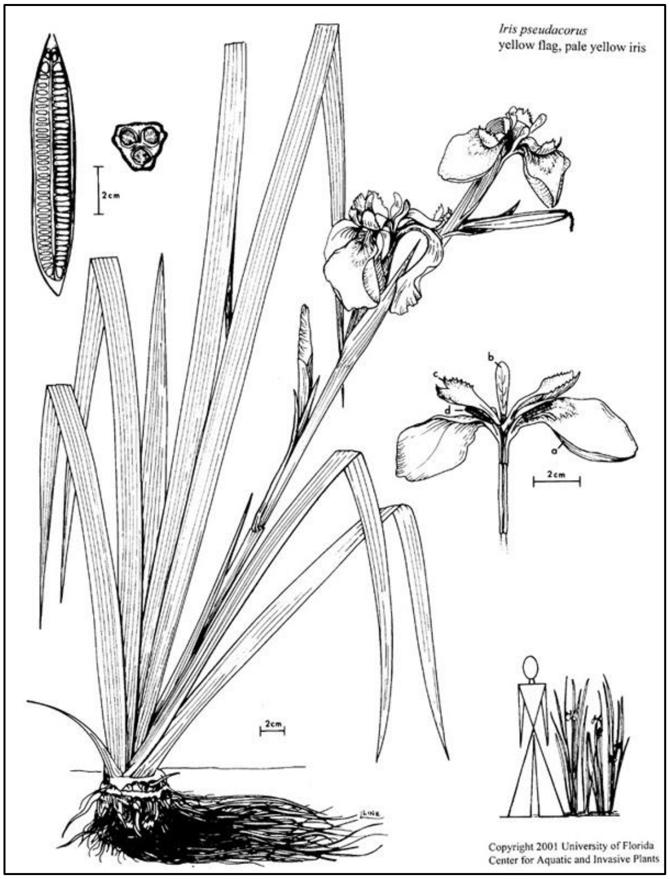


Figure 18: [photo] Yellow flag iris identification drawing

Drawing to identify yellow flag iris ([2]University of Florida Center for Aquatic and Invasive Plants, 2001). Cited with authors permission.

Figure 19: [photo] Yellow flag iris proliferation

Yellow flag iris displaying its ability to form monocultures in a seasonal stream area. Photo taken by Jennifer Petrie (Jennifer P., 2020).

4.3.1 Dichotomy

The following dichotomy is taken directly from the second edition of the Flora of the Pacific Northwest (2018), in which the genus *Iris* begin on page 695 (Hitchcock & Conquist, 2018).

> ***Iris*** (p. 695)
> Flowers 1-several, subtended by paired leaf like spathes; perianth segments fused at base, forming a short to much-elongate, slender to more or less flaring tube; sepals (the outer 3 segments) showy, spreading to reflexed, strongly pencilled with brown to purple and with a thickened ridge or line of hairs near the base (signal); petals generally ascending to erect, generally narrower than the sepals; stamens opposite the sepals; style branches opposite the sepals and generally curved over them and concealing the stamens, generally petaloid, with 2 terminal lobes (crests), the stigma generally a short flap projecting on the lower side at base of the crests; capsule fusiform to subglobose, generally coriaceous; ours rhizomatous herbs with linear, generally flattened, chiefly basal leaves and leafy to naked flower stems.
>
> 1a. Widest leaves 2-6 centimeters wide; rhizomes 1.2-3 centimeters wide; stems 6-15 decimeters
>
> > 2b. Sepals glabrous; seeds 6-10 millimeters
> >
> > > 3b. Seeds dull brown, flattened; flowers bright yellow; leaves deciduous, grass-green to light green, not foul-smelling when crushed; wet areas to shallow water around lakes, ponds, ditches, and stream banks; invasive European intro; British Columbia southward, both sides Cascades, to California, eastward across most of North America; yellow forms or i. ["i." is not defined; assumed to mean irises] 3 ***I. pseudacorus*** L.

4.3.2 Overall Biodiversity (Flora, Fauna, Invertebrates)

Much like several of the invasive vegetative species mentioned in this project, yellow flag iris has been shown to from dense proliferations in the areas it dominates. This can result in a drastic reduction in floristic complexity of aquatic ecosystem which may diminish natural functions in wetland environments (Jacobs et al., 2010). Several biological and physical characteristics of this invasive plant may provide it with an effective arsenal of adaptations to outcompete native species in infested areas.

The high tolerance to environmental stress may give yellow flag iris a foothold in settings where local conditions are less suitable to its native counterparts. Research has been shown that yellow flag iris can withstand freezing temperatures, acidic soils, and brackish waters (Fagerstedt, 1988; Simon, 2008; Sutherland, 1990). Additionally, this wetland invader can tolerate sustained periods of full submersion in water without suffering irreparable damage (Jacobs et al., 2010; Hetherington et al., 1983). Furthermore, yellow flag iris is considerably tolerant of drought, and has been observed growing three months during the absence of water (Sutherland, 1990). The large carbohydrate storage potential within this plant's rhizome, upwards of 80% total weight, may give it the ability to persevere through stressful conditions (Hanhijarvi and Fagerstedt, 1994 as cited in Tarasoff et al., 2016).

In his doctoral thesis for the University of St. Andrews, Scotland, Fagerstedt (1988) detailed his study on the anoxic tolerance of three barley cultivars in comparison to yellow flag iris. The author conducted several lab experiments which subjected the four plant species to prolonged periods of anoxia, then analyzed the biochemical changes that occurred in their tissues (Fagerstedt, 1988). The results of this study indicated that yellow flag iris possessed a far greater resistance to anoxic stress than the barley species (Fagerstedt, 1988). By producing high quantities of a plant enzyme (superoxide dismutase), during and after anoxia, yellow flag iris was able to negate any potential oxidative damage its tissues would have incurred upon reintroduction to aerobic conditions; "It can be seen that the extraordinarily high anoxic [superoxide dismutase]

SOD activity in rhizomes of *I. pseudacorus* in comparison to that of barley and rice, is correlated with the ability to survive prolonged anoxia…" (Fagerstedt, 1988 pg. 123). This adaptive biochemical ability, in addition to the possession of well-developed air sacks in their rhizomes (aerenchyma), provide yellow flag iris with an exceptional tolerance for natural flooding conditions which most plant species are ill-equipped to cope with (Fagerstedt, 1988).

Mopper et al. (2016) performed a common garden experiment which studied the effects of competition between yellow flag iris and a native Southern U.S. iris species (*I. hexagona*) when subjected to a series of salinity treatments. The researchers measured the growth of each plant and then applied the collected data to a predictive statistical model in order to evaluate the long-term probability of domination in a natural setting for each iris species. The yellow flag iris plants appeared to be unaffected by the intra- and interspecific competition, but the native iris showed significantly diminished growth when grown together with yellow flag iris (Mopper et al., 2016). The researchers noted that in some of the pots containing both species, the native iris was literally pushed out of the substrate by the aggressive growth of the invasive (Mopper et al., 2016). The data collected from the salinity treatments and the competition experiment, when entered into a computer simulated model, predicted that yellow flag iris would eventually exclude the native iris in freshwater wetlands, but the native plant was predicted to dominate in saline or brackish environments (Mopper et al., 2016).

Invasive vegetative species do not always limit abundance, biodiversity, richness of all native organisms in the areas which it dominates. In some circumstances, invasive plants may demonstrate a strong supportive function to the survival of certain species of flora, fauna, or microbes (Sagoff, 2009). In other instances, non-native plants may have no impact, positive or negative, on native species. Forecasting the potential impact of an invasive species to an introduced range often fails to approach the outcome of many widely used predictive models of invasion ecology. The complexity of natural systems and interspecific relationships dilute such predictions with a substantial margin of error. Prolonged field observations and rigorous data collection remains the most accurate method for assessing the potential impact of invasive species on native ecosystems. In fact, general scientific literature on yellow flag iris' effect on Pacific Northwest ecology remains scarce. Substantial knowledge gaps regarding the impacts by yellow flag iris could be bridged by conducting further research with respect to Pacific Northwest ecology.

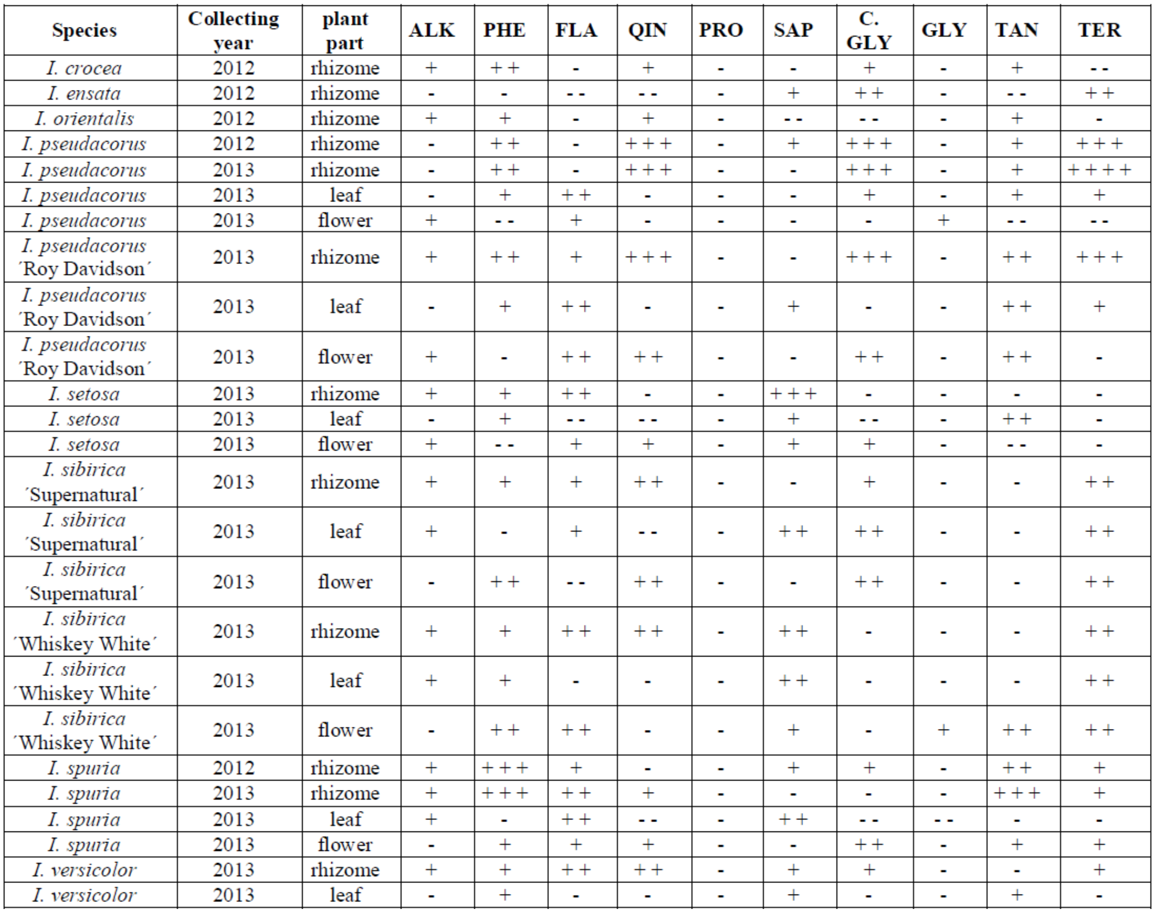
4.3.3 Sediment Loads

Because yellow flag iris mostly inhabits low-lying marshlands rather than high streambanks, the threat of erosion by this species is not a concern widely expressed in the available literature. Though, the ability of this aggressive invader to trap sediment has been the topic of much discussion in invasion ecology circles. Due to its tendency to form dense rhizome mats, yellow flag iris can effectively collect suspended solids that flow through a stream. This sediment retention can eventually lead to a narrowing of stream channels and increase flow velocities, thereby increasing the sediment carrying capacity of lotic water bodies (Spaak, 2016). There exists a potential for drastic hydrologic obstruction if infestations of yellow flag iris are permitted to encroach into the central region of a flow field. When this occurs, yellow flag iris can sprout new plants from rhizomes to form a figurative wall of tangled rhizomes, leaves, and stems that spans the width of the stream (**Figure 19**).

4.3.4 Stream Chemistry

This aggressive invasive flowering plant possesses potent chemistry which may adversely impact aquatic organisms, though most studies on this subject are inconclusive. Yellow flag iris contains various compounds which are toxic to animals and humans. The glycoside content in yellow flag iris has been attributed to its general unpalatability for grazing animals and can cause harmful gastrointestinal effects when consumed (Jacobs et al., 2010). Contact with its resin can cause skin irritations, and prolonged exposure can even cause blistering (USFWS, 2019). It is difficult to discern the effects of chemical inputs on aquatic organisms by yellow flag iris because of the complex nature and abundance of the compounds it produces. Some of the chemicals contained in the tissues of yellow flag iris have been extensively studied, while others have only recently been verified to exist in this invasive plant.

A 2014 study analyzed eight different iris species to determine the presence or absence of eleven chemical compounds (alkaloids [ALK], phenols [PHE], flavonoids [FLA], quinones [QIN], proteins [PRO], saponins [SAP], cardiac glycosides [C. GLY], glycosides [GLY], tannins [TAN], terpenoids [TER], and steroids [STE]) within their tissues (Kaššák, 2014). The conclusion of this study indicated that, out of all eight iris species assessed for presence of those eleven compounds, yellow flag iris had the strongest results (**Figure 20**) (Kaššák, 2014).



Species	Collecting year	plant part	ALK	PHE	FLA	QIN	PRO	SAP	C. GLY	GLY	TAN	TER
I. crocea	2012	rhizome	+	+ +	-	+	-	-	+	-	+	- -
I. ensata	2012	rhizome	-	-	- -	- -	-	+	+ +	-	- -	+ +
I. orientalis	2012	rhizome	+	+	-	+	-	- -	- -	-	+	-
I. pseudacorus	2012	rhizome	-	+ +	-	+ + +	-	+	+ + +	-	+	+ + +
I. pseudacorus	2013	rhizome	-	+ +	-	+ + +	-	-	+ + +	-	+	+ + + +
I. pseudacorus	2013	leaf	-	+	+ +	-	-	-	+	-	+	+
I. pseudacorus	2013	flower	+	- -	+	-	-	-	-	+	- -	- -
I. pseudacorus ´Roy Davidson´	2013	rhizome	+	+ +	+	+ + +	-	-	+ + +	-	+ +	+ + +
I. pseudacorus ´Roy Davidson´	2013	leaf	-	+	+ +	-	-	+	-	-	+ +	+
I. pseudacorus ´Roy Davidson´	2013	flower	+	-	+ +	+ +	-	-	+ +	-	+ +	-
I. setosa	2013	rhizome	+	+	+ +	-	-	+ + +	-	-	-	-
I. setosa	2013	leaf	-	+	- -	- -	-	+	- -	-	+ +	-
I. setosa	2013	flower	+	- -	+	+	-	+	+	-	- -	-
I. sibirica ´Supernatural´	2013	rhizome	+	+	+	+ +	-	-	+	-	-	+ +
I. sibirica ´Supernatural´	2013	leaf	+	-	+	- -	-	+ +	+ +	-	-	+ +
I. sibirica ´Supernatural´	2013	flower	-	+ +	- -	+ +	-	-	+ +	-	-	+ +
I. sibirica ´Whiskey White´	2013	rhizome	+	+	+ +	+ +	-	+ +	-	-	-	+ +
I. sibirica ´Whiskey White´	2013	leaf	+	+	-	-	-	+ +	-	-	-	+ +
I. sibirica ´Whiskey White´	2013	flower	-	+ +	+ +	-	-	+	-	+	+ +	+ +
I. spuria	2012	rhizome	+	+ + +	+	-	-	+	+	-	+ +	+
I. spuria	2013	rhizome	+	+ + +	+ +	+	-	-	-	-	+ + +	+
I. spuria	2013	leaf	+	-	+ +	- -	-	+ +	- -	- -	-	-
I. spuria	2013	flower	-	+	+	+	-	-	+ +	-	+	+
I. versicolor	2013	rhizome	+	+	+ +	+ +	-	+	+	-	-	+
I. versicolor	2013	leaf	-	+	-	-	-	+	-	-	+	-

Figure 20: Chemical Compounds Within Tissues of Multiple Iris Sp.
*Header Acronyms are the eleven chemicals listed as follows: alkaloids [ALK], phenols [PHE], flavonoids [FLA], quinones [QIN], proteins [PRO], saponins [SAP], cardiac glycosides [C. GLY], glycosides [GLY], tannins [TAN], terpenoids [TER], and *steroids [STE]. *STE is missing from this table; it may have been accidentally cut off from the original paper due to the large size of the table. "Complete results from all the tests are in [this table]. Reactions were evaluated on a scale with six values. The best results, strongest reaction, are marked with four plus marks (++++), samples without any reaction are marked with two minus marks (- -). Other reactions are marked as follows: weak uncompleted reaction (-), weak reaction (+), strong reaction, but with some deficiencies in coloration (++), strong reaction (+++). From the results we can see that the best result, the richest reactions were in the sample I. pseudacorus 'Roy Davidson', rhizome from 2013[, while the] weakest reaction, the lowest content of researched chemicals has I. pseudacorus, flower from 2013"* ***(****Kaššák, 2014, Table 1)*

Since yellow flag iris contains high concentrations of reactive chemical compounds and populations of this plant are most often found in or near aquatic environments, its potential to chemically alter Pacific salmon habitat must be carefully scrutinized. The effects that these compounds may have on salmon, as well as the invertebrate prey species which they depend on for growth and development, is not yet conclusive. Future research into the potential of this invasive wetland invader to contribute toxic chemicals to freshwater ecosystems in the Pacific Northwest must be conducted in order to determine the full impact of yellow flag iris on salmon habitat.

Yellow flag iris has been effectively used as a phytoremediation method in wetlands which receive high toxic inputs from sewage, urban runoff, and industrial waste. A study conducted in Iran suggested that wetlands planted with yellow flag iris could provide an effective secondary filtration for wastewater management and found that it removed 51% to 74% of phosphorus, 48% organic nitrogen (TKN), and 67% to 75% of O-PO_4 in constructed wetlands (Yousefi & Mohseni-Bandpei, 2010). Wang et al. (2008), performed a previously similar experiment, which compared the contaminant removal potential of yellow flag iris to those of common reed (*Phragmites australis*), and broadleaf cattail (*Typha latifolia*). The scientists performing this study concluded that yellow flag iris was inferior in its ability to remove total Kjeldahl nitrogen (TKN) and statistically similar in removal of phosphorus when compared to *Phragmites* and *Typha* species (Wang et al., 2008). Another project in 2012 tested the phytoremediation potential of soft rush (*Juncus effusus*), reed canarygrass, yellow flag iris, and a mix of grass seeds (25% tall fescue [*Festuca arundinacea*], 25% red fescue [*Festuca rubra*], and 50% perennial ryegrass [*Lolium perenne*]) in the removal of polycyclic aromatic hydrocarbons (PAHs) (Leroy et al., 2015). This study concluded that yellow flag iris provided high initial removal of PAHs, but in time this effect was damped, and the contaminants began to concentrate in the lower substrate levels; all other plant species in this study showed better long-term benefits of PAHs removal than yellow flag iris (Leroy et al., 2015).

Based on previous studies, yellow flag iris does appear to have some value in removing and processing toxic compounds from contaminated sites, but when assessed in the context of natural riparian ecosystems, the benefits of this invasive in providing high quality water conditions remains questionable. The determination of how this plant chemically impacts Pacific salmon habitat, comes down to a cost-benefit analysis; are the capabilities of this plant to intercept and neutralize toxic compounds greater than its negative chemical contributions to salmon habitat? Only further research will provide a definitive answer to this question.

4.3.5 Water Flow Regimes

The ability of yellow flag iris to clog waterways has been widely accepted as a common trait of the plant by many environmental restorationists and invasive ecologists. The potential effects that this invasive plant may have on water flow, flooding, and stream obstruction have been frequently observed in wetlands throughout the world, yet definitive studies on this subject are rare. The obstructive capability of this aggressive plant resides in the robust architecture of its extensive rhizome networks, which often form in subsurface net-like structures.

Single clones from yellow flag iris rhizomes can commonly form masses up to four feet in diameter (Simon, 2008). Tightly clustered mats of intertwined yellow flag iris were observed growing in masses up to 20 meters (65.6 feet) across in Ireland (Sutherland, 1990). Rhizome mats of yellow flag iris can be anchored to the substrate or found in floating mats on the water’s surface (Jacobs et al., 2010), where they collect and accrete drifting suspended matter and sediment. This depositional process can create raised topography in areas of high yellow flag iris concentrations, and result in further increased sedimentation rates along the margins of a stream (Tu, 2003). In time, this can lead to a narrowing of a stream channel, alterations to flood regimes, and negative impacts to native species diversity.

4.3.6 Stream Temperatures

As previously discussed in **Chapter 4.3.2**, yellow flag iris has a strong tendency to exclude other vegetative species in the areas which it dominates. By doing so this invasive flower can limit the ecosystems services provided by many naturally occurring riparian plants. In the Pacific Northwest, yellow flag iris commonly displaces many native wetland tree species that provide shade to waterbodies by their large extensive canopies. Like many of the previously discussed IVS that form monocultures in riparian zones, yellow flag iris can drastically effect stream temperatures by increasing the amount of solar radiation striking the water's surface. Since this invasive plant neither possesses a canopy to adequately shade streams nor permits the establishment and growth of vegetative species that do, it must be viewed as an aggravating factor in rising water temperatures that have become a major threat to salmon in Washington.

4.3.7 Shelter Abundance (Woody Debris)

Similar to many other invasive riparian plants which have the propensity to produce monocultures in riparian areas, yellow flag iris greatly inhibits natural woody debris recruitment into riverine environments. If left uncontrolled, this plant can form dense colonies which severely diminish the abundance of large native trees which normally provide stream shelter components to Pacific salmon in the form of DWD. Since DWD plays such a significant role in the survival of juvenile salmon, any threat to that crucial aspect of salmon habitat must be considered a major hinderance to salmon conservation efforts.

4.3.8 Migration Route Obstruction

The biological characteristics of this wetland perennial enable it to form massive colonies of densely clustered material that can collect vast quantities of sediment in lotic environments. This rate of sediment trapping is so extreme that it can raise the elevation of local topography directly under yellow flag iris stands (Tu, 2003). Repeated deposition in areas dominated by yellow flag iris often accumulate in layers that can be substantially higher than the water level of the local environment. Sediments, which are released during high flow periods, floods, or disturbance, can be efficiently intercepted by substantial stands of yellow flag iris, thereby increasing the depth of sediment in low velocity zones; in lotic systems, this typically occurs in the margins of the stream and along the embankment (Gurnell et al., 2012). Yellow flag iris has been shown to narrow stream channels and form raised vertical banks which are impenetrable by fish and large aquatic organisms. In salmon bearing streams, yellow flag iris can substantially diminish the area of available salmon habitat by limiting access to floodplains and lateral channels.

4.3.9 Predator Habitat

More work needs to address yellow flag iris' ability to promote salmon predator habitat. Future research to identify the potential connection of yellow flag iris to predators, disease, pathogens, parasites, and parasitoids of Pacific salmon is strongly recommended. It is possible that no connection exists, yet there should be research into this subject to explain why such habitat does not exist.

4.4 Brazilian elodea (*Egeria densa*)

Listed as a Class B noxious weed in Washington State in 1993, Brazilian elodea (*Egeria densa*) has successfully established a substantial presence in most of the counties west of the Cascade Range. Although this perennial submergent plant's common name is elodea, its taxonomic designation places it in the genus *Egeria*; it is not truly a species of elodea. Native to South America, Brazilian elodea populations elsewhere in the world are believed to have originated by escaped specimens from the aquarium trade (Darrin, 2009; Drexler et al., 2021; Rimac et al., 2018; Tamayo & Olden 2014). Brazilian elodea has spread to dozens of countries and has an established presence ranging from the southern tip of South Africa to the Canadian Arctic circle (Matthews et al., 2014). This submergent macrophyte thrives in lacustrine environments but has also become a problem in several river basins in Washington. As of 2014, Brazilian elodea has been reported in 27 separate water bodies in Western Washington ([1]WISC, 2016). Currently, the observed population of Brazilian elodea in Washington consists of only male plants which have become widely distributed strictly through vegetative reproduction (KCNWCP, 2014). In the temperate Pacific Northwest climate, Brazilian elodea experiences seasonal dieback in autumn and overwinters in a dormant state on the bottom of the water body it inhabits (Matthews et al., 2014). In spring when water temperatures reach approximately 10°C (50°F), resurgence of growth occurs (Thiébaut et al., 2016).

Brazilian elodea possesses long buoyant vertical stems with short internodes and bright green leaves configured in whorls (**Figures 21 - 24**). Each whorl typically contains four linear minutely serrated leaves (NWCB, 2014) that are one to three centimeters long and around five millimeters (0.2 inches) wide (Walsh et al., 2013). Stems of Brazilian elodea are approximately one to three millimeters (0.4 - 1 inch) in diameter and can grow to more than three meters long (Yarrow et al., 2009). Typically rooted one to two meters (3 - 6.5 feet) below the water's surface, this aquatic plant can also form floating mats or exist as small fragments drifting in the water column (Yarrow et al., 2009). Fragments of Brazilian elodea with as few as two nodes can sprout roots to form a new plant (Vincent et al., 2016). This invasive macrophyte can negatively affect aquatic ecosystems by displacing native plants and animals, altering water quality, increasing sedimentation rates, and changing nutrient cycling regimes.

Brazilian elodea ranked the last out of the top four species from the survey results, with 27% of respondents mentioning this invasive species as having a high impact on freshwater ecosystems. When asked why this plant was specifically a priority, respondents mentioned that Brazilian elodea:

1) easily clogs sloughs and small channels thereby blocking salmon migration (75% of Brazilian elodea respondents),
2) is a widespread aggressive invader (50%),
3) is difficult to control and can have invasive management techniques associated with the species (50%),
4) alters water chemistry, such as disrupting oxygen flow important to rearing salmon, (50%),
5) considered costly to manage (25%),
6) can alter the predator/prey relationship (25%), and
7) overall, has impacts on freshwater (25%).

According to field professionals, this invasive submergent macrophyte poses significant harm to Pacific salmon habitat by clogging waterways, altering water chemistry and dissolved oxygen concentrations, altering salmon-predator dynamics, and can be very challenging to manage.

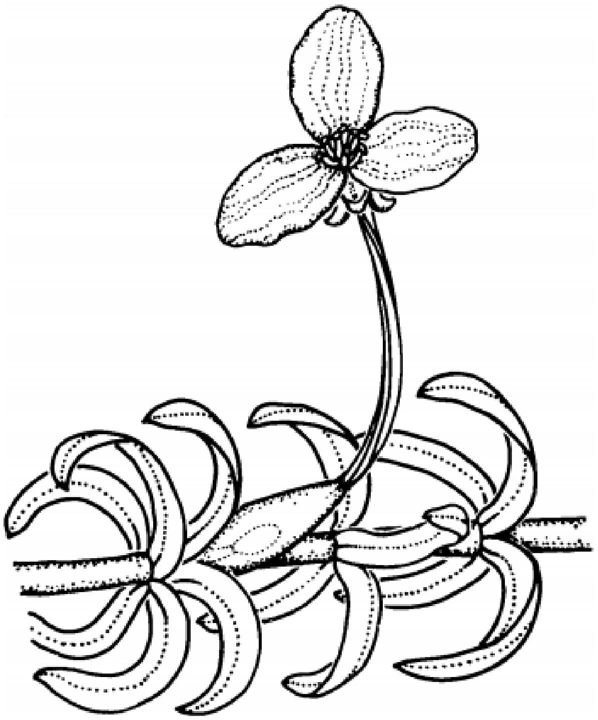


Figure 3. Egeria densa (×0.5) leaves densely clustered towards end of branches, in whorls of mostly 4-5; flowers obvious. (Illustration by Christine Payne, from Sainty and Jacobs 1988).

Figure 21: [photo] Egeria densa identification drawing

Drawing of Brazilian elodea by Christine Payne, from Sainty and Jacobs, 1988 (as cited in Bowmer et al., 1995).

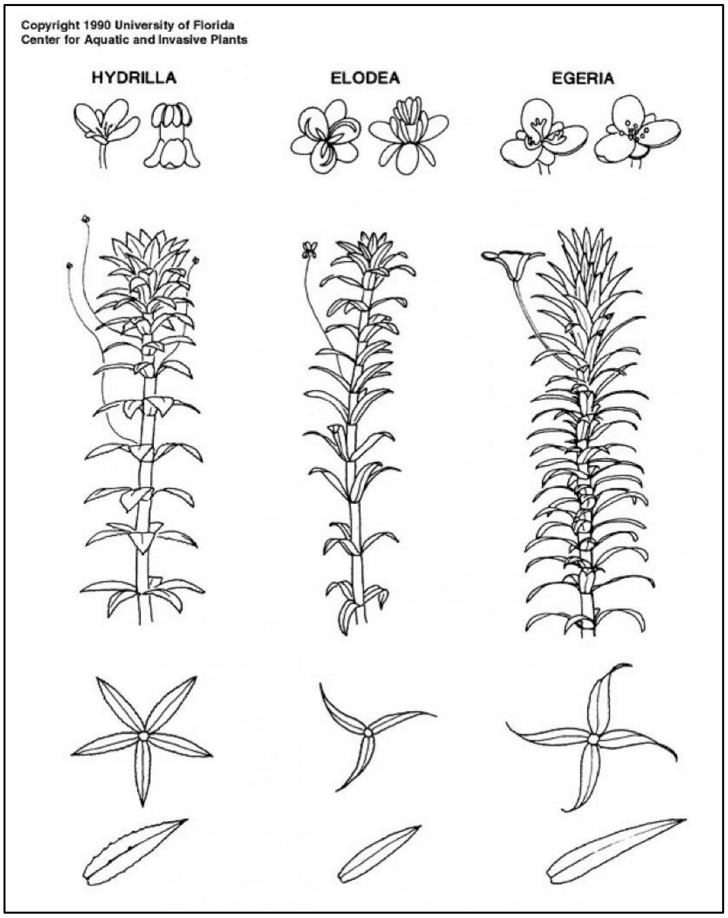


Figure 22: [photo] Comparison drawing of Hydrilla, Elodea, and Egeria

Drawing to identify Brazilian elodea "Egeria" to the far right (University of Florida Center for Aquatic and Invasive Plants, 1990). (Cited with authors permission)

Figure 23: [photo] Brazilian elodea in flower

Photo of Egeria densa in flower taken by Hörður Kristinsson (Hörður K., 2010).

Figure 24: [photo] Egeria densa proliferation
A combination of Egeria densa and Egeria najas; predominantly Egeria densa (William T. Haller, University of Florida, Bugwood.org). This image was cited as specified by the author.

4.4.1 Dichotomy

The following dichotomy is taken directly from the second edition of the Flora of the Pacific Northwest (2018), in which the genus *Egeria* begin on page 669 (Hitchcock & Conquist, 2018).

> ***Egeria*** (p. 669)
> Plants staminate, pistillate; spathes axillary, sessile, 1-flowered; staminate flowers with 9 stamens; pistillate flowers solitary, with pedicle-like hypanthium generally elongating to bring rest of flower to the water surface, stigmas 3, generally 3-4 lobed, tending to float, the styles slender; fruits ovoid, smooth, irregular dehiscent; seeds fusiform, mucilaginous; submersed, perennial herbs with rooting stems and whorled, rarely opposite, sessile leaves.
>
> ***E. densa*** Planch. Stems erect, 2-3 millimeters wide, rooting directly in substrate, rhizomes lacking; main leaves 12-40 x 2-5 millimeters, mostly in whorls of 4(up to 9), recurved, margins entire to finely serrate; staminate flowers 2-4(or 5) per spathe, petals 8-10 millimeters; South American intro, commonly used in aquaria and often planted or allowed to escape; in our area chiefly lowlands west Cascades, south Vancouver Island to California, Blaine County, Idaho, and central and eastern US

4.4.2 Overall Biodiversity (Flora, Fauna, Invertebrates)

The competitive effects of Brazilian elodea on native Pacific Northwest biodiversity have not been thoroughly studied, though there have been numerous claims by ecologists and land managers of this invasive macrophyte rapidly displacing native aquatic plant species in Western Washington (Darrin, 2009; Matthews et al., 2014; Rimac et al., 2018; Yu et al., 2018). Quantitative data regarding Brazilian elodea's effectiveness to exclude native species remains uncommon in scientific literature. Based on the scientific literature investigated during this project and the survey results, the following section will attempt to relate the attributes of this aquatic invader to native biodiversity reductions and the implications for salmon habitat.

Studies indicate that Brazilian elodea may not be a superior competitor when compared to some other aquatic plant species. For example, Mony et al. (2007) provided evidence that common hornwort (*Hydrilla verticillata*) may readily outcompete Brazilian elodea in the presence of adequate nutrients, but the opposite is true in oligotrophic conditions. Similarly, Pierini et al. (2004) conducted a study which indicates that Brazilian elodea may be displaced by the closely related narrowleaf anacharis (*E. najas*) when grown in water with low dissolved gas concentrations. Researchers performed another experiment in Mongolia, China, examining the interspecific competition between Brazilian elodea and the native submergent grass narrowleaf bur-reed (*Sparganium angustifolium*) when grown in close proximity to each other (Yu et al., 2018). The researchers planted the invasive Brazilian elodea in plastic pots with narrowleaf bur-reed and also planted monoculture of each species as control samples. In this case, Competition by narrowleaf bur-reed significantly reduced the growth of Brazilian elodea.

By the end of the experiment, Brazilian elodea showed a decrease of 27.13% in ramet abundance, 32. 76% in plant Height, 18.11% in root length, and total reduction in biomass of 63.88% when compared to control samples (Yu et al., 2018).

Brazilian elodea does appear to have several physiological and biological limitations which may indicate that it cannot survive for extended periods under extreme circumstances. For example, this invasive plant experiences tissue damage at a temperature below 3°C (37°F) or above 30°C (86°F) (Matthews et al., 2014). Brazilian elodea is most often found in still or gently flowing waters and its stem tissues are easily fragmented in higher water velocities (Coetzee et al., 2011). This plant is not tolerant of water velocities over one meter (~ 3.3 feet) per second (Matthews et al., 2014). Additionally, Brazilian elodea does not tolerate salinity concentrations greater than 0.5 parts per thousands (Poirrier et al., 2010). Considering that Pacific salmon contribute seasonal salinity inputs to freshwater during post-spawning decay, further investigation of Brazilian elodea’s compatibility in salmon habitat must be conducted. The sensitivity of Brazilian elodea to these water quality parameters may indicate reasons why this IVS was rated below knotweed, reed canarygrass, and yellow flag iris in the survey results. Since Brazilian elodea has inherent susceptibility to the factors mentioned above, it may not establish in areas where these conditions are present.

Despite these competitive shortcomings, Brazilian elodea has been shown to aggressively outcompete many Pacific Northwest native aquatic plants and continues to negatively impact ecosystems in the region. This aquatic invader may not be an apex competitor in every environment, situation, or circumstance found in aquatic ecosystems; yet, scientific research alludes to Brazilian elodea’s proficiency as an opportunistic dominator; an IVS which establishes substantial populations when and where environmental conditions are optimal. By capitalizing on its inherent biological and physiological strengths, Brazilian elodea has efficiently spread throughout the world from its point of origin.

A New Zealand study by Wells and Clayton (1991) indicated that Brazilian elodea may reproduce and spread at an alarming rate. At the initial introduction site in a large lake, Brazilian elodea coverage increased from 10% to 100% in near shore areas over the course of two years (Wells & Clayton, 2010). After five years, this invasive macrophyte became the most abundant aquatic plant in the lake (Wells & Clayton, 2010). Within six years the researchers showed that this prolific plant was able to establish in 96% of sampled sites (Wells & Clayton, 2010). The drastic displacement of native vegetative species demonstrated in this study exemplifies the potential dangers of Brazilian elodea on ecosystems which it dominates.

The biological characteristics and adaptive traits possessed by Brazilian elodea may provide it with a competitive advantage over other native aquatic plants in the Pacific Northwest. This aquatic invader has been documented to tolerate stressful environmental conditions that many native species of Pacific Northwest plants may be more sensitive to. For instance, Brazilian elodea demonstrates rapid growth in a high temperature range between 16 to 28°C (61 - 82°F) but can also survive for extended periods below ice (Matthews et al., 2014). Brazilian elodea has also shown a higher competitive capacity in oligotrophic environments, where it allocates energy reserves into tissue growth used for passive diffusion of soluble nutrients drifting within the water column (Mony et al., 2007). Literature on photonic requirements of Brazilian elodea have conflicting perspectives. According to Barko and Smart (1981), this macrophyte is intolerant of low light environments, where other researchers assert that it tends to increase competitiveness in turbid dim waters (Yarrow et al., 2009; Rodrigues & Thomaz, 2010).

In the San Joaquin River delta of California, Brazilian elodea has caused major negative impacts to the local biodiversity and the economy since the 1980's (Caudill et al., 2019). A post restoration assessment of the region provides strong evidence for resurgence of native species diversity and abundance following removal and control of Brazilian elodea. During the invasive vegetation management project timeline, from 2006 to 2017, relative frequency of non-native plants significantly decreased while native plant occurrence showed the opposite trend (Caudill et al., 2019). The successful control of Brazilian elodea in the project area has translated to an overall prevalence of native aquatic plant species in the San Joaquin River delta (Caudill et al., 2019). By 2017, native plant frequency was observed at around 80% occurrence within the study area (Caudill et al., 2019). These management efforts were predicted to improve native fish habitat, water quality, and navigation within the waterway.

Brazilian elodea has been confirmed to alter the community composition of certain species of invertebrates. A paper by Espinosa-Rodriguez et al. (2017) details the allelopathic effects of Brazilian elodea on the abundance of three species of littoral cladocerans (*Diaphanosoma birgei, Macrothrix triserialis* and *Simocephalus mixtus*), and the pelagic cladoceran (*Daphnia mendotae*). This study established a strong correlation between high abundance of cladocerans and the allelochemicals exuded by Brazilian elodea (Espinosa-Rodriguez et al., 2017). Two of the cladoceran species showed an abundance increase three to four times higher than control studies with an absence of allelochemicals (Espinosa-Rodriguez et al., 2017). This study provides one example of how Brazilian elodea may alter the trophic structure in an ecosystem. If this manner of change were to occur in Pacific salmon habitat, it could alter abundance of the macroinvertebrate species which salmon depend on for growth and development.

Not all observable effects by Brazilian elodea on biodiversity are negative. References within scientific literature cite the benefits to some cooccurring organisms. Mazzeo et al. (2003) found that this macrophyte had a significant correlation to high densities of certain species of zooplankton in an Uruguayan lake. The authors postulated that these zooplankton were using Brazilian elodea for refuge from predators as well as a feeding zone and the result may have been an increased rate of survival (Mazzeo et al., 2003). Many bird species rely on Brazilian elodea for a substantial portion of their diet during parts of the year. In its native range, this aquatic plant can constitute the majority of the dietary consumption for the black-necked swan (*Cygnus melancoryphus*) (Corti & Schlatter, 2002). Populations of several avifauna species in Florida have improved hunting success and foraging opportunities while feeding in stands of Brazilian elodea (Bartodziej & Weymouth, 1995). The benefits to Pacific Northwest wildlife due to Brazilian elodea presence have yet to be documented.

4.4.3 Sediment Loads

Based on the literature reviewed for this project, it appears as though increases to erosion rates do not occur as a direct cause of Brazilian elodea infestation. The survey results confirm this account, as none of the respondents mentioned erosion or sedimentation as a negative ecological impact caused by this IVS. Conversely, there exists evidence that Brazilian elodea may be effective at trapping and collecting suspended sediments and organic materials. According to a study conducted on the San Joaquin River delta California, Brazilian elodea accounted for 85% of the submergent vegetation biomass in 2010 (Hestir et al., 2016). The researchers of this study asserted that the proliferation of this invasive aquatic plant played a major role in the hydrological sediment yield reductions experienced in the region since the mid-1900s, ranging from -1.1% to -2.3% in turbidity per year (Hestir et al., 2016). In dense occurrences of this invasive plant, yearly sedimentation rates in the San Joaquin delta were measured to range from 1,103 to 5,989 grams per square meter (Drexler et al., 2021). Furthermore, Brazilian elodea inhabits the littoral zone of waterbodies and does not impose influence on riparian sediment inputs. Therefore, this invasive macrophyte does not contribute to bank erosion as many other IVS discussed in this thesis do.

4.4.4 Stream Chemistry

Brazilian elodea can effectively alter the chemical composition of freshwater ecosystems which it infests by altering nutrient cycling regimes, depleting DO, and contributing organic materials during senescence. In regions with pronounced seasonal variations, Brazilian elodea demonstrates clearly defined periods of growth and senescence; although, in climates which do not feature significant temperature amplitudes, this aquatic plant may persist as an evergreen perennial (NWCB, 2014). When Brazilian elodea experiences senescence, it can cause various alterations to water chemistry.

During autumn in temperate regions, this macrophyte typically loses the majority of its biomass due to sloughing and decay of stems and foliage in response to shorter photoperiod and reduced temperatures (Matthews et al., 2014). Decomposition of organic material consumes oxygen from the water column and releases nutrients which in turn are consumed by various fungi, saprophages, and bacteria. This process of Brazilian elodea decomposition and decay may have pronounced effects on the nutrient cycling regime, potentially alters the trophic web, and reduces the aqueous oxygen supply in areas of severe proliferation. In Pacific salmon habitat this could lead to a drastic change in macroinvertebrate prey resource abundance and diversity as well as threaten the survival of salmon. Careful study of such processes in the Pacific Northwest is required to definitively quantify the impacts of Brazilian elodea on salmon habitat.

Confirmed observations of direct chemical contributions to freshwater environments by Brazilian elodea have been documented. Through the exudation of allelopathic compounds, this plant can significantly alter the chemical composition in aquatic ecosystems which it dominates (Espinosa-Rodriguez et al., 2017; Fujii, 2009; Wolters et al., 2019). Brazilian elodea is known to produce reactive chemical agents, but the specific mechanisms involved have not been thoroughly investigated (Fujii, 2009). Quantitative data regarding the number of compounds produced by Brazilian elodea and the composition of allelochemicals was not discovered in the research while developing this project. These allelochemicals appear to primarily suppress species of epiphytic algae and cyanobacteria as a possible evolutionary competitive strategy (Wolters et al., 2019). These chemicals also effect the abundance and diversity in some species of grazing invertebrates that preferentially feed on the epiphytes (Espinosa-Rodriguez et al., 2017). The full effect of allelochemical exudation by Brazilian elodea on Pacific salmon habitat is poorly understood.

The ability of Brazilian elodea to sequester nutrients directly from the water column enables it to drastically transform the trophic dynamics of freshwater systems it inhabits. Reddy et al. (1987) studied the effects of nutrient use by Brazilian elodea under non-limiting nutrient conditions and found that the macrophyte preferentially assimilated NH_4 over NO_3 when both ions were present (Reddy et al., 1987). The rate of nitrogen removal increased significantly during summer months when compared to the winter (Reddy et al., 1987). The researchers asserted that this was due to the alterations to water chemistry by Brazilian elodea and an increase in NH_3 volatilization during warmer temperatures (Reddy et al., 1987).

Weragoda et al. (2009) published a paper in the *Journal of Freshwater Ecology* discussing their experiment to study the nitrogen removal rate of Brazilian elodea. The researchers determined that high densities of the aquatic plant, when grown in low nutrient substrate, were able to remove 69% to 81% of soluble nitrogen, rendering the system extremely oligotrophic (Weragoda et al., 2009). The scientists determined that the mechanisms responsible for this efficient nitrogen removal by Brazilian elodea were NO_3 assimilation as well as volatilization of NH_4, into its gaseous form NH_3 (Weragoda et al., 2009). In fact, the results of this study indicated that upwards of 60% of nitrogen removal occurred because of volatilization and emission into the atmosphere (Weragoda et al., 2009).

Urrutia et al. (2000) provided one example of the severity and rapidity of nutrient depletion by Brazilian elodea in a freshwater environment. By analyzing the sedimentary layers in a Chilean lakebed, the researchers reconstructed the sedimentary history and nutrient composition over the last 150 years (Urrutia et al 2000). Using core samples of the lakebed, and examining diatom community composition at each strata layer, the scientists determined that the lake's history was punctuated by three distinct periods of trophic states (Urrutia et al., 2000). The first two periods, from 1883 to 1972, experienced gradual shifts in species diversity and nutrient composition; the last period however, featured an initial sharp increase in sedimentation and organic inputs (Urrutia et al., 2000). The diatomic record indicated that around 1980, a drastic depletion of nutrients occurred, which coincided with the first introduction of Brazilian elodea into the lake (Urrutia et al., 2000). After careful analysis, the researchers asserted that the oligotrophic conditions were caused directly by proliferation of Brazilian elodea.

The capability of Brazilian elodea as a potential phytoremediation species has been reviewed by several scientific researchers (Abu Bakar et al., 2013; Harguinteguy et al., 2015; Kobayashi et al., 2014; Mustafa & Hayder, 2021). Harguinteguy et al. (2015) conducted a short duration seven-day study to compare the heavy metal removal ability of parrotfeather (*Myriophyllum aquaticum*) and Brazilian elodea. This study indicated that parrotfeather outperformed Brazilian elodea in almost every metric of the experiment (Harguinteguy et al., 2015). The researchers noted that during Pb retention, Brazilian elodea suffered photosynthetic dysfunction as a result of chlorophyl production inhibition caused by Pb toxicity, whereas parrotfeather did not appear to be significantly affected (Harguinteguy et al., 2015). In another study, Brazilian elodea was compared with fanwort (*Cabomba piauhyensis*) and hydrilla (*Hydrilla verticillata*) in its ability to extract As, Al, and Zn (Abu Bakar et al., 2013). The researchers determined that the Brazilian elodea was highly efficient in removing As and Zn but was inferior to fanwort in its ability to remove Al (Abu Bakar et al., 2013). Like reed canarygrass, Brazilian elodea may be effective for phytoremediation in some cases but not all.

The ultimate assessment of this IVS' impact to stream chemistry in Pacific salmon habitat may be determined only by carefully weighing the positive and negative effects of its presence. Based on the literature reviewed for this thesis project, the detrimental effects of this invasive macrophyte species appear to outweigh its benefits, and thus, management of Brazilian elodea infestations in salmon habitat remains warranted. This notorious global invader can reduce the concentrations of available nutrients in the freshwater ecosystems it infests, especially during warmer seasons. It can create low oxygen environments during seasonal senescence and decomposition of its biomass. Yet, Brazilian elodea also has value as a phytoremediation species in some toxic water conditions. More research into the ability of this aquatic plant to alter water chemistry will only strengthen invasive species management and salmon conservation efforts.

4.4.5 Water Flow Regimes

Defining characteristics of Brazilian elodea invasion include formation of massive monotypic stands, sediment accumulation, and reductions to water flow. In fact, results from the thesis survey indicated that this aspect of the invasive plant was the most concerning for its proliferation in Western Washington. The literature reviewed throughout this project confirmed the professional opinion that Brazilian elodea can drastically reduce water flow and alter hydrologic function in freshwater environments which it infests.

The determining factors regarding any macrophyte's ability to restrict water flow include the physical structure of the plant and stand density (Wolters et al., 2019). Brazilian elodea can clog waterways to the point at which adjacent land may be at risk of flooding (Matthews et al., 2014). This aquatic plant is also capable of tremendous primary production and forms dense standing biomass which can regularly reach concentrations of 800 to 1,000 grams dry weight per square meter in optimal conditions (Yarrow et al., 2009). Not only can the organic biomass of Brazilian elodea create flow obstructions, but the high sedimentation rate of this macrophyte can also effectively raise the elevation of the bottom surface of the water body it inhabits, thereby restricting water flow further. An analysis of sedimentation in the San Joaquin River delta, California determined that the rate of vertical sediment deposition caused by Brazilian elodea ranged from 0.4 to 1.3 centimeters (0.2 - 0.5 inches) per year (Drexler et al., 2021).

Brazilian elodea has become a major problem in its native range, and each year this macrophyte is directly responsible for substantial economic losses, due to its tendency to impede water flow in municipal reservoirs and hydroelectric systems (Barreto et al., 2000). This invasive aquatic plant poses a threat to the agricultural industry by clogging irrigation channels and restricting water supply to crops (Matthews et al., 2014). Considering these examples, the implications for adversely affecting Pacific Salmon habitat must be taken seriously. Dams and culverts already impede salmon passage; additional challenges on their way to and from spawning grounds decrease survivability. The experts surveyed for this thesis expressed concern of this IVS' ability to impose negative impacts to water flow regimes in Western Washington, and the need for including management of Brazilian elodea in salmon conservation strategies.

4.4.6 Stream Temperatures

Although Brazilian elodea does not impact riparian vegetation and decrease canopy cover the way that Knotweed, reed canarygrass, or yellow flag iris do, this IVS can indirectly alter water temperatures in environments it infests. By reducing water flow, this invasive macrophyte allows water to absorb solar radiation for a longer duration than it would if it were flowing at higher velocities. This flow reduction can lead to thermally stratified water bodies (Durand et al., 2016) and temperatures, which negatively impact salmon survival. Additionally, floating mats of Brazilian elodea have a higher rate of sunlight absorption than surface water does, due to their photosynthetic capabilities. Santos et al (2009) provided evidence that the water temperature surrounding floating canopies of Brazilian elodea can be 1 to 5°C (33 - 41°F) higher than in adjacent areas without a presence of the invasive. This aquatic plant does not directly inhibit the establishment of native riparian tree species that provide shade to streams; which could explain why ‘increase to water temperature’ was not a priority factor expressed in the survey results. Based on the literature reviewed for this thesis, Brazilian elodea’s effects on stream temperatures does not appear to be of significant concern for salmon habitat.

4.4.7 Shelter Abundance (Woody Debris)

This criterion is not applicable to Brazilian elodea. Large wood recruitment into salmon habitat is not affected by this invasive species.

4.4.8 Migration Route Obstruction

Since Brazilian elodea commonly grows in substantial stands of dense biomass, it may effectively impede the navigation of large fish species (Darrin, 2009). In recent years, this aquatic IVS has become a major concern in many Western Washington salmon migration routes, including the Chehalis River Basin, Columbia River Basin, Lake Washington, Sammamish Lake, and throughout the Puget sound estuary (Morgan et al., 2021). The responses from the survey indicated that water flow impediments and salmon migration route obstruction are the highest priority concerns for this species.

The physical structure of this aquatic plant is such that it grows in densely packed stands, dominating all available space. Brazilian elodea could potentially clog confined areas of water flow and prevent salmon from advancing farther upstream during homing migrations. Thus, while it can provide refuge for small fish and juvenile salmon, it may obstruct migration of larger fish (Roberts et al., 1999).

Ecologists from the State of California Department of Boating and Waterways (2006) conducted a field survey and recorded 14 separate species of fish commonly observed within the stands of this Brazilian elodea. Although the San Joaquin Estuary exists as a major Pacific salmon migration route, none of the fish species observed were salmon (State of California Department of Boating and Waterways, 2006). In fact, salmon migration route obstruction caused by this invasive plant was one of the points explicitly outlined in the Brazilian elodea Control Program (State of California Department of Boating and Waterways, 2006).

Brazilian elodea has the potential to drastically limit salmon access to available habitat when left unmanaged. By dominating vast areas of littoral zones in lakes and slow flowing waterbodies this invasive aquatic plant can limit passage opportunities for populations of migrating salmon. For these reasons, Brazilian elodea must be considered a substantial threat to Pacific salmon habitat.

4.4.9 Predator Habitat

Many studies link the largemouth bass (*Micropterus salmoides*), a voracious predator of salmon, and Brazilian elodea patches (Conrad et al., 2016; Ferrari et al., 2014; Grossman et al., 2013). The largemouth bass is not native to Washington. Interestingly, Ferrari et al. (2014) found that in locations of dense Brazilian elodea patches, adult large-mouth bass tended to have a reduced foraging ability, while juvenile largemouth bass utilized the elodea as habitat as well as protection from the adult bass, which may suggest an advantage for juveniles who also feed on salmon.

Another predator of salmon is the northern pikeminnow (*Ptychocheilus oregonensis*). This predatory fish species is native to Washington and has been shown to hide in Brazilian elodea, effectively ambushing salmon as they swim above (Celedonia et al., 2008). Brazilian elodea also provides cover allowing the northern pikeminnow to hide from predatory birds (Celedonia et al., 2008). To help salmon populations, the Pacific States Marine Fisheries Commission has offered monetary rewards for catching northern pikeminnow (Pacific States Marine Fisheries Commission, 2021).

Chapter 5: Conclusion

The information contained within this work provides a wealth of knowledge from the fields of invasive vegetation ecology and Pacific salmon conservation. This thesis project answered the question: Which invasive vegetative species have the greatest negative impact on Western Washington’s freshwater salmon habitat in 2021? To answer this question, I explored the literature and surveyed professionals. The following subsections detail a recap of the thesis information (**Chapter 5.1**), overarching management of IVS (**Chapter 5.2**), and the future direction for this ongoing project, such as the ways in which this project can be best utilized in future salmon habitat enhancement efforts (**Chapter 5.3**).

5.1 Thesis Recap

As a result of this research, I narrowed down a list of 52 potential Western Washington invasive vegetative species to the four most impactful on Pacific salmon habitat (**Appendix B**). Based on survey responses, these four species were ranked in the following order based on the survey results: knotweed, reed canarygrass, yellow flag iris, and Brazilian elodea.

Industry professionals, mentioned that knotweed was highly detrimental to salmon habitat due to its prolific occurrence and severe ecological destruction. The literature collected supported the results of the survey. Knotweed aggressively outcompetes native vegetation, commonly forms monocultures, triggers erosion events, can deplete ecosystems of nutrients, and reduces native biodiversity.

Reed canarygrass negatively impacts the quality of Pacific salmon habitat by altering stream morphology, displacing native wetland species, and limits stream channel accessibility to salmon. The literature coincided with these survey results as well as brought forth additional information on this IVS' influence on salmon habitat. For instance, one author suggested that reed canarygrass has extremely high-water use requirements, which can reduce local hydrologic resources in areas of infestation. Reed canarygrass was shown to be a useful phytoremediation species for environmental heavy metal extraction. The most notable traits possessed by this IVS were ability to trap sediment in its root mats as well as to alter stream temperatures by impeding the flow of water. Some evidence suggested that reed canarygrass could provide suitable habitat for the invasive northern pike, which preferentially preys upon salmon.

The majority of survey respondents cited aggressive proliferation as yellow flag iris' most notable negative trait, while the minority noted changes to hydrology. Cross referencing the literature did not confirm the survey results; there was an abundance of anecdotal accounts but a lack of quantifiable data. However, the literature reviewed did provide additional information on reed canarygrass, such as the plant's toxicity to both humans and livestock, and its use in phytoremediation. Furthermore, this plant's ability to obstruct water flow and block salmon migration routes was underrepresented in the survey results when compared to the available literature.

Quantifying the effects of Brazilian elodea on Pacific salmon habitat was complicated, since it was the least represented species in the survey results and had limited scientific literature associated with it. This IVS is an opportunistic competitor, one which only thrives when conditions are optimal, and in the absence of extreme adversity. Literature revealed that this invasive plant possessed intolerance to adverse environmental conditions. Cascading effects have been associated with Brazilian elodea's seasonal growth cycles; first, altering stream chemistry during senescence, which can alter macroinvertebrate abundance and diversity, and ultimately affecting the survival of salmon. The literature suggested that this macrophyte can drastically alter nutrient cycling regimes by directly absorbing nutrients from the water column. The research referenced alluded to Brazilian elodea's ability to increase water temperatures by slowing water velocities and photosynthesizing at the water's surface. Furthermore, this invasive plant has been documented to provide habitat to salmon predators, such as the non-native largemouth bass and the native northern pikeminnow. As a result of these impacts, this IVS must be controlled when found near salmon migration routes, and it must not be allowed to spread into waterbodies used by salmon at any life stage.

5.2 IVS Management

The goal of management for IVS relies on a series of steps determined by the species' current degree of proliferation in an area (**Figure 25**). As an invasive, or undesirable plant species, becomes more established in an area, the management shifts between *prevention*, *eradication*, *containment*, and *asset-based protection* (Victorian Department of Primary Industries, 2010). *Prevention* typically occurs before any species arrives and is the most cost-effective option (**Figure 5**). *Prevention* is also the most difficult approach because it is not easy to predict when and where a plant will become established. Class A noxious weeds fall into the *eradication* approach as they have populations that are small and thus easiest to control. *Eradication* involves the removal of all viable individuals in an ecosystem. Often this removal consists of either chemical, mechanical, or cultural methods – or a combination thereof. Class B noxious weeds are generally managed under the *containment* approach which still includes eradication of smaller satellite populations, as well as preventing the spread of the current larger populations. There are some cases in which Class C noxious weeds are also managed with the *containment* approach, depending on location and abundance. The majority of Class C noxious weeds are managed under the approach of *asset-based protection*. *Asset-based protection* consists of preventing further encroachment of the invasive into the desired plant populations while simultaneously promoting the spread of those desirable species, such as native plants, into the area currently inhabited by the invasive vegetation.

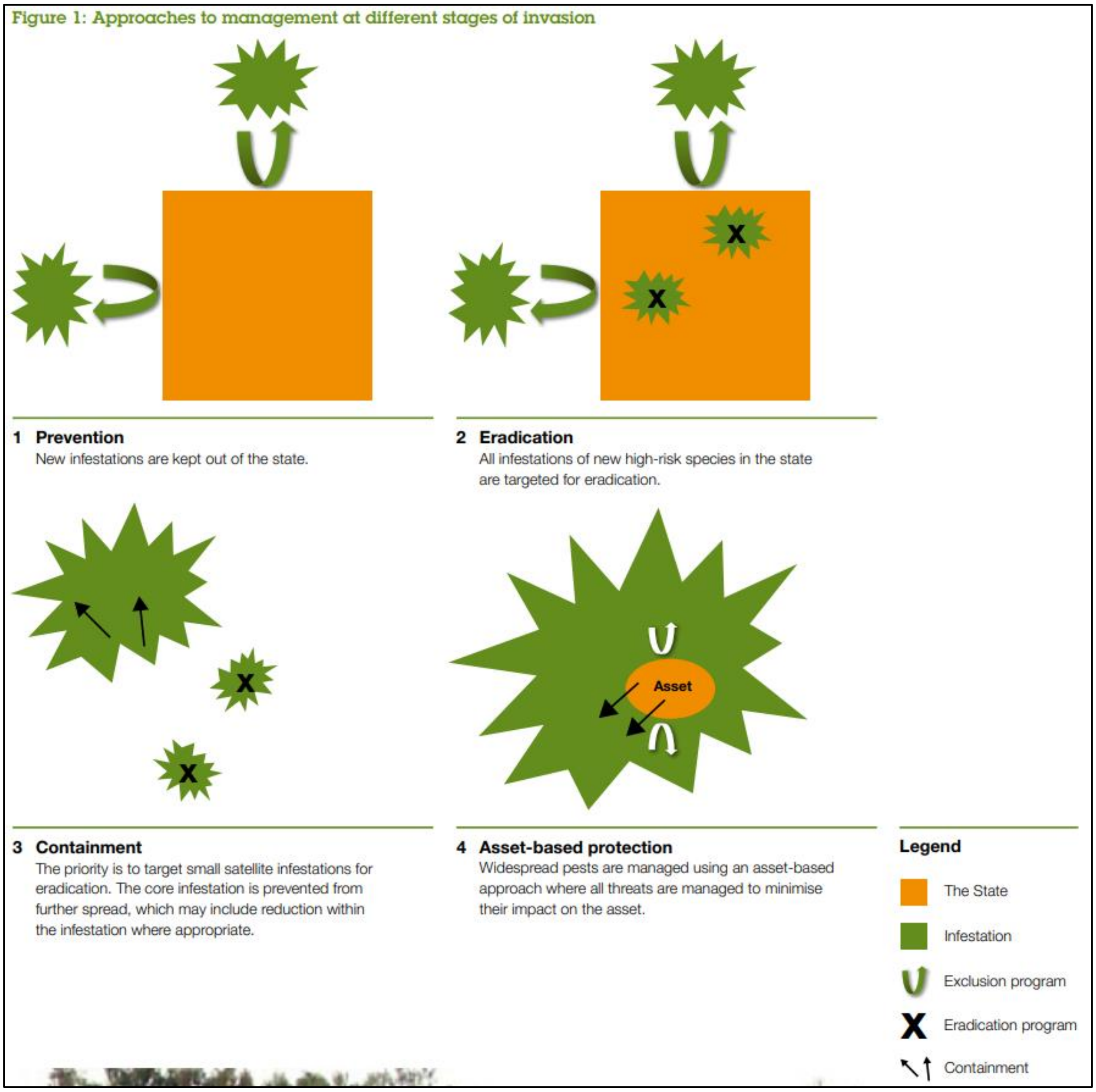


Figure 1: Approaches to management at different stages of invasion

1 Prevention
New infestations are kept out of the state.

2 Eradication
All infestations of new high-risk species in the state are targeted for eradication.

3 Containment
The priority is to target small satellite infestations for eradication. The core infestation is prevented from further spread, which may include reduction within the infestation where appropriate.

4 Asset-based protection
Widespread pests are managed using an asset-based approach where all threats are managed to minimise their impact on the asset.

Legend
🟧 The State
🟩 Infestation
Exclusion program
X Eradication program
↖↑ Containment

Figure 25: Stages of IVS management

These are the various management stages that occur as infestations increase. For instance, once prevention is no longer an option the best management is for eradication, but as the species proliferation increases containment becomes the next viable option, and so on (Victorian Department of Primary Industries, 2010).

5.3 Next Steps

Management of IVS yields the greatest benefit when all stakeholders work together. I have prepared this thesis so that agencies, groups, organizations, and others can easily access information and a multitude of scientific resources that could help direct management decisions or funding. It is my hope that science researchers may choose to pursue research to fill the knowledge gaps outlined within this body of work. For instance,

- What are the specific mechanisms that are at work which increase the rate of erosion in knotweed infested areas?
- How does prolonged occurrence of knotweed impact soil chemistry and nutrient availability (i.e., nitrogen, phosphorous, carbon)? If soil nutrient depletion is confirmed by knotweed presence, does that translate to a reduction in aqueous nutrients derived from soil?
- Is alteration to water quality parameters (such as pH and DO) a feature of knotweed?
- What are the exact processes involved with knotweeds widely understood ability to alter water flow regimes, such as increased flood risk, water flow reduction, and stream obstruction?
- Are there salmon predators that use knotweed and/or yellow flag iris as available habitat? If so, what predator species reside in knotweed or yellow flag iris?
- Does reed canarygrass produce high enough concentrations of alkaloid compounds, primarily Phenols, Indoles, and β-carbolines, to impact Pacific salmon habitat?
- Does yellow flag iris produce high enough concentrations of toxic compounds (**Chapter 4.3.4**) to impact Pacific salmon habitat?
- Is there a statistical correlation between water flow/flooding/stream obstruction and yellow flag iris?

- Does Brazilian elodea displace native vegetation to the degree that it could be detrimental to Pacific salmon habitat?

While many of these questions have been answered anecdotally, scientific studies of these questions will provide a more complete understanding of Pacific Northwest invasion ecology. Furthermore, they will provide an opportunity for individuals who are not working in this field to learn more about invasive species and why it is so important to help manage them. I also recommend that landowners reach out to their county Noxious Weed Control Board to learn more about what they can do on their own property. Additionally, the public has the opportunity to be citizen scientists by downloading the Washington Invasive Species reporting app (**Figure 26**). Observing invasive species and reporting the findings helps with early detection and rapid response (EDRR) and assists ecologists with knowing where to focus management efforts.

Figure 26: [photo] Invasive Species Application Reporting
Download the WA Invasive Species app and report your findings. This is one of the best ways the public can help in the war on invasives. Image used with permission by Alexis Haifley, Education Specialist with the Invasive Species Council (Haifley, 2020). Image cited with permission.

This thesis may be written, but the project is not over. I want to reach out to each of the county Noxious Weed Control Boards to gather the data they have on the locations of these four IVS. By gathering this data, many of the tables will need to be updated periodically, which I plan to do as the information becomes available. These updates will be published within the ArcGIS story map created for presenting this thesis and is shared as a link in the **Abstract**. The information will continue to evolve, as well as become more refined in scale. This data should be used by everyone, from the environmental enthusiast to the consummate professional.

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Appendices

Appendix A: Survey Part I

2021 Survey of Freshwater Priority Noxious Weeds Impacting Salmon Habitat in Western Washington

Survey Introduction

This survey has been created by a current Master of Environmental Studies student at Evergreen State College working on a thesis project in collaboration with a team of professionals specializing in related fields; including the WA Invasive Species Council, the WA State Noxious Weed Control Board, WA State Department of Ecology, WA State Department of Agriculture: Pest Program, and the Salmon Section of the Recreation and Conservation Office. This survey is designed to seek additional expert knowledge to identify high priority riparian and estuarine noxious weeds within western Washington that affect ecosystem services as well as salmon bearing streams and salmon habitat. Additionally, this survey is designed to compile pre-existing peer reviewed research and documented information that may be already associated with the invasive vegetative species inquired herein. We greatly appreciate your input and look forward to reading and analyzing your responses. The answers provided from this survey will go far to help with invasive vegetation management, as well as addressing funding gaps and possible future funding opportunities. **If you have been given this survey, it is because you have been chosen as somebody who is valuable to this survey and your responses will be greatly appreciated.** Please read the letter of consent and confidentiality agreement so that you know how your information will be used and how your privacy will be protected. ***If possible, please have this survey filled out and submitted by February 1st at the latest.***

Once the survey has been started, you may not be able to come back to it or start a new survey... please allow for a minimum of 15 minutes to complete this survey (more time may be needed if answering information about multiple species or if the information is not readily available).

1. Dear [Participant]:

I am a student at The Evergreen State College (ESC). As part of my thesis work in the program, Master of Environmental Studies (MES), I will be conducting a research project titled "**Determining the top five most impactful noxious weeds affect freshwater salmon habitat in western WA in 2020: A literature review and surveying professionals**". The purpose of my project is to provide a bridge between various stakeholders to maximize efforts/strategies/funding in the eradication/management of the most impactful noxious weeds to ecosystem services within salmon habitats. I will be conducting an online survey over the next couple months.

Any risks to you are minimal. I plan to minimize the risks/discomforts by **1) providing**

complete information about the study, **2) coordinating with team of related professionals about this study**, and **3) removing individual names from the final report**. There will be no compensation of any kind available for your participation, which is completely voluntary. You may withdraw your participation at any point or skip any question you do not wish to answer without penalty. You may not directly benefit from this research; however, **we hope that your participation in the study may better allow for a healthier environment and for species like the salmon species and resident orca whales to be around for future generations**.

Your answers will not be linked with your name. However, I may share your answers with Shawn Hazboun, PhD (MES professor at ESC); John Withey, PhD (MES professor at ESC); Kevin Francis, PhD (MES director at ESC); Mary Fee (Washington State Noxious Weed Control Board); Justin Bush (Washington Invasive Species Council); Chad Phillips (Washington State Department of Agriculture Pest Program); Alice Rubin (Recreation and Conservation Office Salmon Section); Lizbeth Seebacher (Washington State Department of Ecology); and Jennifer Parsons (Washington State Department of Ecology).

As mentioned above, I will use your responses as resource material for my research project on **determining the top five most impactful noxious weeds affect freshwater salmon habitat in western WA in 2020**. At your request, I will provide you with a copy of the thesis paper as well as any supporting aides, such as documentation or story-maps, as well as an invitation to the thesis presentation delivered to the ESC and any other presentation venue that occurs within the first year of finishing the thesis.

Your survey answers, collected as part of the research, could be used for future research studies or distributed to another investigator for future research studies, with all identifiable information removed, without additional informed consent from the subject or the legally authorized representative.

If you have any questions about this project or your participation in it, you can call me at 253.XXX.XXXX (cell). My email address is keepingusgreen@yahoo.com. If you have questions concerning your rights as a research subject or experience problems as a result of your participation in this project, contact Karen Gaul, IRB administrator at The Evergreen State College, Library 2008, Olympia, WA 98505; Phone 360.867.6009.

Thank you for your participation and assistance!
Sincerely,
Danielle Kies

-----Letter of Consent-----

I, ____, hereby agree to serve as a subject in the research project titled "Determining the top five noxious weeds that affect freshwater salmon habitat in western WA". It has been explained to me that its purpose is to generate a list of the most impactful invasive vegetative species to ecosystem services within salmon habitats.

□ Agree **□ Disagree**

2. ------Confidentiality Form------

You are being invited to participate in a research study titled "**Determining the Top Five Invasive Vegetation Affecting Freshwater Salmon Habitat in Western WA**". This study is being done by ***Danielle Kies*** from The Evergreen State College.

The purpose of this research study is to **generate a list of priority species for interagency collaboration in riparian management efforts across Western WA**. If you agree to take part in this study, you will be asked to complete an online survey/questionnaire. This survey/questionnaire will ask about noxious weeds that you are familiar with and it will take you approximately 5-20 minutes to complete, depending on how much information you are willing to incorporate into your answers.

You may not directly benefit from this research; however, we hope that your participation in the study help to **promote a healthier environment for species like salmon and the resident orca whales to have an increased chance to be around for future generations**.

Risks to you are minimal and are likely to be no more than mild discomfort with sharing your opinion. To the best of our ability your answers in this study will remain confidential. With any online related activity, however, the risk of a breach of confidentiality is always possible. We will minimize any risks by **1) providing complete information in the protocol regarding the experimental design and the scientific rationale underlying the proposed research, 2) participating in regular meetings with a team of related professionals about this study, 3) ensuring that the projected sample size is sufficient to yield useful results, and 4) removing any grouping final results so that no individual names are known in the final product.** Your participation in this study is **completely voluntary and you can withdraw at any time.** You are free to skip any question that you choose.

Your survey responses, collected as part of the research, could be used for future research studies or distributed to another investigator for future research studies, with all identifiable information removed, without additional informed consent from the subject or the legally authorized representative.

If you have questions about this project or if you have a research-related problem, you may contact the researcher(s), Ms. Danielle Kies, 253.XXX.XXXX (cell), KeepingUsGreen@Yahoo.com. If you have any questions concerning your rights as a research subject, or you experience problems as a result of participating in this research project, you may contact Karen Gaul, IRB Administrator at The Evergreen State College at 360.867.6009 or irb@evergreen.edu.

By clicking "I agree" below you are indicating that you are at least 18 years old, have read and understood this consent form and agree to participate in this research study. Please print a copy of this page for your records.

☐ **I agree** ☐ **I do not agree**

3. Please provide your contact information:

Name (optional) (open text box)

Organization or Agency Represented (recommended) (open text box)

Area of Work: i.e. County, WRIA, Region (recommended) (open text box)

Email Address (optional) (open text box)

Phone Number (optional) (open text box)

4. What type of organization are you associated with? (drop down list of the following options: County Conservation District, County Noxious Weed Control Board, Educational Institution, Federal Agency, Non-Profit, Salmon Recovery Funding Board, State Agency, Tribal, Other- please specify)

*****_If you choose other, there will be a textbox to write in your answer._

5. Would you like to participate and/or be included in further discussions about this project?

*****_Some form of contact information (i.e., name & email address from Question 3) will be required for inclusion in future activities/information._

☐ **Yes** ☐ **No**

6a. In your opinion, what are the priority noxious weed species and why. Please ONLY select species that are within Washington State AND can be found in the freshwater ecosystems. Select one species at a time.

*After submitting responses for the first species you picked, there will be a page prompting you to continue with another species or finish the survey.
**Please only add up to ten different species total.
***Information about Washington State noxious weeds can be found at: https://www.nwcb.wa.gov/classes-of-noxious-weeds.

Appendix B: Species List

List of species included in survey; ***Top 4**; **Top 11
Organized by: Class; Number of surveys mentioned; common (scientific names)

[Between class and name is number of survey responses]			A, B	0	Knapweed (2 = class A; 6 = class B) *Centaurea* spp. & *Rhaponticum repens* (B)
A	0	common crupina (*Crupina vulgaris*)	A	0	giant hogweed (*Heracleum mantegazzianum*)
A	1	cordgrass (4 species – all class A) (*Spartina spp.*)	A	1	hydrilla (*Hydrilla verticillata*)
A	0	floating primrose (*Ludwigia peploides*)	A	0	ricefield bulrush (*Schoenoplectus mucronatus*)
A	3	**flowering rush (*Butomus umbellatus*)	A	0	small-flowered jewelweed (*Impatiens parviflora*)
A	0	garlic mustard (*Alliaria petiolata*)	A	0	variable leaf milfoil (*Myriophyllum heterophyllum*)
B	**4**	***Brazilian elodea** **(*Egeria densa*)**	C	0	Canada thistle (*Cirsium arvense*)
B	2	**butterfly bush (*Buddleja davidii*)	C	0	common St. John's wort (*Hypericum perforatum*)
B	2	**common reed (*Phragmites australis*)	C	0	common tansy (*Tanacetum vulgare*)
B	3	**Eurasian watermilfoil (*Myriophyllum spicatum*)	C	0	common teasel (*Dipsacus fullonum*)
B	0	European coltsfoot (*Tussilago farfara*)	C	0	curlyleaf pondweed (*Potamogeton crispus*)
B	0	fanwort (*Cabomba caroliniana*)	C	1	English ivy (*Hedera* sp.)
B	0	garden loosestrife (*Lysimachia vulgaris*)	C	1	Eurasian watermilfoil (hybrid) (*Myriophyllum spicatum* x *M. spicatum*)
B	**10**	***Knotweed (4 species- all class B)** **(*Polygonum* spp.)**	C	1	evergreen blackberry (*Rubus laciniatus*)
B	3	**parrotfeather (*Myriophyllum aquaticum*)	C	0	field bindweed (*Convolvulus arvensis*)
B	0	poison hemlock (*Conium maculatum*)	C	0	fragrant waterlily (*Nymphaea odorata*)
B	1	policeman's helmet (*Impatiens glandulifera*)	C	3	**Himalayan blackberry (*Rubus bifrons*)
B	2	**purple loosestrife (*Lythrum salicaria*)	C	0	Japanese eelgrass (*Nanozostera japonica*)
B	0	saltcedar (*Tamarix ramosissima*)	C	1	non-native cattail (*Typha* sp.)
B	1	Scotch broom (*Cytisus scoparius*)	C	0	old man's beard (*Clematis vitalba*)
B	0	shiny geranium (*Geranium lucidum*)	C	0	pampas grass (*Coraderia selloana*)
B	0	spurge laurel (*Daphne laureola*)	**C**	**7**	***reed canarygrass** **(*Phalaris arundinacea*)**
B	1	tansy ragwort (*Jacobaea vulgaris*)	C	1	Russian olive (*Elaeagnus angustifolia*)
B	1	water primrose (*Ludwigia hexapetala*)	C	0	spotted jewelweed (*Impatiens capensis*)
B	1	yellow archangel (*Lamiastrum galeobdolon*)	C	0	tree-of-heaven (*Ailanthus altissima*)
B	0	yellow floatingheart (*Nymphoides peltata*)	**C**	**5**	***yellow flag iris** **(*Iris pseudacorus*)**

Appendix C: Survey Part II

**Question numbers may be different depending on which species was chosen to report on, as each species has its own version of the following questions.*

7. In your opinion, why is this species a high priority for freshwater management?

(open text box)

8. Date noxious weed was first discovered. *Skip or select clear if unknown*.

(date box with calendar attachment)

9. Which county is the invasive species located in?

(drop down box of Washington State counties)

10. To the best of your knowledge, approximately how many acres are currently known to be infested within your watershed? **amount based on plant density rather than total land coverage.*

(multiple choice of ranges from: 0-5 acres; 5-10 acres; 10-25 acres; 25-50 acres; 50-100 acres; 100-200 acres; over 200 acres; unknown; other (please specify))

11. To the best of your knowledge, approximately how many total acres within the watershed are known to be impacted (for example, additional acreage that could potentially be infested or close to a vector of spread)**?**

(see same option choices as Q10)

12. To the best of your knowledge, approximately how many acres (*of those infested*) **are currently known to be actively managed/controlled?**

(see same option choices as Q10, with an additional 'does not apply' option)

13. In your opinion, does the amount of current research available adequately meet your agency's needs (*i.e., peer reviewed papers, documented research, etc*.)**?**

(slider bar from 0 – 100; where 0 is "No research available", around the middle is "some research, but more needed", and 100 is "More than enough research available")

14. Please include any available resources, such as a research project or peer reviewed article, that can attest to the impacts of any of the before mentioned species.

(open text box)

15. If you have any additional information regarding this species, please state it here (for example, multiple counties or WRIA information).

(open text box)

Appendix D: Survey Part III

17. Out of all the species you have reported in this survey, please list them in order of importance, with the first species listed as the one you feel is most important to focus on.

(open text box)

18. Do you have any additional questions, comments, or concerns?

(open text box)

19. How easy or difficult was this survey to navigate?

(5-point Likert scale ranging from very easy to very difficult)

20. Comments

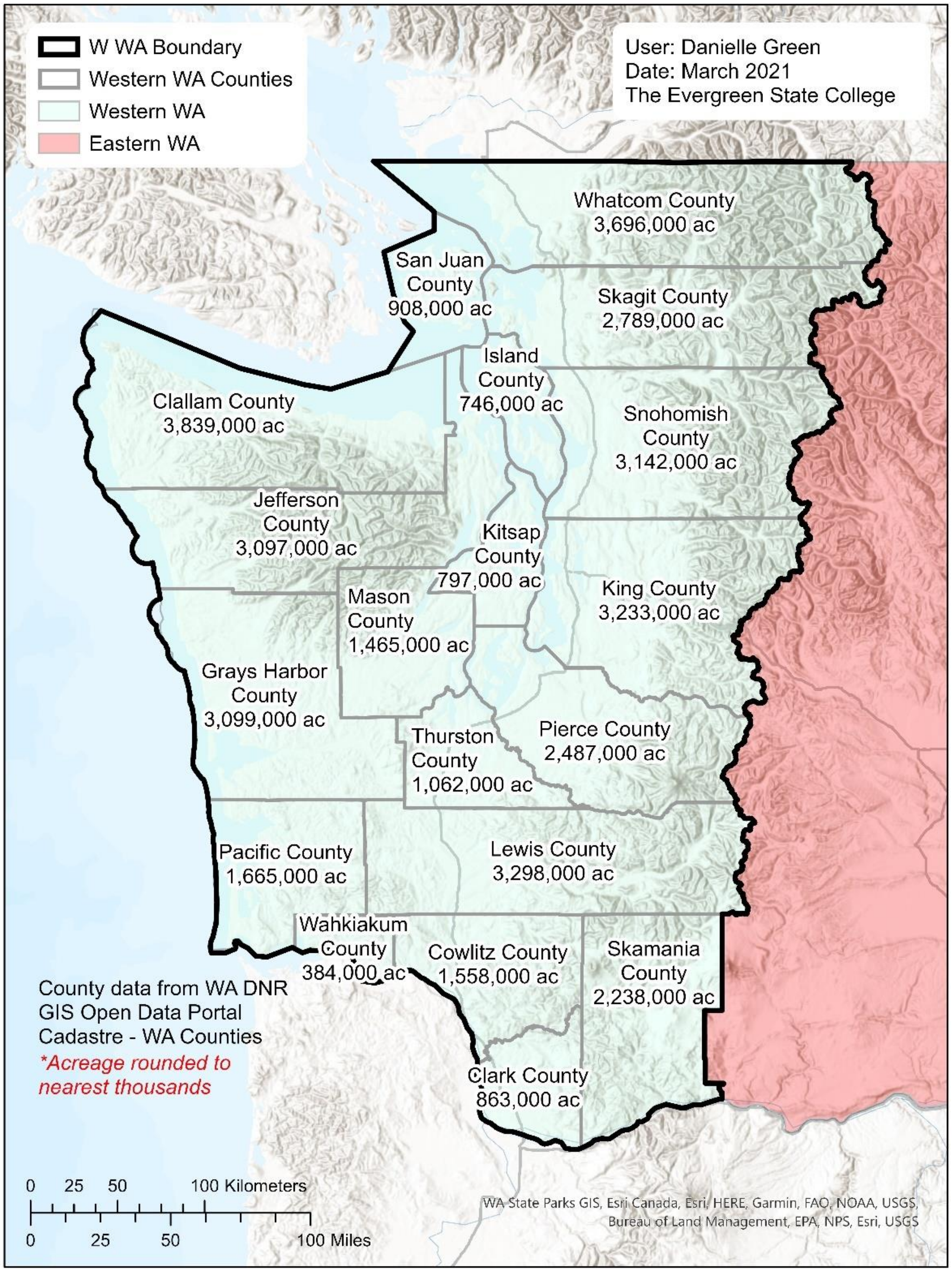
(open text box)

Thank you very much for your time and important information! Your contributions are greatly appreciated.

Appendix E: Study Maps

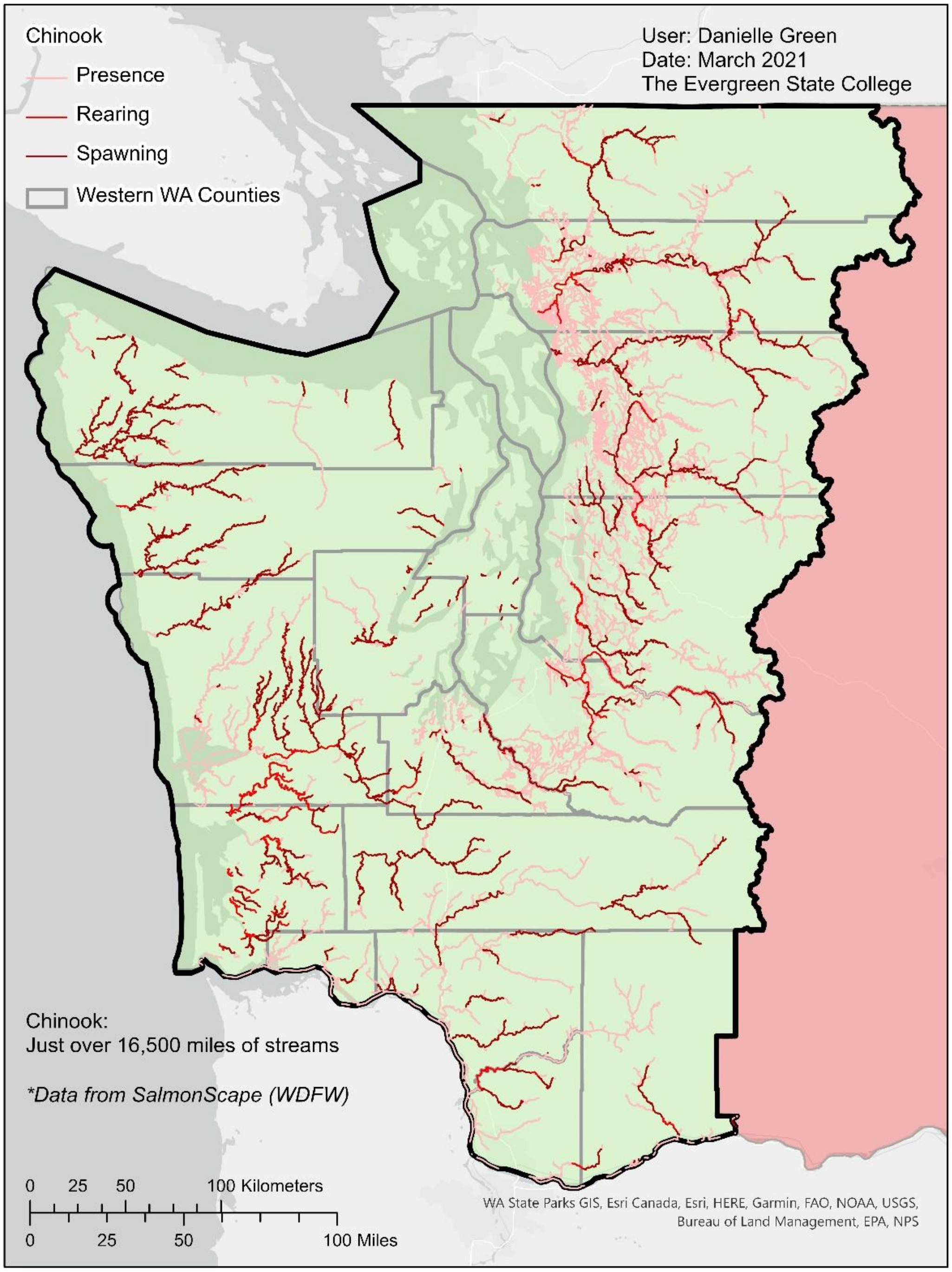
Appendix E1: Study Area of Western WA Counties

Study area map of the nineteen Western Washington counties and their corresponding acreage rounded to the nearest thousand acres.



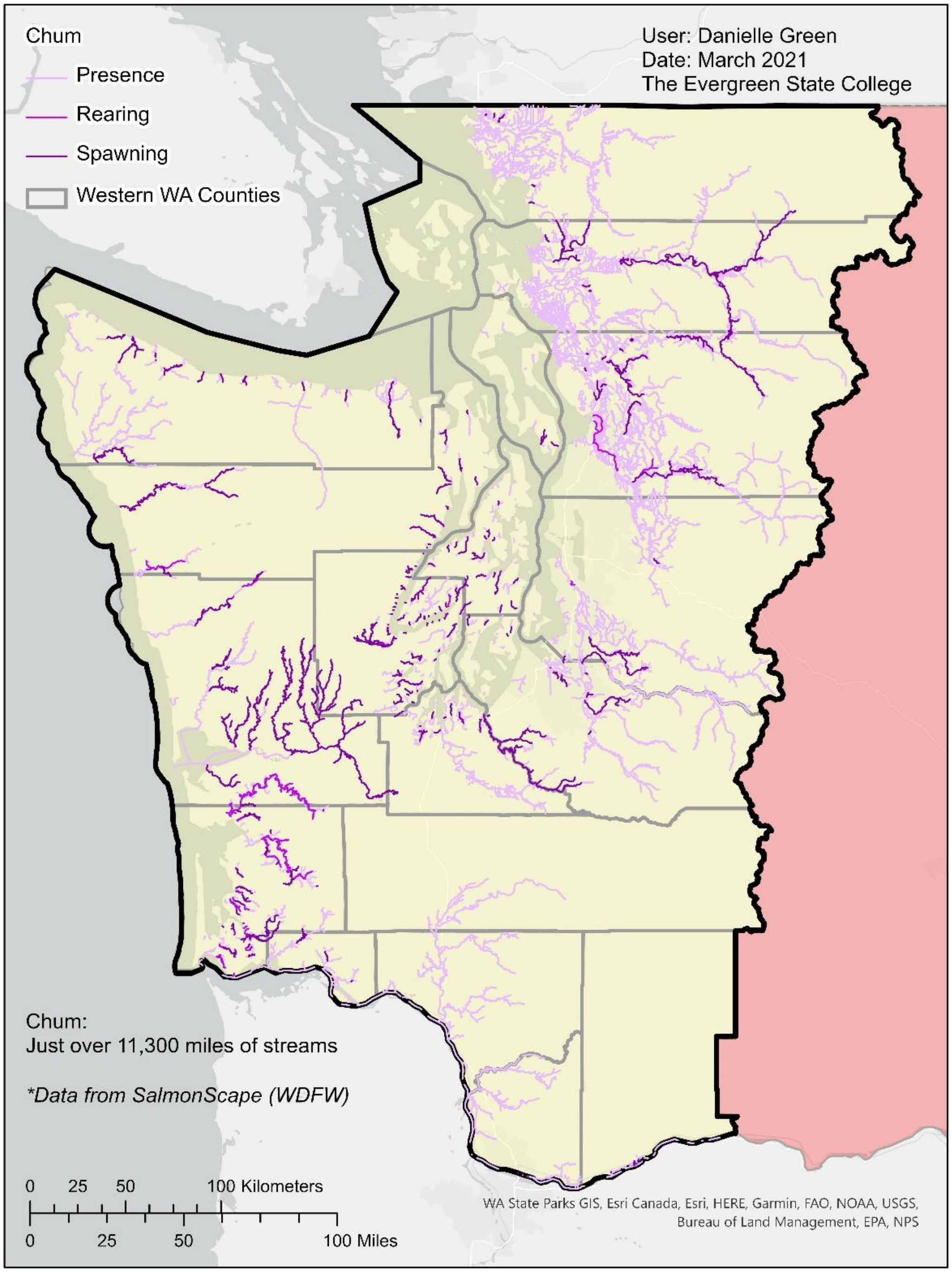
Appendix E2: Western WA Chinook Streams

Chinook salmon (Oncorhynchus tshawytscha) streams classified by salmon stages. There are just over 16,500 miles of streams for Chinook in Western WA.



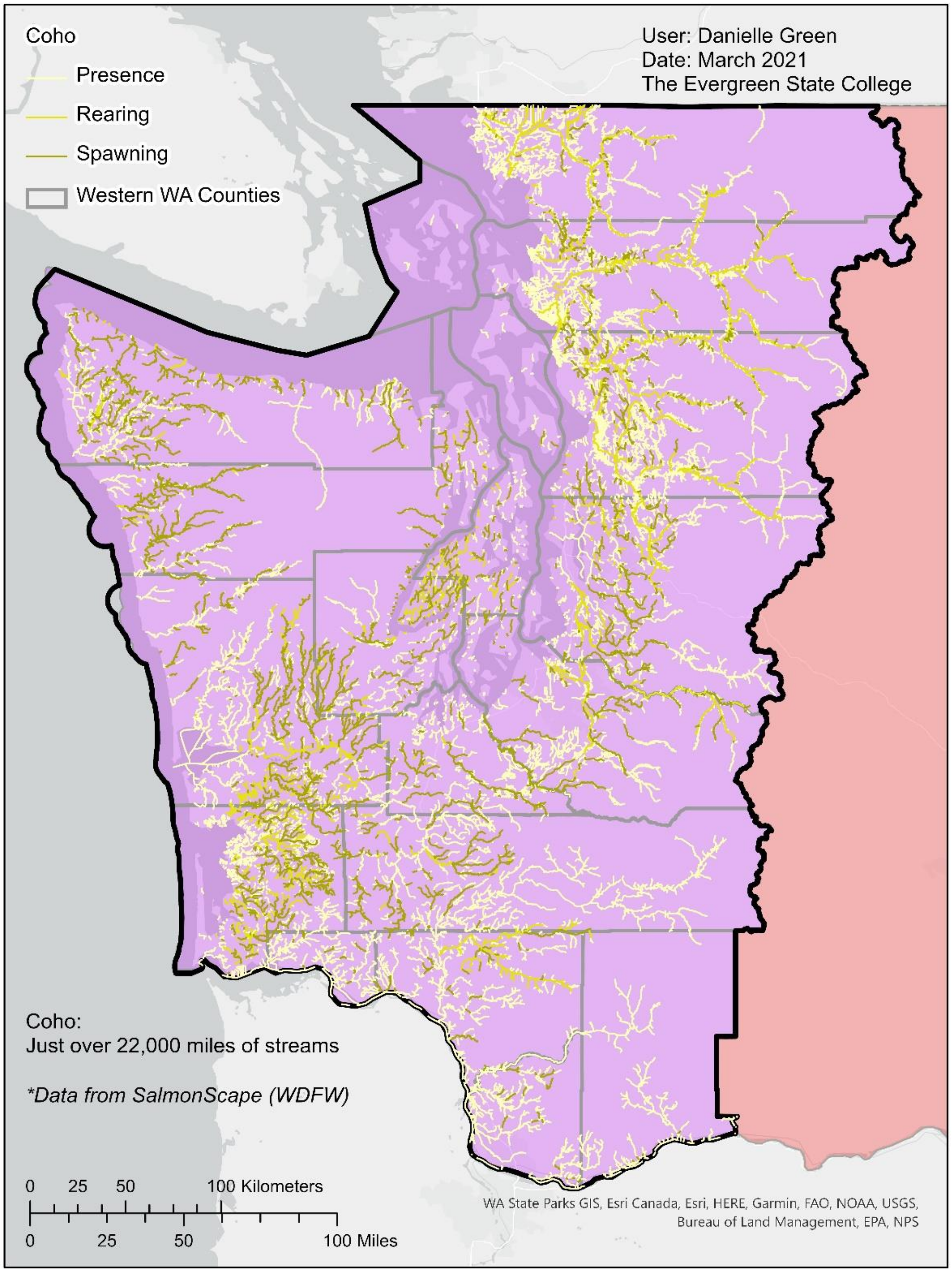
Appendix E3: Western WA Chum Streams

Chum salmon (Oncorhynchus keta) streams classified by salmon stages. There are just over 11,300 miles of streams for Chum in Western WA.



Appendix E4: Western WA Coho Streams

Coho salmon (Oncorhynchus kisutch) streams classified by salmon stages. There are just over 22,000 miles of streams for Coho in Western WA.



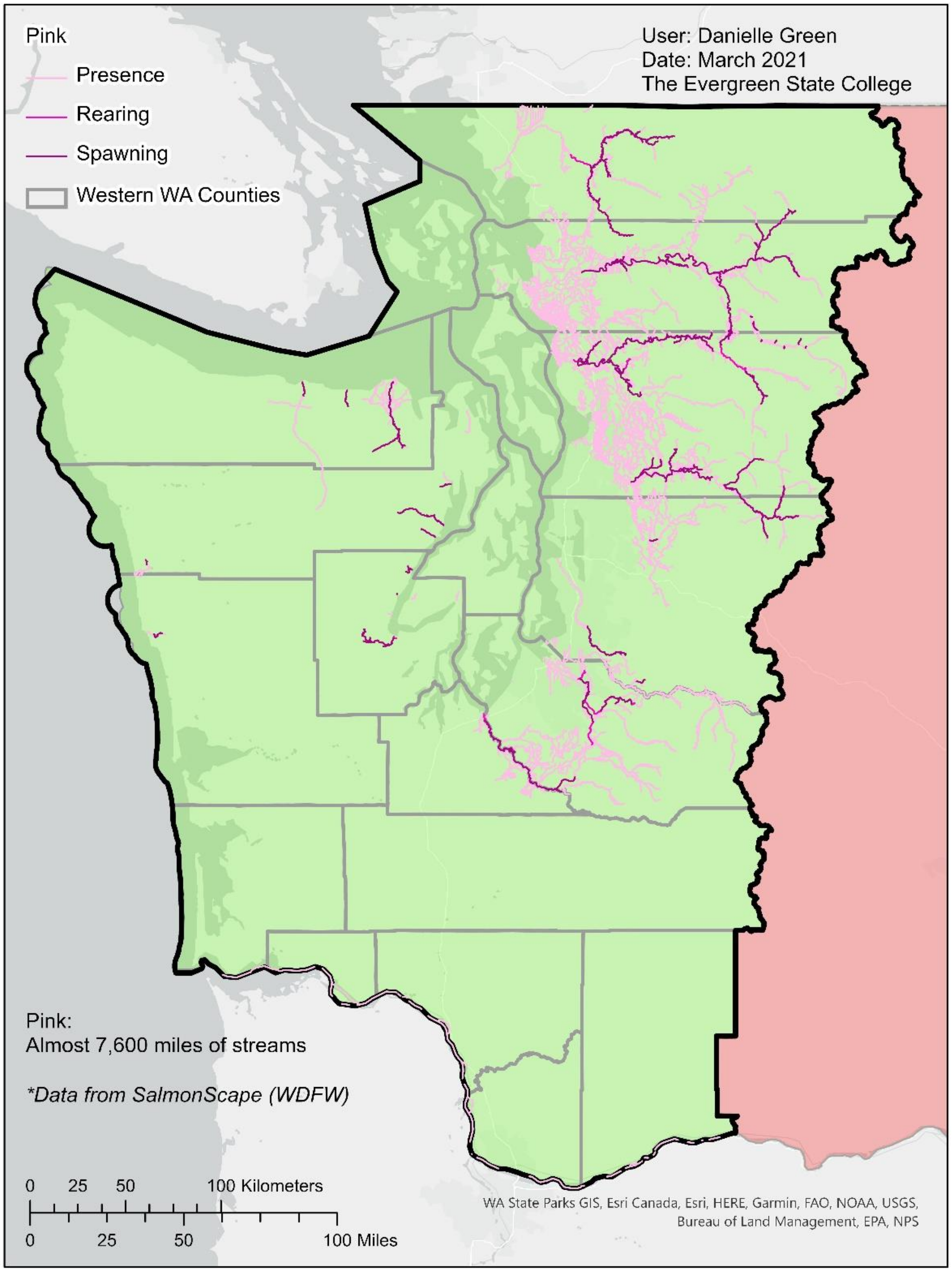
Coho:
Just over 22,000 miles of streams

**Data from SalmonScape (WDFW)*

WA State Parks GIS, Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, Bureau of Land Management, EPA, NPS

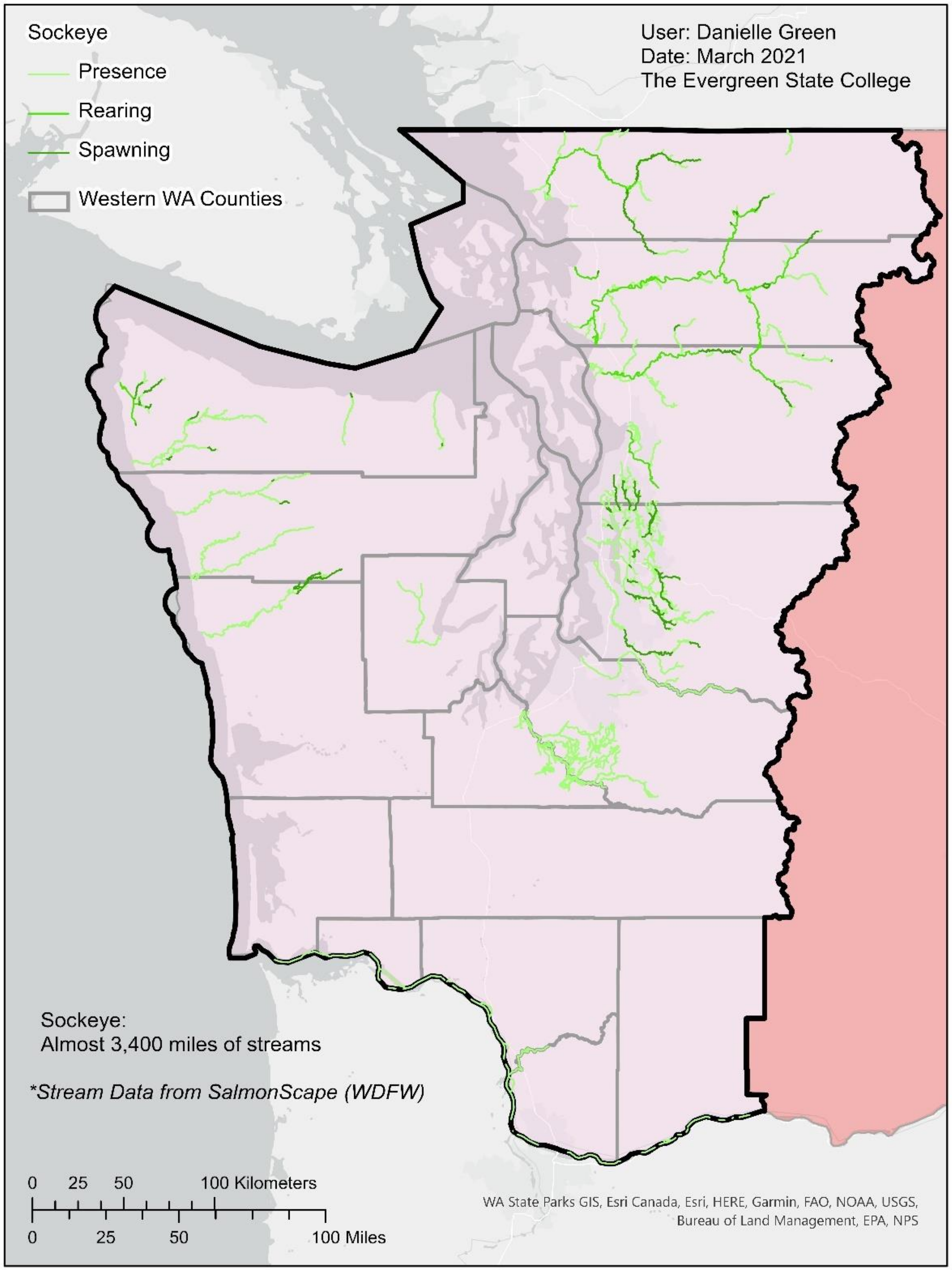
Appendix E5: Western WA Pink Streams

Pink salmon (Oncorhynchus gorbuscha) streams classified by salmon stages. There are almost 7,600 miles of streams for Pink in Western WA.



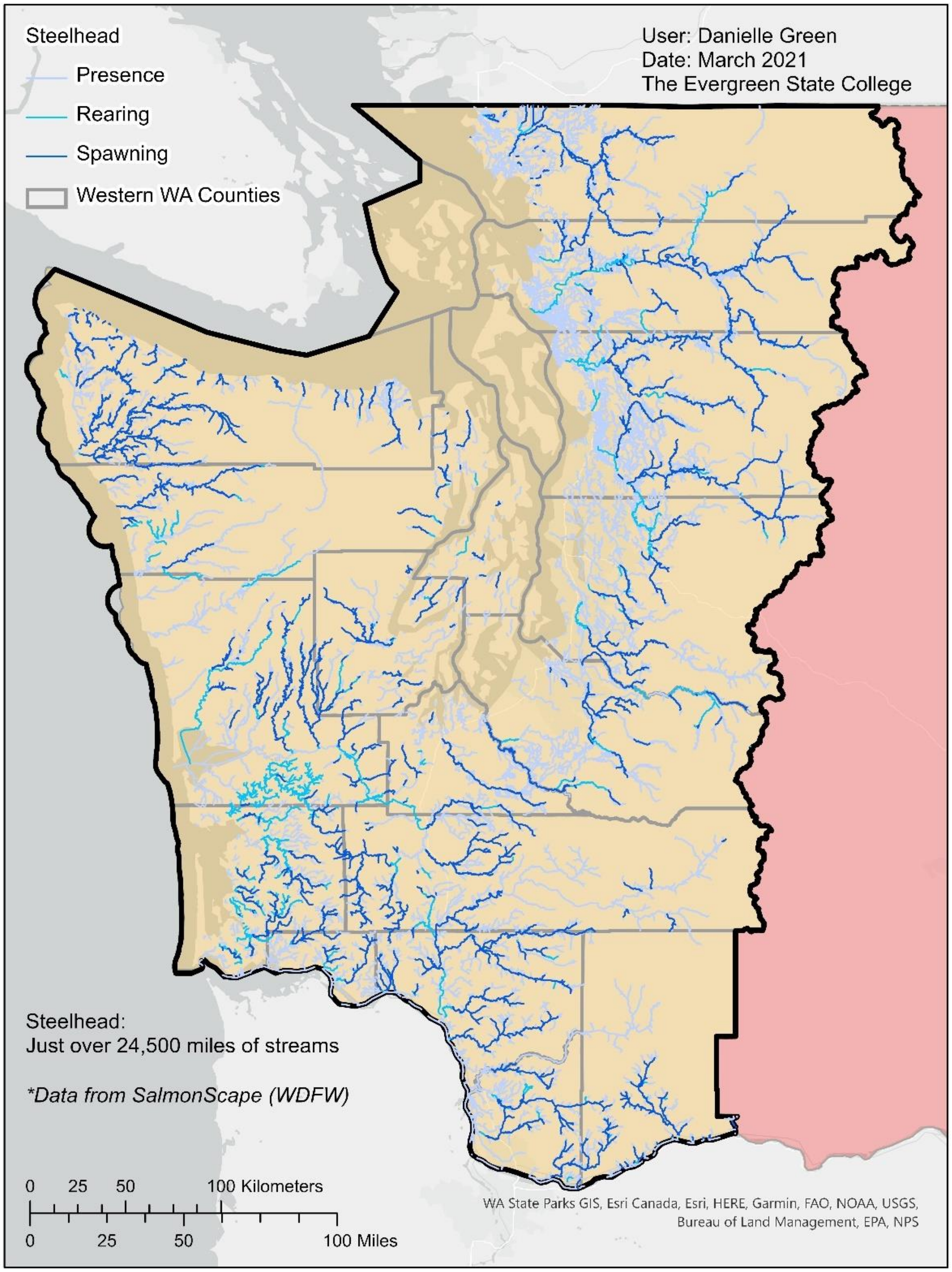
Appendix E6: Western WA Sockeye Streams

Sockeye salmon (Oncorhynchus nerka) streams classified by salmon stages. There are almost 3,400 miles of streams for Sockeye in Western WA.



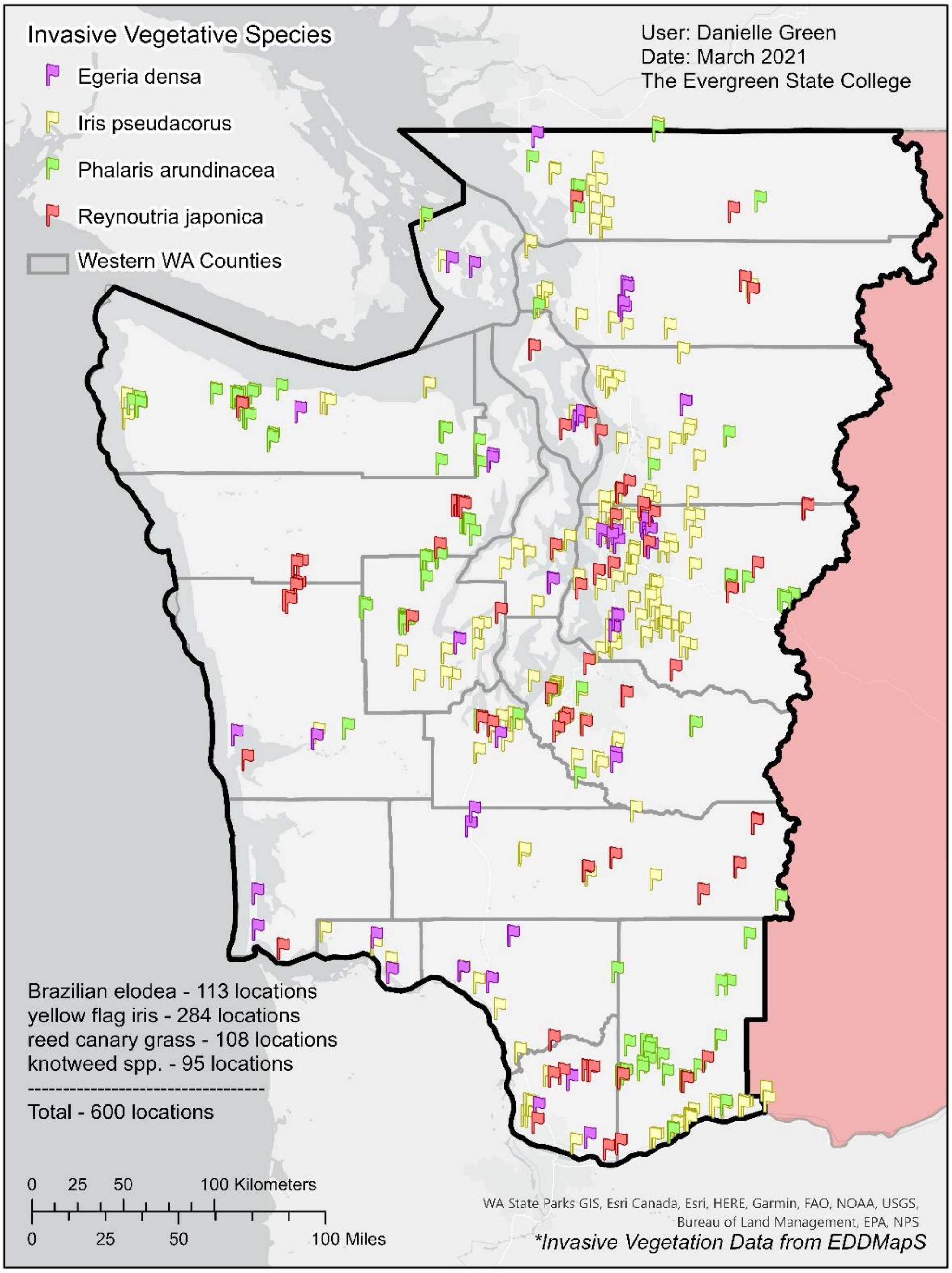
Appendix E7: Western WA Steelhead Streams

Steelhead salmon (Oncorhynchus mykiss) streams classified by salmon stages. There are just over 24,500 miles of streams for Steelhead in Western WA.



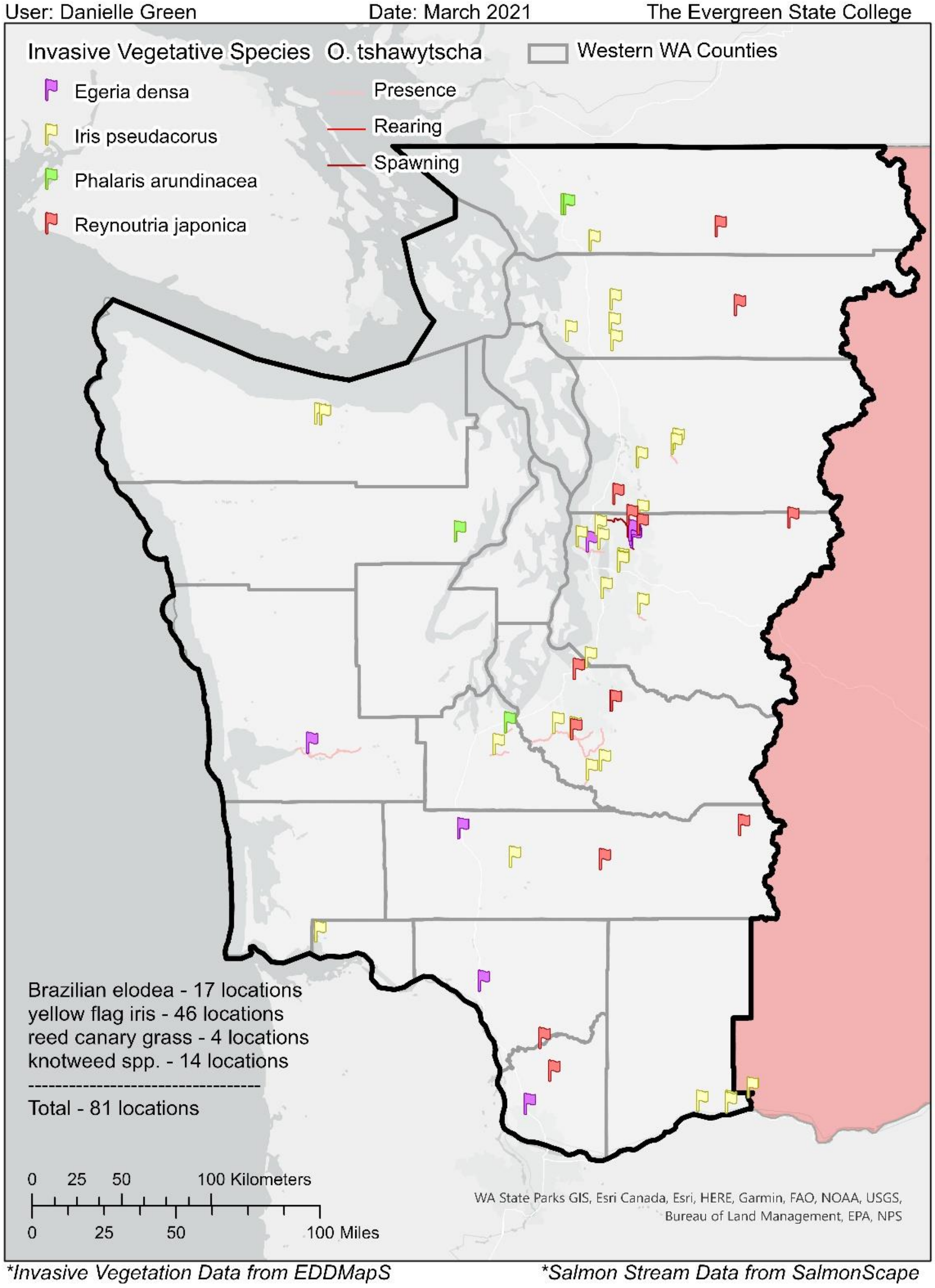
Appendix E8: Top Four IVS Locations

Map of four noxious weed locations in Western WA. These noxious weeds include Brazilian elodea (Egeria densa), yellow flag iris (Iris pseudacorus), reed canarygrass (Phalaris arundinacea), and Japanese knotweed (Reynoutria japonica). To see these various IVS counts by county, please refer to ***Table 4****.*



Appendix E9: IVS Presence on Chinook Streams

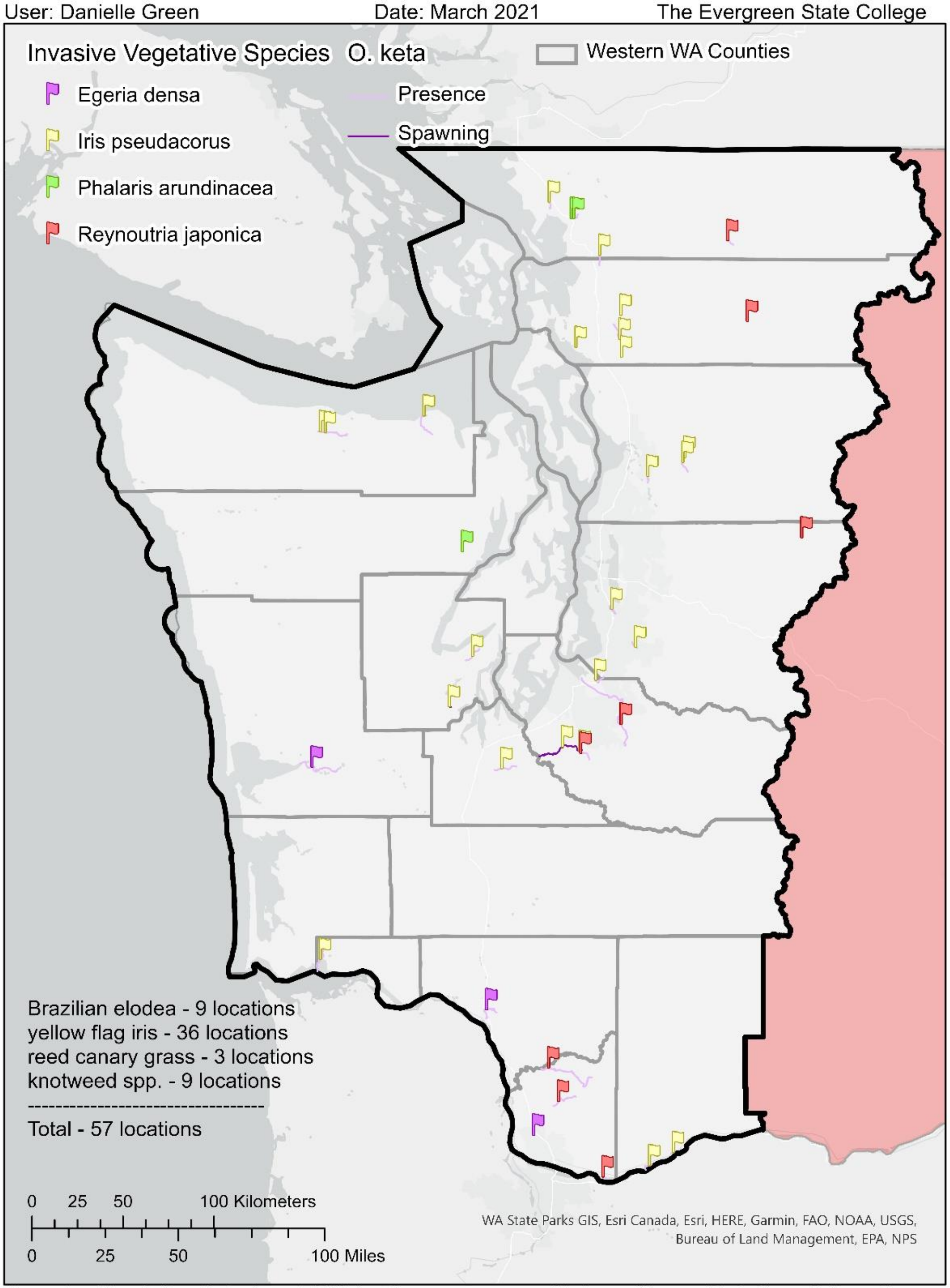
The locations where the top invasive vegetative species are within 200 feet of chinook streams.



Appendix E10: IVS Presence on Chum Streams

The locations where the top invasive vegetative species are within 200 feet of chinook streams.

User: Danielle Green Date: March 2021 The Evergreen State College

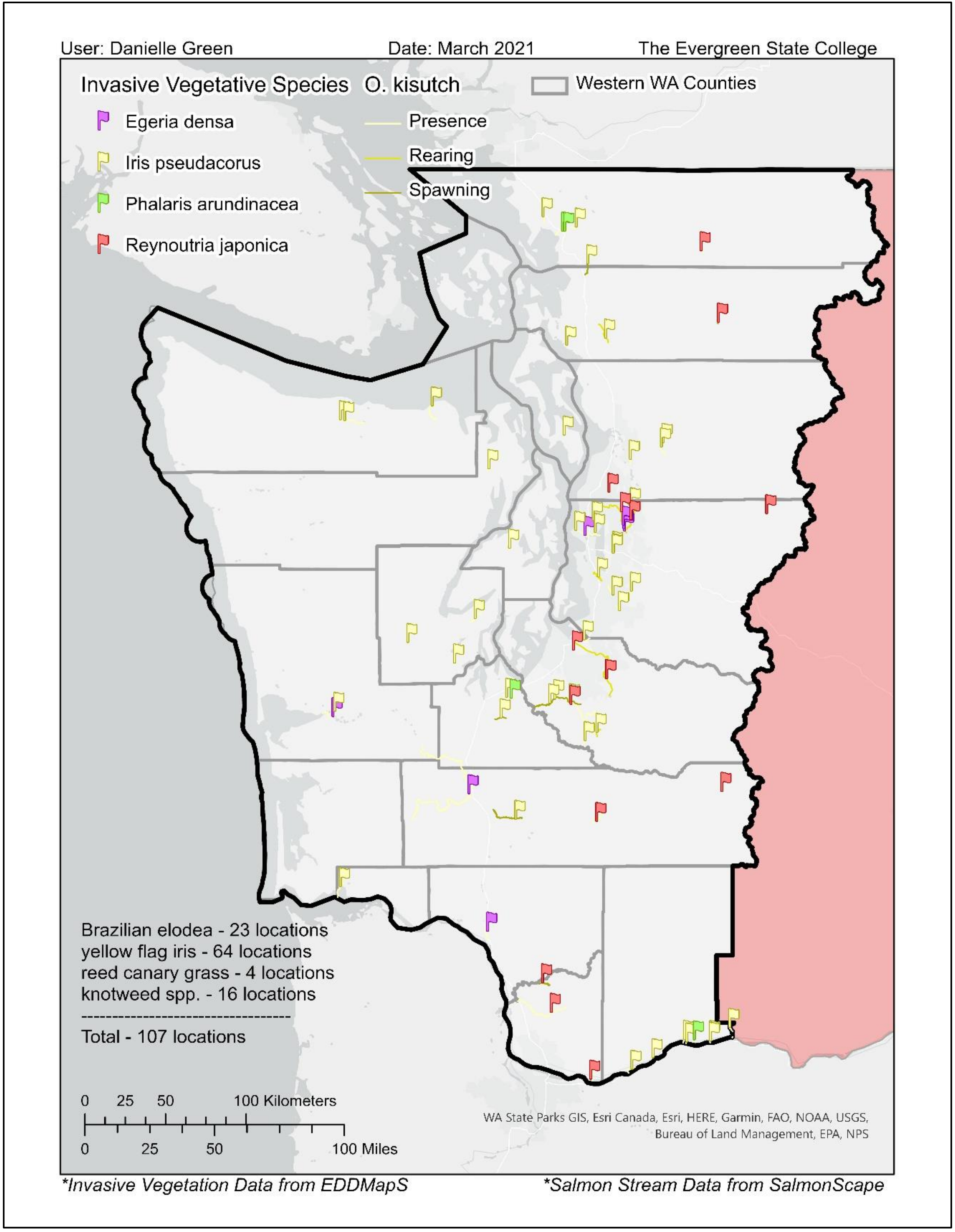


WA State Parks GIS, Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, Bureau of Land Management, EPA, NPS

**Invasive Vegetation Data from EDDMapS* **Salmon Stream Data from SalmonScape*

Appendix E11: IVS Presence on Coho Streams

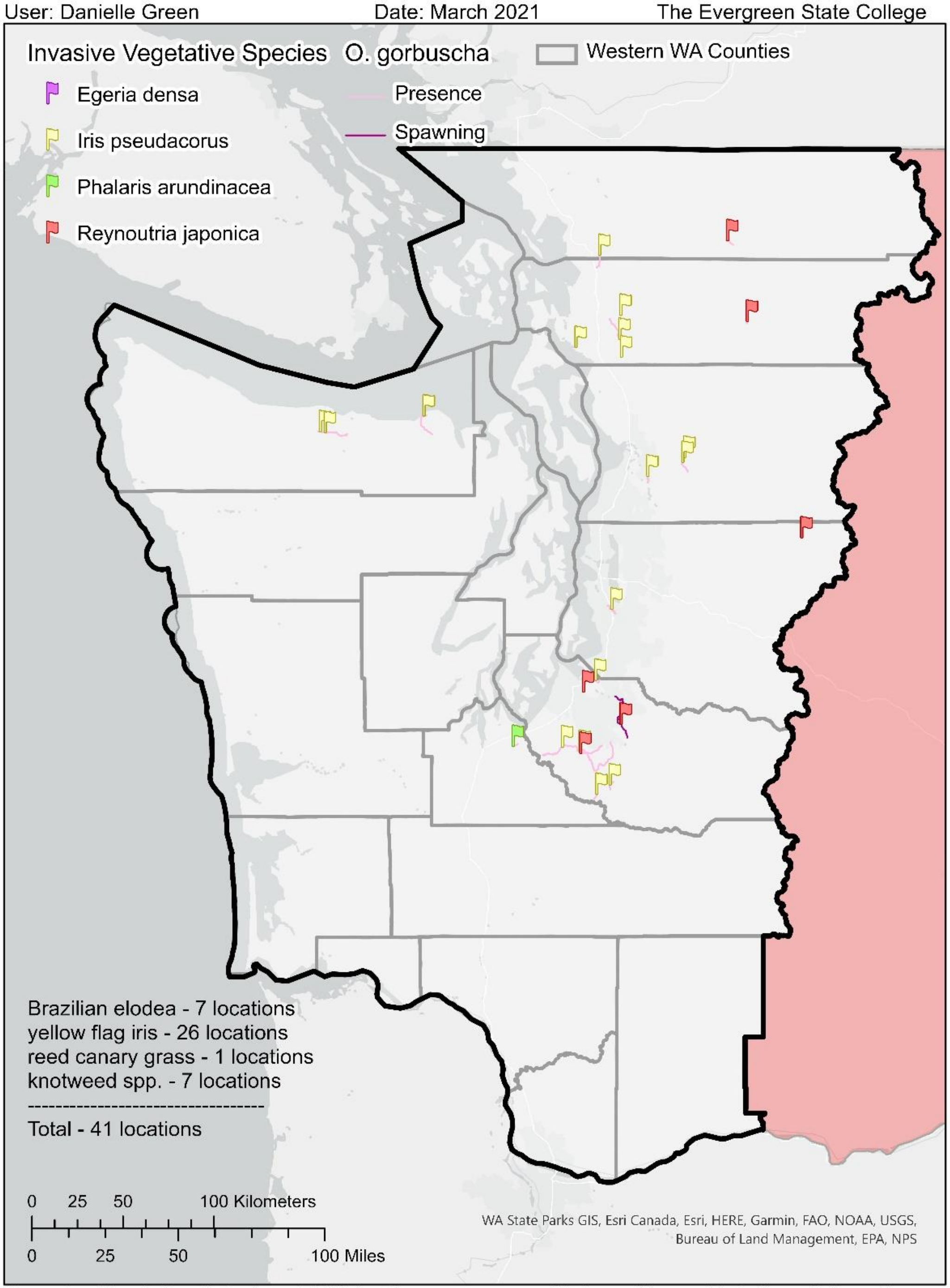
The locations where the top invasive vegetative species are within 200 feet of coho streams.



Appendix E12: IVS Presence on Pink Streams

The locations where the top invasive vegetative species are within 200 feet of pink streams.

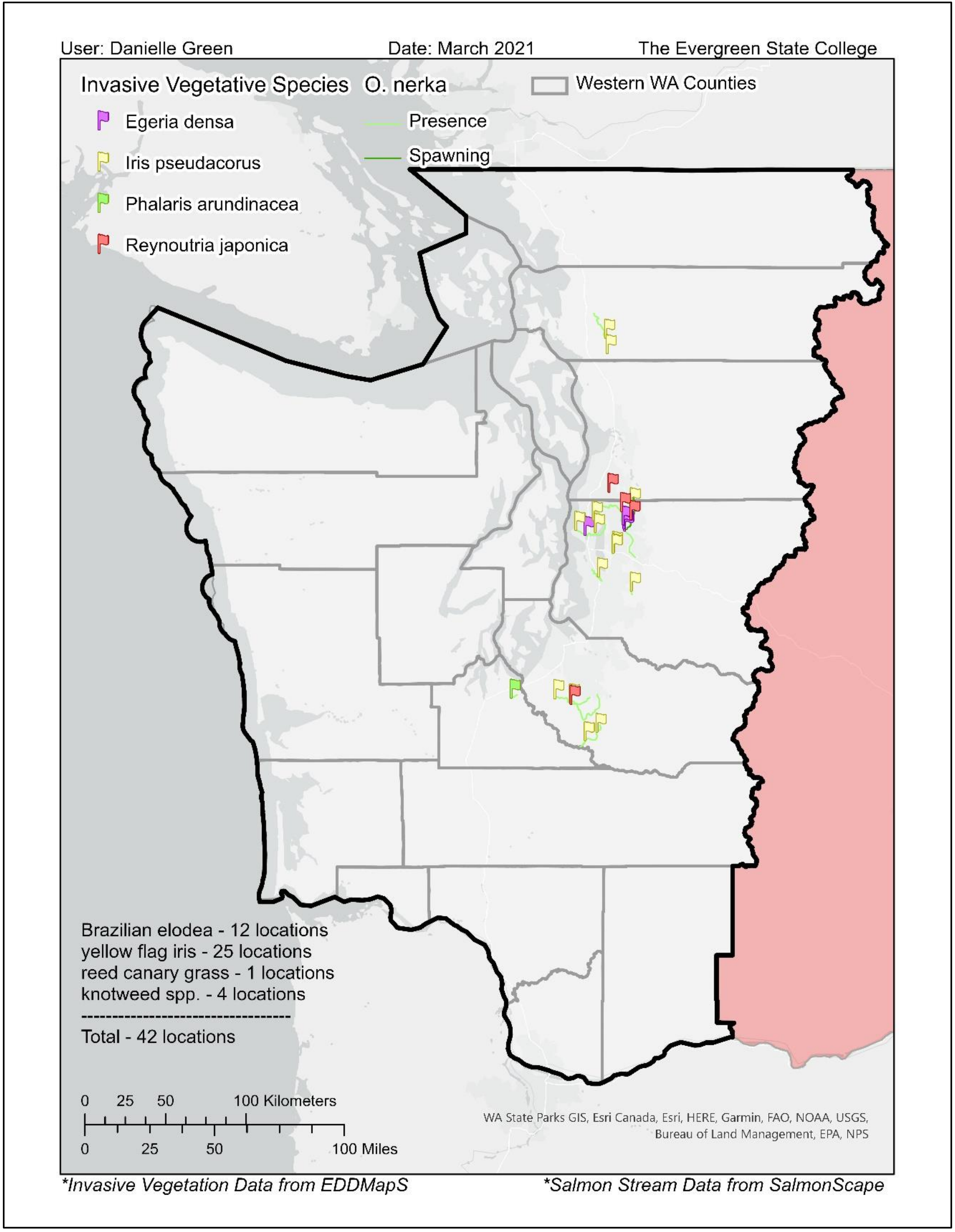
User: Danielle Green Date: March 2021 The Evergreen State College



**Invasive Vegetation Data from EDDMapS* **Salmon Stream Data from SalmonScape*

Appendix E13: IVS Presence on Sockeye Streams

The locations where the top invasive vegetative species are within 200 feet of sockeye streams.

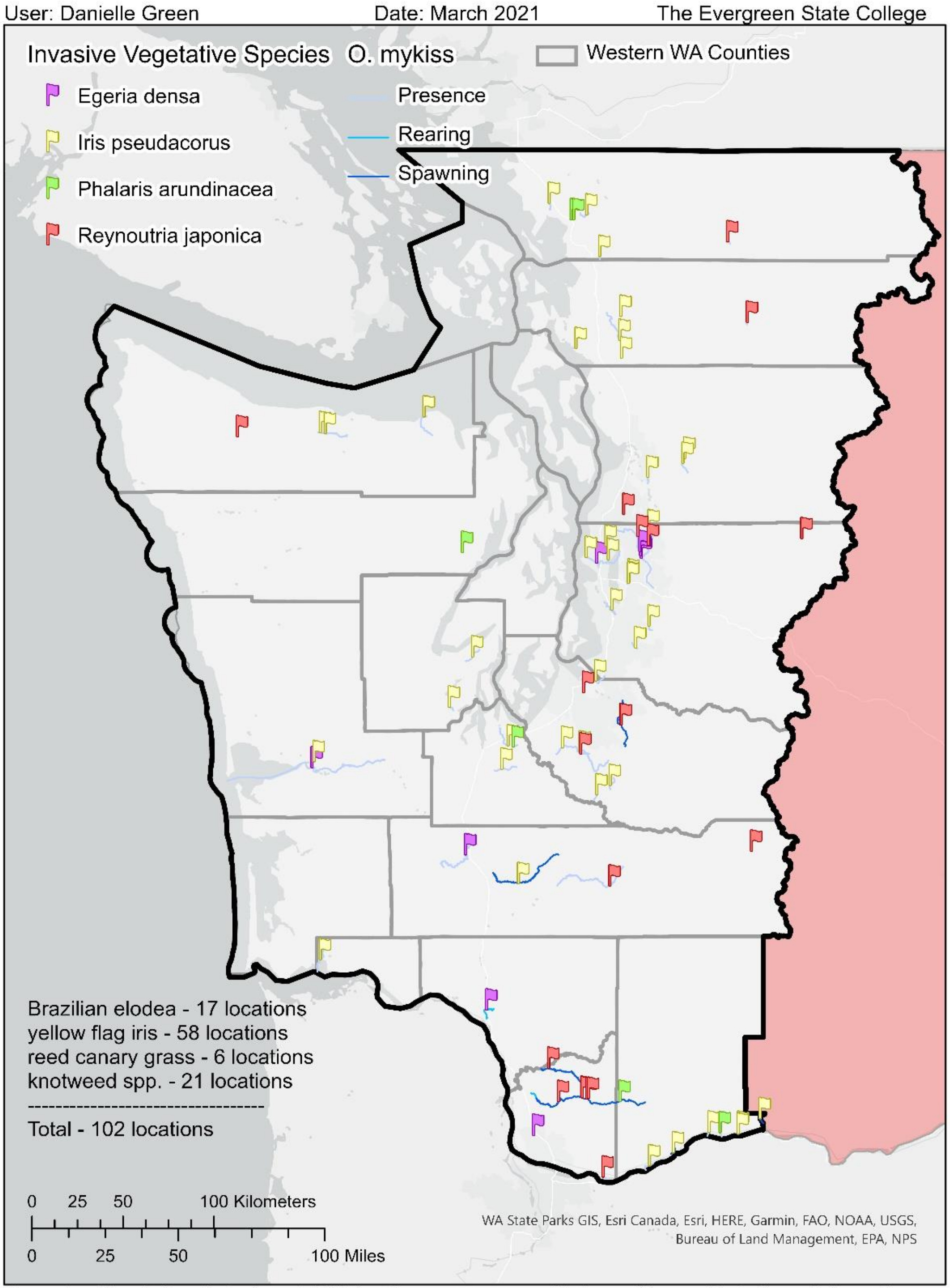


**Invasive Vegetation Data from EDDMapS*

**Salmon Stream Data from SalmonScape*

Appendix E14: IVS Presence on Steelhead Streams

The locations where the top invasive vegetative species are within 200 feet of steelhead streams.



**Invasive Vegetation Data from EDDMapS*

**Salmon Stream Data from SalmonScape*