Capstone Study

Invasive Species in Riparian Habitats of Washington: Using Species Distribution Models to Guide Monitoring Efforts

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Contents

Abstract

Riparian ecosystems provide critical habitat for a broad diversity of aquatic and terrestrial species. However, due to their connectivity along river corridors, and the tendency for people to build roads, infrastructure, and other settlements next to rivers, riparian ecosystems are vulnerable to colonization by invasive plant and animal species. Early Detection and Rapid Response (EDRR) is vital for monitoring and managing novel invasions as well as population expansions of known invasive species. Species distribution modeling (SDM) can be used to identify high priority locations for monitoring to catch early colonization by invasive species when there is still time for complete eradication. This case study targeted 8 invasive plant and animal species of concern to forest managers that are associated with riparian habitats. A literature review was completed to understand the biological and ecological factors that influence potential species distributions. Species distribution models were created for the 8 plant and animal species using Maxent program and bioclimatic variables. Generally, model results show high predicted suitability in the Puget Sound for all 8 species, with lower predicted suitability in the northeastern portion of the state. This paper demonstrates how SDM can be used to identify potential species distributions of invasive species thereby allowing forest managers to identify new infestations and plan cost-effective and efficient early detection monitoring efforts. With swift eradication efforts managers can minimize the impact that new infestations of invasive species have on riparian forests.

Introduction

Riparian Habitat

The riparian ecosystem is considered a vital transitional zone connecting terrestrial and aquatic ecosystems (Everest and Reeves 2006). In the Pacific Northwest, the riparian forest ecosystem is the transition between forest and freshwater environments include riverbanks, floodplains, and wetlands. These forest riparian ecosystems are resilient and provide critical habitat for a variety of aquatic and terrestrial species including threatened and endangered trout such as Chinook salmon (*Oncorhynchus tshawytscha*) and bull trout (*Salvelinus confluentus*). The forested rivers and streams provide vegetation cover to regulate stream temperatures and allows for the recruitment of large woody debris. Throughout the world, riparian zones are recognized for the complexity of species they support, and the habitats that they provide (Naiman and Decamps 1997). These critical riparian zones provide ecological functions such as streamflow, water quality, stream nutrients and complex habitats for a variety of fish and wildlife (Everest and Reeves 2006).

Riparian habitats also provide important ecosystem services for human populations by removing excess nutrients and sediments from water (Lee et al., 2003, Poff et al., 2012). Urbanization has drastically altered the watersheds and hydrology of Washington State. Increased surface water runoff from urban developments can lead to surges of pollutants and sediments into local waterways from storm events. Discharges of water and pollutants poses extreme risks to survival of fish and wildlife (Burton and Pitt 2002), as does chronic pollution from roads (Tian et al. 2020). Riparian habitats help to mitigate and minimize the effects of storm events by naturally filtering and lowering pollutants in waterways from agriculture and municipal water runoff thereby cleaning water. Riparian areas are inherently resistant to change associated with predictable cyclical patterns of river flow and flooding. However, riparian ecosystems that are resilient to natural changes and disturbance are still vulnerable to colonization by invasive plant and animal species. Management of riparian habitats is vital to protect the diversity and maintain the ecosystem services that they provide.

Invasive Species

Invasive species alter the communities and structures of the ecosystems they invade (Mack et al., 2000). With time, invasive species can influence the native flora and fauna as they manipulate and modify their surroundings and can outcompete native species. For example, scientists in Europe and North America have reported that invasive Japanese knotweed leads to a reduction of native plants and invertebrate species abundance and richness (Gerber et al. 2008; Claeson et al. 2014). This decreased species abundance and diversity can change the composition of native plants in riparian forests and thus change the ecosystem benefits that these forests provide. Invasive species may also impact the abiotic components of the ecosystem. These abiotic factors include physical structure, nutrient availability, and water temperature and depth (Simberloff 2013). One example of this environmental modification can be found in zebra and quagga mussels that have invaded the soft substrates of Lake Erie, USA (Berkman et al., 2000). These colonies generate a hard substrate with their shells allowing for easier attachment of mussel larvae. These new harder mussel bed substrates lead to changes in water flow dynamics. All these changes are often enough to damage the original ecosystem effecting biodiversity and can have economic impacts through loss of commercial fish or cost of managing invasions (Mack et al., 2000).

Monitoring Invasive Species

Early Detection and Rapid Response (EDRR) is vital for monitoring and managing invasive species (Simberloff, 2013). EDRR allows for practical and effective control or eradication of invasive species before populations become widespread. Common methods for the detection of invasive species include surveys and monitoring programs (Simberloff, 2013). These programs can often be expensive and may suffer from a lack of resources. New advances in technology can help to target monitoring resources more effectively.

Species distribution modeling (SDM) can be used to identify high priority locations for monitoring and identify potential locations of new infestations. Species distribution modeling methods can be used to visualize a distribution where a species may occur. The generated models can be mapped to visually represent the fundamental niche of a species, essentially where a species could occur. This is separate from the realized niche, where a species currently occurs. SDM uses environmental, and species occurrence data to extrapolate the distribution of a species using statistical models (Franklin 2010). SDM can be used for understanding invasive species and their potential establishment zones.

Social, Cultural, and Ethical Considerations for Invasive Species Management

Invasive species can pose threats to the health of forested riparian habitats across Washington state. While understanding the biological and ecological aspects of this natural resource issue is crucial, it is also important to consider the social, cultural, and ethical aspects. Recreation is a large and important industry in the United States including Washington State. It is estimated that half of the adult population in the United States participates in either hunting, fishing, birdwatching, or wildlife photography (Jones. 2008). Washington has a large recreation industry that heavily utilizes aquatic waterways and their associated riparian environments. Approximately 75% of outdoor recreation opportunities in the United States occur just one-quarter mile from waterways (Swanson. 2008) which is a concern because recreationalists can be a vector for the distribution and introduction of invasive aquatic species. Preventing, monitoring, and controlling invasive species and education of recreationists is crucial in sustaining the recreation industry that provides both economic and social importance to the region.

Public opinion can conflict with invasive species management at times due to a portion of the public does not see a justification for the killing of invasive species for the benefit of native species (Cowan et al. 2011).

Objectives

There are two objectives of this study: First, examine and review literature of targeted invasive species of concern to forest managers in Washington state (Table 1). Second, develop species distribution models for these target species using relevant environmental data and Maxent software. The invasive species identified for this study were first identified by aquatic managers at the USDA Forest Service, Region 6, in collaboration with other invasive species experts and include aquatic animals, aquatic plants, and terrestrial plants. The species were identified due to their potential economic and environmental impacts in relation to their high chance for invasion and establishment in forested environments (Flitcroft et al., 2016). These species are reviewed to better understand their life history and the environmental characteristics and conditions that may influence the occupancy of these species in riparian habitats and other habitats in the state of Washington. This contributed to the identification of environmental parameters applicable to use in modeling. SDM helps examine and understand regions of concern for current and future invasions that can help guide future monitoring efforts to identify new infestation locations.

Table 1: Target Invasive Species List

Type	Common Name	Scientific Name	Documented in Washington State
Aquatic Animals	New Zealand mudsnails	*Potamopyrgus antipodarum*	Yes
	Bullfrog	*Rana catesbeiana*	Yes
	Chinese mystery snail	*Cipangopaludina chinensis*	Yes
Aquatic Plants	Eurasian Watermilfoil	*Myriophyllum spicatum*	Yes
	Brazilian elodea	*Egeria densa*	Yes
	Flowering rush	*Butomus umbellatus*	Yes
Terrestrial Plants	Japanese knotweed	*Reynoutria japonica*	Yes
	Giant knotweed	*Polygonum sachalinese*	Yes

Review of Literature on Select Washington Invasive Species

Potamopyrgus antipodarum (New Zealand mudsnail)

Introduction

Potamopyrgus antipodarum is an aquatic snail in the family Hydrobiidae. It is commonly known as the New Zealand mudsnail. It is found in fresh to brackish water inhabiting areas such as lakes, rivers, and reservoirs. The New Zealand mudsnail is native to New Zealand and was introduced into the United States in 1987. It has quickly spread to a variety of waterways in Washington. The New Zealand mudsnail can impact the ecology of regions it inhabits through its influence on trophic food webs.

Biology

Biological Description

The New Zealand mudsnail is an aquatic prosobranch snail. The shell of the snail varies in color from a gray to brown. The shell grows in a right-handed spiral consisting of 5 to 7 whorls measuring from 4 to 6 mm in size that can be seen in Figure 1 (Hoddle 2020). The mudsnail also has an operculum that covers the mouth of the shell when the animal is inside of the shell (Alonso 2013).

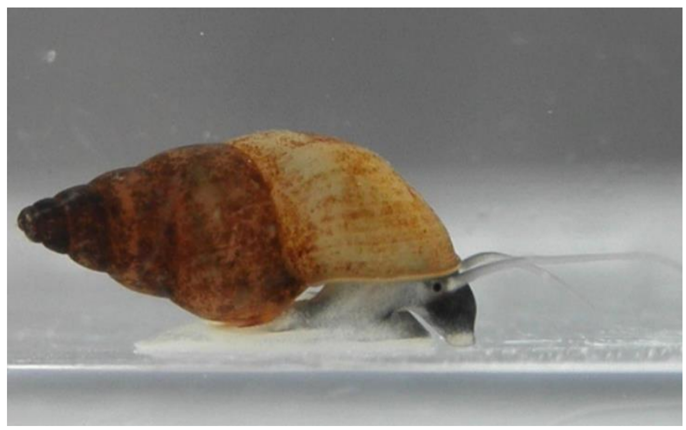

FIGURE 1: NEW ZEALAND MUDSNAIL (PHOTO CREDIT: MICHAL MAŇAS, 2014)

Lifespan

The natural life span for the New Zealand mudsnail is unknown, however, in captivity they can live approximately a year (Gustafson et al., 2004).

Diet

The New Zealand mudsnail is a nocturnal grazer that consumes plant and animal detritus, algae, sediments, and diatoms (Kelly and Hawes 2005, James et al. 2000).

Reproduction

The New Zealand mudsnail has a high reproductive rate. They can produce on average 230 offspring in a year (Gerard and Krist 2004). Most New Zealand mudsnails found in the United States are believed to be female (Alonso 2013). Reproduction timing has been linked to water temperature. Warmer water temperatures can increase reproduction rates leading to peak reproduction rates in the summer. The mudsnail is ovoviviparous and parthenogenic which influences the high reproductive rates and speed in which populations increase (Benson et al. 2020a).

Ecology

Environmental Factors Affecting Occurrence and Growth.

The New Zealand mudsnail is found in fresh to brackish water. It is typically found in waters with salinity less than 2.6 ppt but is known to be able to survive in higher salinity for short periods of time. One study showed the mudsnail being able to survive in up to 3ppt for seven days (Hylleberg and Siegismund 1987).

The New Zealand mudsnail is unable to withstand complete desiccation. It needs permanent waterbodies that maintain water throughout the seasons. However, some studies have found that New Zealand mudsnails are able to survive short periods of time out of water. Researchers have found that the New Zealand mudsnail are able to survive at least 48 hours on a damp substrate or up to 50 days on a wet substrate or at least 48 hours on a damp substrate (Richards et al., 2004, Winterbourn 1970).

The snails are susceptible to freezing and cannot survive water temperatures below 0° C (Hylleberg and Siegismund 1987). Experiments show complete mortality if the snail is exposed to freezing temperatures for at least 3 days (Moffitt and James, 2012). The New Zealand mudsnail is found in water depths less than 25 meters which may limit the spread and establishment to certain bodies of water (Zaranko et al. 1997).

Establishment in the United States

The New Zealand mudsnail is native to New Zealand. It was first documented in North America in 1987 in the Snake River of Idaho (Zaranko et al., 1997). They have been introduced to the United States multiple times and are able to establish in a wide variety of habitats such as temperate streams, coastal waterways, and lakes (Bennett et al., 2015). One method of introduction is believed to have been through ship ballast water (Zaranko et al., 1997).

Aquatic recreationists and anglers are another vector of spreading (Richards et al. 2004). The small mudsnail can attach to boots, boats, and other aquatic recreational gear allowing for transportation to different bodies of water.

Effects on Invaded Systems

The ecological impacts of New Zealand mudsnails have been shown to negatively impact native organisms. They have been shown to impact the trophic food web when populations increase in regions where they are established. The New Zealand mudsnail can reach densities of 28,000 snails per square foot of substrate and can comprise up to 95% of invertebrate biomass in such systems (U.S. Department of the Interior 2020). This dense biomass increases resource competition for other species and results in the mudsnail becoming the primary invertebrate food source for fish, birds, and other wildlife that utilize these waterways. Rainbow trout (*Oncorhynchus mykiss*) whose diet consists only of the New Zealand mudsnails were found to lose body weight each day (U.S. Department of the Interior 2020). Decreased body condition and growth rates of other fish species with New Zealand mudsnails in their stomach has also been reported (Vinson & Baker, 2008). The mudsnail has been shown to be a poor food source for many native fish species in the United States.

Economics

Knowledge of how New Zealand mudsnails impact the economy is limited. It is believed that trout fisheries are negatively impacted in regions where New Zealand mudsnail densities are high due to the mudsnail being a poor source of food (Vinson & Baker, 2008). There is also concern that this same impact could be seen in Chinook salmon, rainbow trout, and steelhead trout fisheries in the Pacific Northwest (Oregon Sea Grant, 2019).

Lithobates catesbeianus (American Bullfrog)

Introduction

Lithobates catesbeianus is an amphibian frog in the family Ranidae. It was previously known as *Rana catesbeiana* and is commonly known as the American Bullfrog (Figure 2). It is found in slow moving freshwater habitats such as lakes, reservoirs, wetlands, and ponds. The American bullfrog is native to the central and eastern United States and introduced to the western United States in the early 1900s. The bullfrog was able to spread quickly in the western United States where it competes with and preys upon local native species. *Lithobates catesbeianus* is commonly found throughout the lowlands of Washington State (Invasive Species Council 2016).

Biology

Biological Description

FIGURE 2: AMERICAN BULLFROG (PHOTO CREDIT: BRETT M. 2018)

Lithobates catesbeianus is the largest frog species in North America weighing up to 0.5 kg. It reaches a size of approximately 17 to 25 cm length with outstretched legs (Bruening 2002). The skin of the bullfrog varies from brownish to green with varying spots or splotching as seen in 2. The hind feet of the frog are webbed. Females and males can be visually differentiated by the size of the tympanum. Males have tympanums that are larger than the eye while for females the tympanums are smaller (Bruening 2002).

Lifespan

The American bullfrog has an average life span of 7 to 9 years in the wild, and up to 16 in captivity (Bruening 2002).

Diet

The American bullfrog is an opportunistic omnivorous with a wide and varied diet. The adult bullfrog will consume insects, crustaceans, frogs, tadpoles, salamanders, fish, reptiles and occasionally small mammals and birds (Graves and Anderson 1987) as well as other bullfrogs. (Bruening 2002). The bullfrog tadpole primarily feeds on algae and diatoms (Graves and Anderson 1987).

Reproduction

American bullfrogs have a long mating season and breed once per year typically between May and July in the northern states (Bruening 2002, Emlen 1976). Bullfrogs reproduce in permanent bodies of water where water depth fluctuation is minimal. The female bull frog can produce 1000 to 40,000 eggs that hatch in approximately 3 to 5 days (Snow and Witmer 2009). Bullfrogs reproduce utilizing external fertilization (Bruening 2002). Once the eggs have hatched, the tadpoles will overwinter for 1 to 2 years in the northern states (Harding 1997). The male and female bullfrogs reach sexual maturity between 3 to 5 years old.

Ecology

Environmental Factors Affecting Occurrence and Growth

American bullfrogs require permanent bodies of water to allow for reproduction, overwintering of tadpoles and adults. The American bullfrog is vulnerable to desiccation and freezing if water levels drop because they typically hibernate in the mud (Graves and Anderson 1987). This requirement prevents the American bullfrog from establishing in seasonal wetlands and other temporary waterways. The American bullfrog is well adapted to warmer water temperatures. The eggs require temperatures higher than 15°C to develop and breeding occurs at air temperatures higher than 27°C (Viparina and Just 1975, Howard 1978). However, water temperatures higher than 31°C will impact egg development (Degenhardt et al. 1996). The critical thermal maximum for bullfrogs is 38.2°C (Lillywhite 1970).

American bullfrogs require both shallow and deep water. Shallow water is important for tadpole growth and temperature regulation for adults and deep water is important to escape predators. American bullfrogs need to have access to waters of 1.5 m deep or greater along with shallow shoreline areas (Graves and Anderson 1987). The pH of the water can impact hatching of bullfrog eggs. The American bullfrog needs a water pH of 4.3 or higher for effective hatching (Graves and Anderson 1987). The tadpoles and eggs are susceptible to salinity of 6ppt or higher (Ward et al., 2015).

Establishment in the United States

The American Bull Frog is native to the central and eastern United States. It was introduced west of the Rocky Mountains in the early 1900's as a human food source and populations quickly expanded (Sinow and Witmer 2009). The frogs were raised in aquaculture where some were able to escape from captivity. Some were also introduced to local ecosystems to create naturally producing populations (Gherardi and Scalera 2007).

Effects on Invaded Systems

American bullfrog readily consumes native frog species contributing to declines in species-specific distributions, and local biodiversity. For example, correlations have been observed between the absence of the California red-legged frog (*Rana aurora draytonii*) and the presence of the American bullfrog (Doubledee et al., 2003). The American bullfrog has also been shown to compete for the same food sources as native frogs. Further, they mat alter life stage transition timing for native species leading to changes in the onset of metamorphosis in native frogs and salamanders (Boone et al. 2004). However, some studies have observed that predation by bullfrogs may not be a significant factor of decline of native frog populations compared to changes in habitat structure and presence exotic fish, especially in the Puget Sound Region of Washington state (Adams 1999.)

Economics

The economic impact of invasive populations of bullfrogs in the Pacific Northwest is not clear. There is some indication that American bullfrogs can be positive for the economy as a food source and they are also a popular research specimen (Snow and Witmer 2010). Current attempts at eradication are difficult and have not been economically feasible (Gherardi 2007).

Cipangopaludina chinensisis (Chinese Mystery Snail)

Introduction

Cipangopaludina chinensisis is a gastropod from the family Viviparidae. It is also referred to by the scientific names *bellamya chinensis*, and *viviparus malleatus* (Kipp et al. 2020). It is commonly known as the Chinese mystery snail, Asian applesnail, or trapdoor snail. It is found in slow moving and standing fresh water inhabiting areas such as lakes, ponds, ditches, and streams (Global Invasive Species Database 2015). The Chinese mystery snail is native to East Asia and was introduced into the United States in the 1890's. The Chinese mystery snail impacts trophic food webs in the regions that they invade. The Chinese mystery snail was first documented in Washington in 1970 and is now found in many lakes across the state (Olden et al., 2009).

FIGURE 3: CHINESE MYSTERY SNAIL (PHOTO CREDIT: ODFW 2010

Biology

Biological Description

Cipangopaludina chinensis is a freshwater snail with a large spherical shell with an operculum (Figure 3). The operculum is why this snail is often referred to as a "trapdoor" snail. The shell is lighter colored in juveniles deepening into an olive green to brown coloration as the snail matures.

Lifespan

The lifespan of Chinese mystery snail is approximately 4 to 5 years with females living longer than males (Jokinen 1982).

Diet

The Chinese Mystery Snail is a non-selective filter feeder and detritivore that feeds on inorganic and organic matter (Jokinen 1982). This nonselective feeding makes the mystery snail a popular aquarium organism.

Reproduction

The Chinese mystery snail is ovoviviparous and has a high fecundity. The female mystery snail can contain as many as 133 embryos at a time in its brood pouch but the average number of embryos per female per year is between 27.2 and 33.3 (Stephen et al. 2013). As the female grows larger, so does its brood pouch, allowing for higher fecundity.

Ecology

Environmental Factors Affecting Occurrence and Growth

The temperature thresholds *of Cipangopaludina chinensis* have been tested. One study found the Chinese mystery snail can withstand high water temperatures of 40°C to 45°C. The same test also exposed the snail to freezing temperatures for extended periods of time, but the snail was not affected showing that the mystery snail has a high tolerance for cold (Burnett et al. 2018). The mystery snail can survive at least four weeks in air exposure depending on the humidity. Higher humidity allowed for increased tolerance of air exposure (Havel 2010). The snail occurs at water depths of 0.2 to 3 meters (Kipp et al. 2020). The mystery snail is found in a pH range of 6.5 to 8.4. Low pH affects the calcium of the snail's shell (Jokinen 1982).

Establishment in the United States

The Chinese mystery snail is native to east Asia where it is a food item in Chinese markets. The first introduction to North America was in the early 1890's. The mystery snail has been introduced in regions through intentional and unintentional means. The snail was sold in food markets of San Francisco in the 1890's where it was likely released into local waterways (Kipp et al. 2020). These snails are also sold in the aquarium trade. There have also been incidents of these snails being released through aquarium dumping. For example, from 1931 to 1941 the Chinese mystery snail was documented to have been released into the Niagara River from a local aquarium (Milles et al. 1993).

Another significant factor in the spread of the mystery snail has been through recreational boating. The mystery snail, especially juveniles, are found on aquatic plants. When the plants get attached to boats, the snail can be transported along with the plant to other waterways (Havel 2010). The earliest appearance in Washington State was in 1965 when a specimen was collected in Green Lake, Seattle (Kipp et al. 2020).

Effects on Invaded Systems

Documentation of the ecological effects of the Chinese mystery snail are limited. Some studies have shown that the Chinese mystery snail may compete with native species for food. Lab studies have found that the Chinese mystery snail can cause decreases in populations of native gastropods *Physella gyrina* and *Lymnaea stagnalis,* however, this has not been demonstrated in field studies (Johnson et al., 2009, Solomon et al., 2010). The Chinese mystery snail can reduce algae biomass and algae species composition through grazing which can then increase the nitrogen and phosphate ratio of the water column (Johnson et al., 2009). Some studies have found that Chinese mystery snails are becoming a prey substitute in lakes where native snail populations are decreasing (Twardochleb and Olden, 2016). This ample supply of mystery snails as a food source are may also assist in the establishment and success of other invasive species such as invasive crayfish in Washington state (Olden et al., 2009).

Economics

The economic impact of the Chinese mystery snail has not been well researched and remains unknown. The snail is a popular aquarium and pond snail. The mystery snail is also a carrier of parasites that can potentially infect humans and other native shellfish (Kipp et al. 2020). This could lead to economic impacts in regions where populations become dense. Another potential economic impact can occur when large die offs of the Chinese mystery snail occurs. Large die offs can result in decaying snails and shell buildup up along beaches which can limit and reduce recreation to the region (Bury et al. 2007).

Myriophyllum spicatum (Eurasian Watermilfoil)

Introduction

Myriophyllum spicatum is a perennial aquatic plant from the family Haloragaceae. It is commonly known as Eurasian watermilfoil. It is found in fresh to brackish water inhabiting areas such as lakes, rivers, and reservoirs. Eurasian watermilfoil is native to Europe, Asia and Northern Europe and was introduced into the United States in 1881 (Mills et al. 1993) and quickly spread impacting local ecosystems and recreation opportunities waterways. It was first observed in Washington State in 1965 and was found in 150 lakes in Washington as of 2014 (Pfingsten 2020)

Biology

Botanical description

Myriophyllum spicatum is a submerged perennial aquatic plant that has finely dissected leaves in a whorl around the stem. The leaves contain 12-24 leaflets that produce a feather-like appearance (Figure 4; Prather et al., 2007). The stems are smooth and display a green, brown, or pinkish color. The flowers grow on inflorescence that form on terminal spike on the plant allowing it to float above the water for pollination (Smith and Barko 1990). The small yellow flowers are grouped in fours with male flowers higher up the inflorescences and females lower. The female flowers produce a hard-segmented seed capsule that contains four seeds (Prather et al., 2007).

FIGURE 4: EURASIAN WATERMILFOIL (ZIKA 2016)

Eurasian watermilfoil produces roots along buried portions of the stem and can produce roots along nodes when fragmentation occurs (Smith and Barko, 1990).

Pollination

Flowers of Eurasian milfoil flower between June and September. Pollination occurs while the flowers are exposed to wind above the water's surface (AERF 2014).

Seed production and dispersal

The fruit of the plant can float on the surface before dispersing. The seed of this plant can exhibit dormancy, but germination of seeds is limited (Prather et al., 2007). This limited germination results in minimal spread of Eurasian watermilfoil by seed.

Vegetative reproduction

Eurasian watermilfoil can spread vegetatively through stem fragmentation and stolons. Stolons from the plant allow for short distance spread. The reproduction through stem fragments allow this plant to spread greater distances. This fragmentation can occur naturally or mechanically. The plant produces roots from the nodes of the plant after fragmentation occurs (Smith and Barko 1990). These fragments are primarily carried to new waterways through human recreation activities such as boating and fishing gear or by the improper disposal of aquarium materials (AERD 2014).

Ecology

Environmental Factors Affecting Occurrence and Growth

Eurasian watermilfoil's ability to grow and spread are influenced by certain environmental factors. One factor is the clarity of the water that the plant is growing in. The depth in which milfoil can occur is determined by the clarity of the water. Waterways that are more turbid or have limited clarity restricts the depth in which milfoil can occur (Smith and Barko 1990). Typically, Eurasian watermilfoil occurs at depths of 1 to 4 meters but has been found at depths up to 10 m (Nickols and Shaw, 1986., Aiken et al. 1979). Another important factor in occurrence is water temperature. The plant can grow and photosynthesize between 15°C and 35°C which allows the plant to occur across a wide thermal range (Smith and Barko 1990). The plant is not able to withstand freezing temperatures (Stanley 1976). The plant is also intolerable to desiccation, preventing it from establishing in non-perennial waterways.

Establishment in the United States

Eurasian watermilfoil is native to Europe and Asia. It was first documented in the United States in 1881 (Mills et al. 1993). It was introduced intentionally through the aquarium and aquatic garden trade (Reed 1977) and is now found in 48 states (Pfingsten 2020). It is often transported to different waterways on recreational equipment. This transportation allows fragmented plant segments to establish in new waterbodies. In Minnesota, road checks found Eurasian watermilfoil comprised 23% of all aquatic vegetation found on boats (Bratager 1996). Eurasian Watermilfoil was first discovered in Washington State in 1965 and can now be found in 150 lakes in Washington as of 2014 (Pfingsten 2020)

Effects on Invaded Systems

Eurasian watermilfoil can outcompete native vegetation in aquatic habitats when it becomes established. Watermilfoil can grow extremely dense and shade out competing vegetation (Madsen et al., 1991). In habitats invaded by Eurasian watermilfoil, a decline in both abundance and species diversity of native vegetation has been observed (Boylen et al., 1999). When this vegetation decays in the Fall, oxygen can be quickly depleted in lakes resulting in fish die offs (Engle 1995). The dense vegetation has also been shown to reduce the number and diversity of invertebrates that are important food sources for small fish (Keast 1984). While this vegetation can help provide cover for smaller fish, it has negative effect on foraging for larger fish (Engle 1995).

Economics

Eurasian watermilfoil infestations can be aesthetically unappealing and impact recreation to waterbodies. Dense mats of Eurasian milfoil can restrict swimming, fishing, boating, and clog water intakes (Pfingsten 2020). The plant can also wash up on beaches and shorelines where it decays and becomes a nuisance. A study in Vermont has shown Eurasian watermilfoil infestations have significant effects on lakefront property values (Zhang and Boyle 2010).

Egeria densa (Brazilian Elodea)

Introduction

Egeria densa is a perennial aquatic plant from the Hydrocharitaceae family (Figure 5). It is known commonly as Brazilian elodea, giant elodea, and anacharis. Brazilian elodea is native to South America and was introduced to United States in 1915 as a part of the aquarium trade (Cook & Urmi-König 1984). The invasion of Brazilian elodea impacts aquatic recreation, agriculture and hydroelectric generation requiring costly removal. It is currently found in many Western Washington lakes (Haubrich 2018).

Biology

Botanical Description

Egeria densa is a submerged perennial plant that resides in freshwater systems. *Egeria densa* is identified by its bright green finely serrated leaves that grow in whorls of four along an erect stem (Knoke, 2003). The plant has small internodes giving the plant a very leafy appearance (Figure 5). The female plant produces small white three petaled flowers that appear on the surface of the water. Fruits are ovate and transparent measuring 7-8 mm long that produces many seeds (CABI 2018). *Egeria densa* can produce roots from nodes along the stem.

FIGURE 5: EGERIA DENSA (PHOTO CREDIT: BEN LEGLER)

Pollination

Brazilian elodea produces dioecious flowers characterized by three white petals. These flowers are attached to the top of the growing portions of the plant with a thin hypanthium (Walsh et al., 2012). This structure allows the flowers to float on the surface. The flowers of the Brazilian elodea flowers between July to September (Knoke 2003). The flowers can also be present under the surface of the water. When flowers are above the water surface they are pollinated by insects (Walsh et al., 2012).

Seed Production and Dispersal

The seeds of Brazilian elodea can remain dormant through the winter before germinating once temperatures reach 15°C (Pfingsten et al. 2018). Only male plants have been found to be present in the United states meaning reproduction by seed is currently not a method of spread.

Vegetative Reproduction

Brazilian elodea has a fast growth rate. Vegetative reproduction of Brazilian elodea can occur. Brazilian elodea can root from nodes of the plant allowing for new plants to establish from plant fragments (Walsh et al., 2012). The fragment of elodea must contain at least two nodes to be able to establish roots. These fragments continue growing as a free-floating plant or take root in the sediment of the waterway (Pfingsten et al. 2018). This vegetative reproduction is the primary means of reproduction in the United states due to only male plants being present.

Ecology

Environmental Factors Affecting Occurrence and Growth

Brazilian elodea is an aquatic plant that inhabits lentic and lotic freshwater systems (Yarrow et al., 2009). It typically roots in 1 to 2-meter depths but has been observed at a 7-meter depth in a lake in Columbia (Carrillo et al. 2006). It is unable to survive desiccation and has low light requirements allowing it to survive in turbid environments. It has an ideal light intensity of 100 lux and begins to experience chlorophyll damage at light levels of 1,250 lux (Pfingsten et al. 2018).

Temperature is known to be the most important factor that regulates growth and occurrence of Brazilian elodea. Peak photosynthesis and growth occur when waters are between 16°C and 28°C (Barko and Smart 1981). At temperatures of 32 °C and above, growth is reduced with fewer shoots and smaller lengths. The lower limits of the temperature range of Brazilian elodea occur at 3°C where the plant typically lie dormant or begin to die (Lacoul & Freedman, 2006). Freezing temperatures are lethal for Brazillian elodea but plants have been observed to survive winters under caps of ice (Haramoto & Ikusima 1988).

When Brazilian elodea becomes dominant in aquatic habitats it impacts trophic dynamics. In its native range, the thick vegetation provides complex underwater structures that support diverse communities of fish, algae, and plankton. The complex vegetative shelter is beneficial for zooplankton and planktivorous fish that prey on phytoplankton. Its dense nature is also able to shade out phytoplankton that are lower in the water column further reducing numbers (Yarrow et al., 2009) and biomass (Mazzeo et al. 2003). Brazilian elodea is also acquiring nutrients through the water column which can limit nutrient availability for phytoplankton (Mazzeo et al. 2003).

Salinity has been shown to impact distribution of Brazilian elodea. Experiments conducted in Chile have shown Brazilian elodea is able to tolerates up to 5ppt salinity concentrations in the field, while lab tests indicate survival up to 8 ppt salinity (Hauenstein and Ramirez, 1986). Greater concentrations of salinity inhibit photosynthesis and growth of roots.

Establishment in the United States

Brazilian elodea was introduced to the United States through the aquarium trade. It was first sold in the United Sates in 1915 where it was recommended for oxygenating aquariums (Cook & Urmi-König 1984). It continued to be sold in pet stores under the name anacharis and became very popular amongst hobbyists. It was sold in pet stores in Washington state as an aquarium plant until 1996 and remains available to purchase in other states (GISD, 2020). It is currently found in many lakes across Western Washington (Haubrich 2018a). The plant was also used as study material in schools to help students learn about photosynthesis in plants (GISD, 2020.) Educators and hobbyists sometimes would improperly dispose of Brazilian elodea into local freshwater environments. This improper disposal allowed elodea to establish and spread in many parts of the United States including Washington. As of 2020 Brazilian elodea has been observed in 38 states (EDDMapS 2020). Brazilian elodea is able invade regions because of its biological characteristics and flexible environmental requirements. Elodea is fast growing with ability reproduce vegetatively allowing for high chance to spread. It is also able to tolerate various nutrient levels, light levels, and temperatures.

Effects on Invaded Systems

When Brazilian elodea invades new ecosystems, it has been shown to have negative effects on ecosystem functions. The dense vegetation can lower biodiversity by competing with native aquatic vegetation eventually completely excluding native species. Dense patches of Brazilian elodea can limit water movement and trap sediments leading to changes in water quality (Hoshovsky and Anderson, 2001).

Economics

Brazilian elodea can have a large impact economically to the regions it invades. Brazilian elodea can reduce recreational water activities as it can become a nuisance for boating, fishing, and swimming. Removal of the plant can be costly. The State of California Department of Boating and Waterways has reported the cost of herbicide treatments for Brazilian elodea costs approximately $750 to $1000 USD per acre (Johnson et al., 2006). In addition to impacts on the recreation industry, elodea also poses problems for irrigation and hydroelectric operations. The dense mats of vegetation can clog waterways and intake pipes and get caught in hydroelectric turbines impacting operations (Yarrow 2019).

Butomus umbellatus (Flowering Rush)

Introduction

Butomus umbellatus is a perennial emergent aquatic plant from the Butomaceae family. It is known commonly as flowering rush (Figure 6). Flowering rush is native to Europe and Asia and was first recorded to United States in 1918 (Columbia Basin Cooperative Weed Management Area, 2019). The invasion of flowering rush was first documented in Washington State in Silver Lake (Coa et al. 2020). In Washington, flowering rush has been documented in Silver Lake, Pend Oreille River, Spokane River and along the Yakima River (Columbia Basin Cooperative Weed Management Area, 2019).

Biology

Botanical description

Flowering rush is an aquatic perennial known to be a wetland obligate. Flowering rush can grow as both an emergent and submerged aquatic plant. The leaves of the plant are thin and upright growing to 3 feet or more. The leaves are triangular at the base and are spongy. The base of the leaves is triangular. The flowers of the plant occur on a cylindrical stalk. The light pink flowers are on an umbrella inflorescence with 20 to 50 flowers. Each flower contains three greenish sepals and six pinkish petals. The flower can produce 200 seeds (Jacobs et al., 2011). The roots are rhizomatous forming dense mats. Diploid populations are also able to produce and can produce bulbils (Eckert et al. 2003).

FIGURE 6: FLOWERING RUSH INFLORESCENCE (PHOTO CREDIT: BEN LEGLER, 2004)

Pollination

The light pink flowers are on an umbrella inflorescence with 20 to 50 flowers. Flowering rush flowers from July to September. The flowers are scented and attract pollinators bees, flies, and lepidopterans for external pollination. Diploid populations of flowering rush have been shown to be able to self-pollinate in addition to external pollination (Eckert et al. 2000).

Seed Production and Dispersal

There are two flowering forms that occur in flowering rush. One flower form is the diploid which is fertile. This fertile form can reproduce by seed, bulbils, and vegetative fragments. Each flower can produce approximately 200 seeds. One study has shown the seeds maintain a 68% viability after 5 years in cold storage indicating a long viability period in water (Les and Mehrhoff 1999). The other form is the triploid form that is considered sterile (Jacobs et al., 2011). This triploid form produces little to no viable seeds meaning reproduction only occurs by vegetative methods (Jacobs et al., 2011). The triploid is the form that is currently found in Washington State.

Vegetative Reproduction

Vegetative reproduction is the primary means of spread for flowering rush in Washington State. The roots are rhizomatous and can fragment from even minor disturbances. The fragments can float on the surface of the water allowing for disbursement (Parkinson et al. 2010). The roots of the diploid variety can produce bulbils which can dislodge allowing for further vegetative reproductions. Experiments have shown that one diploid plant can produce as many as 300 bulbils a season (Eckert et al. 2003). The plants typically senesce from September to October resulting in the leaves dying back to the rhizomes (Columbia Basin Cooperative Weed Management Area, 2019).

Ecology

Environmental Factors Affecting Occurrence and Growth

Flowering rush is a freshwater species that is found in shallow wetlands, lake shorelines, irrigation ditches or along slow-moving rivers (Columbia Basin Cooperative Weed Management Area, 2019). Water currents should be less than 2 mph for establishment (Parkinson et al. 2010). As an emergent plant, individuals grow in waters up to 3 meters deep. When submerged it can grow in waters as deep as 6.1 meters (Jacobs et al., 2011). Aquatic habitats with fluctuating water levels, such as those influenced by dams, further increase establishment of flowering rush. This is due to drawdown of water around dams providing more exposed soils for vegetative fragments to establish and warmer water temperatures that promote sprouting (Hroudova et al., 1996 and Parkinson et al., 2010). It is not able to tolerate salinity (GISD 2020). Climates found across the United States (USDA Zones 3-10) support the growth of flowering rush (Sanders et al. 2014). Flowering rush thrives in silty substrates, but can grow well in sandy, loamy, and clay soils that are exposed and wet (Parkinson et al. 2010., GISD 2020).

Establishment in the United States

Flowering rush is present in many parts of Europe, the United Kingdom, Ireland, and western parts of Asia. It was first observed in the United states 1918 in Michigan where it spread around the great lakes, eventually spreading both west and east along the Canadian and United States border. The invasion of flowering rush was first documented in Washington State in 1997 at Silver Lake (Coa et al. 2020). Since then, flowering rush has been documented in Silver Lake, Pend Oreille River, Spokane River and along the Yakima River (Columbia Basin Cooperative Weed Management Area, 2019). Currently the distribution of flowering rush is limited in Washington State.

Flowering rush continues to spread through multiple vectors including accidental spread from disposed floral arrangements, packaging material or boat ballast water. Another source is from the aquatic garden trade. The attractive pink flowers make it an enticing plant for water gardens. It was also introduced to provide a seed source for waterfowl. The seeds are readily consumed by geese and other waterfowl (Les and Mehrhoff 1999).

Effects on Invaded Systems

Flowering rush has also been shown to effect freshwater fish habitat. The plant can produce dense stands in previously limited vegetated waterways. This new dense vegetation can disrupt cutthroat trout and bull trout that require open water to spawn. It also produces better habitat complexity for nonnative fish such as largemouth bass and northern pike that can prey on native fish as has been seen in Flathead lake, MT (Jacobs et al., 2011). This raises concerns for impacts on threatened salmonid species in the Pacific Northwest. Flowering rush can also provide habitat for great pond snails (*lymnaea stagnalis*) which is a host for the trematode parasite (*Trichobilharzia ocellata*) that causes swimmers itch in humans.

In the Czech Republic, it has been shown that other more competitive aquatic vegetation may be able to prevent flowering rush establishment though it has not been researched how native aquatic plants of the United States will be impacted (Jacobs et al., 2011).

Economics

In Montana, the cost to use chemical control methods for flowering rush ranges from $575 to $715 USD per acre (Columbia Basin Cooperative Weed Management Area, 2019). Flowering rush has been shown to inhibit water recreation. The plant can form dense stands that obstruct boat propellers and limit swimming potential of lakes (Jacobs et al., 2011). The habitat provided by flowering rush increases the risk of swimmer's itch reduction recreation until control can be implemented (e.g. Silver Lake, Washington; Columbia Basin Cooperative Weed Management Area, 2019). It has also been shown to rapidly establish in irrigation ditches where it quickly limits and blocks water flow to agricultural fields. resulting in increased costs for ditch maintenance (Columbia Basin Cooperative Weed Management Area 2019).

Reynoutria japonica (Japanese Knotweed) and *Polygonum sachalinense* (Giant Knotweed)

Introduction

Reynoutria japonica, also known by the names of Polygonum cuspidatum or *Fallopia japonica* is commonly known as Japanese knotweed (Figure 7). *Polygonum sachalinense* is commonly known as giant knotweed (Figure 8). Both knotweeds are members of the buckwheat family (polygonaceae). They are native to East Asia and were introduced to the United States in the 1800s. Since initial introduction, both Japanese and giant knotweed have become established in several regions of the United States including Washington State. Japanese knotweed is more widespread than giant knotweed, however both species and hybrid variety are found throughout much of Washington State (Haubrich 2018b).

FIGURE 7: ILLUSTRATION OF JAPANESE KNOTWEED (HARPER, 2019)

FIGURE 8: GIANT KNOTWEED (PHOTO CREDIT: GLENN MILLER 2002)

Biology

Botanical Description (Japanese Knotweed)

Japanese knotweed is a rhizomatous perennial plant (Figure 7). The rhizomes of the plant can spread underground. The underground rhizomes send up shoots allowing the plant to spread through the soil and form dense patches. The leaf of Japanese knotweed has an alternate orientation and is triangular-ovate in shape (King County Noxious Weeds 2018). The leaves are thick with entire margins. The stems of the plant are rigid and erect. The internal portion of the stem is hollow between nodes. The stems are green in color with reddish-purple spots. The plant typically reaches 1-3 m tall (Soll 2004). The plant can grow in dense vegetative thickets. The flower clusters grow on approximately 10 cm inflorescence with small and white flowers.

The fruit of Japanese knotweed is papery and winged with 3 angles (Figure 7). The seed of Japanese knotweed is three sided and black in color and often seen inside of the papery fruit of the plant.

Botanical Description (Giant Knotweed)

Giant knotweed is a rhizomatous perennial plant and is very similar to Japanese knotweed (Figure 8). The plant is larger overall than Japanese knotweed. Giant knotweed leaves have an alternate orientation and a heart shaped base of the leaf shape (**Error! Reference source not found.**8) (King County Noxious Weeds 2018). The leaves are thick with entire margins and the stems are rigid and erect. The internal portion of the stem is hollow between nodes. The stems are green in color with reddish-purple spots. The plant typically reaches 4.5 m tall (Soll 2004). The plant can grow in dense vegetative thickets. The rhizomes of the plant can spread underground and send up shoots allowing the plant to spread through the soil and form dense patches. The fruit of giant knotweed is papery and winged with 3 angles much like Japanese knotweed. The seed of giant knotweed is three sided and black in color and often seen inside of the papery fruit of the plant (King County Noxious Weeds 2018).

Pollination

The flowers of Japanese and giant knotweed begin to form in late July and August. The flowers are insect pollinated. Viable pollination occurs where both female and male plants are present. Japanese knotweed can also be pollinated by giant knotweed resulting in a hybrid known as Bohemian knotweed (*Follopia x Bohemica*) (Groenveld, et al., 2014).

Seed Production and Dispersal

Japanese and giant knotweed can produce by seed in regions where both female and male plants are present. Past studies have reported that reproduction by seed of pure knotweed strains is rare in the United States (Soll, 2004), however recent studies have found this may not be the case. In Pennsylvania, one study found germination rates as high as 90% for Japanese knotweed (Bramm and McNair 2004). Another study from Pennsylvania found both giant knotweed and Japanese knotweed were producing viable seeds (Niewinski 1998). Limited research on seed viability in the state of Washington has been conducted.

Knotweed seeds are wind dispersed over short distances of approximately 50 cm (Tiébré et al. 2007). These seeds are also buoyant, allowing them to travel greater distances in water (Rouifed et al. 2011). The seeds of knotweed can remain dormant and viable for as much as 15 years. If the seed is present in the first 1 inch of the soil layer, it typically only remains viable for 4 to 5 years (King County Noxious Weeds 2015). If the seed is buried deeper then it may remain dormant and viable for a longer period.

Vegetative Reproduction

Both Japanese knotweed and giant knotweed send shoots up from the underground rhizomes in early spring. In the lower elevations of the Pacific Northwest, this occurs in April. In higher elevations this occurs in June (Soll, 2004). Once emerged the plant rapidly grows until reaching full height at approximately 1-3 meters for Japanese knotweed and 4.5 m for giant knotweed (King County Noxious Weeds 2015). Knotweeds can produce new plants and establish new colonies through asexual vegetative reproduction. One method of vegetative reproduction that can occur is through stem fragments. Fragments from knotweed can root and establish new plants if a node is present (Soll 2004). This can occur in fragments as small as 1 cm.

Ecology

Environmental Factors Affecting Occurrence and Growth

Knotweeds are seen in various altitudes, soil types, moisture levels, and sunlight amounts (Stone, 2010) and can tolerate saline conditions and soils with heavy metals (Hayley 2012). Japanese knotweed can be found in regions of lowlands, alpine zones, volcanic deserts, forest edges and areas of high disturbance (Shinmoda and Yamaski, 2016). Areas of disturbance include roadsides, residential lots, and cultivated land. They are found along the water's edge in riparian and wetland systems (Hayley 2012). In Japanese knotweed's natural habitats, it has many natural predators and diseases which compete with it this prevents knotweed populations from expanding and becoming problematic, as is often seen in regions that it invades (Grevstad et al., 2018). Knotweed has been shown to have an annual precipitation threshold of 735 mm per year (Bourchier and Hezewijk 2010).

Establishment in the United States

Japanese knotweed is native to East Asia where its range includes Japan, Taiwan, Korea, and Northern China (Child and Wade, 2000). Both Japanese knotweed and giant knotweed arrived in North America from Asia in the 1800's. They were introduced as an ornamental plant before escaping cultivation (Stone, 2010). The plant was enjoyed in gardens and estates due to the plumes of white flowers and dense green vegetation. Giant knotweed was promoted as a good food source for livestock (Urgenson et al. 2009).

Japanese knotweed has been recorded in 42 states (Gervstad et al. 2018). In the United states, Japanese knotweed typically established itself in areas of disturbed soils. This results in the plant typically being found along roadways, railways, and riparian habitat corridors (Weston et al., 2005). Knotweed can readily spread in riparian habitats because of seasonal flooding and its ability to reproduce vegetatively. Roadways and railways are common habitat because knotweed rhizomes can be transported in fill dirt. Both giant and Japanese knotweed are established in Washington State. Earliest records of Japanese Knotweed occurrence were in 1958 (Toney et al., 1998). Japanese knotweed has been more widespread than giant knotweed, however both species and their hybrid variety are found throughout much of Washington State (Haubrich 2018b).

Effects on Native Systems

Japanese and giant knotweed can have negative impacts on local native ecosystems. Knotweed can establish into dense patches which can displace and outcompete native vegetation (Urgenson et al., 2009; Gervstad, 2018). Japanese knotweed allelopathy effects on native vegetations by releasing phytotoxic compounds such as anthraquinones and polyphenols from its root systems into the surrounding soils (Fan et al., 2010). These phytotoxic compounds have been shown to reduce growth from native tree species such as those in the Salicaceae family (Dommanget et al., 2014). One study in Washington demonstrated that in a region with giant knotweed, litter mass of natives was greatly reduced and the carbon to nitrogen ratio was increased (Ugenson et al., 2009). There are fewer predators and diseases of Japanese knotweed in regions that it has invaded. Knotweed has been shown to impact stream water quality as dense stands prevent establishment of trees on riverbanks thus limiting shade potential and increasing water temperature. Knotweed can also decrease bank stability and increase erosion which affects turbidity (McHugh, 2006).

Economics

Knotweeds have an economic impact associated with their invasions. The exact cost of knotweed control and impacts can be difficult to calculate. Knotweed control can be costly to local, state, and federal governments. For the state of Washington, it is estimated that $30.4 million USD was spent by government agencies to control knotweed between 2004 and 2016 (Gervstad 2018). This estimate does not include the costs associated with private agencies and citizens working to control knotweed. Knotweed is known to cause damage to infrastructure such as roads and home foundations. These damages result in additional cost for continued maintenance and repairs. However, Japanese knotweed and other knotweeds are highly valued by beekeepers as a late season nectar source for honeybees, particularly in the Pacific Northwest (Puget Sound Beekeeping Association, 2020).

Species Distribution Model Methods

Methodology

Species distribution modeling (SDM) is used to predict where a species could occur. SDM can be used to visually represent the fundamental niche of a species. This is different from the realized niche which describes where a species currently occurs. SDM uses various types of environmental data and species occurrence data to extrapolate the distribution of a species using a statistical model (Franklin 2010).

Software

This project utilized an open source SDM software called Maxent. Maxent generates a model by applying maximum entropy modeling which is a generalized machine learning technique. The program uses environmental data and species presence data and applies a probability distribution for each grid cell on a raster.

Data Collection

Environmental data sets used for the SDM models include WorldClim bioclimatic variables (version 2.1) and WorldClim elevation data (version 2) resulting in 20 different environmental data sets. WorldClim bioclimatic data set uses climate data from 1970 to 2000 for variable development (**Error! Reference source not found.**). Both data sets are 1 Km ^{2} resolution (Fick and Hijmans 2017).

Presence-only observational data from Washington State for each species of interest was utilized in the SDM models. Presence data was collected into a single database using the Global Biodiversity Information Facility (GBIF) looking at all target species (GBIF 2020). GBIF is an online open access network that collects data on species occurrence. Data is submitted to GBIF from governments, researchers, organizations, museums, and online crowdsourced applications around the world.

TABLE 2: ENVIRONMENTAL VARIABLES USED IN MODEL SELECTION

Environmental Variables	Source
Elevation	WorldClim Elevation Ver. 2
BIO1 = (Annual Mean Temperature)	WorldClim Bioclimatic 2.1
BIO2 = (Mean Diurnal Range (Mean of monthly (max temp - min temp)))	WorldClim Bioclimatic 2.1
BIO3 = Isothermality (BIO2/BIO7) (×100)	WorldClim Bioclimatic 2.1
BIO4 = Temperature Seasonality (standard deviation ×100)	WorldClim Bioclimatic 2.1
BIO5 = Max Temperature of Warmest Month	WorldClim Bioclimatic 2.1
BIO6 = Min Temperature of Coldest Month	WorldClim Bioclimatic 2.1
BIO7 = Temperature Annual Range (BIO5-BIO6)	WorldClim Bioclimatic 2.1
BIO8 = Mean Temperature of Wettest Quarter	WorldClim Bioclimatic 2.1
BIO9 = Mean Temperature of Driest Quarter	WorldClim Bioclimatic 2.1
BIO10 = Mean Temperature of Warmest Quarter	WorldClim Bioclimatic 2.1
BIO11 = Mean Temperature of Coldest Quarter	WorldClim Bioclimatic 2.1
BIO12 = Annual Precipitation	WorldClim Bioclimatic 2.1
BIO13 = Precipitation of Wettest Month	WorldClim Bioclimatic 2.1
BIO14 = Precipitation of Driest Month	WorldClim Bioclimatic 2.1
BIO15 = Precipitation Seasonality (Coefficient of Variation)	WorldClim Bioclimatic 2.1
BIO16 = Precipitation of Wettest Quarter	WorldClim Bioclimatic 2.1
BIO17 = Precipitation of Driest Quarter	WorldClim Bioclimatic 2.1
BIO18 = Precipitation of Warmest Quarter	WorldClim Bioclimatic 2.1
BIO19 = Precipitation of Coldest Quarter	WorldClim Bioclimatic 2.1

Model Building

Maxent utilized species presence data and environmental data with maximum entropy modeling to create a species distribution model (Figure 9). The initial data for each species were processed by Maxent with all 20 environmental data sets. Each species model was then evaluated to determine the highest performing variables by largest percent contribution. Only the three best performing variables were selected for the final model. The selected three variables can be seen in tables 4 and 5. A second pass of Maxent was then used to produce the final species models utilizing only the selected environmental variables. Output models from maxent were transposed over a Washington state base map using ArcPro Regions of low (blue) and high (red) suitability for each species of interest.

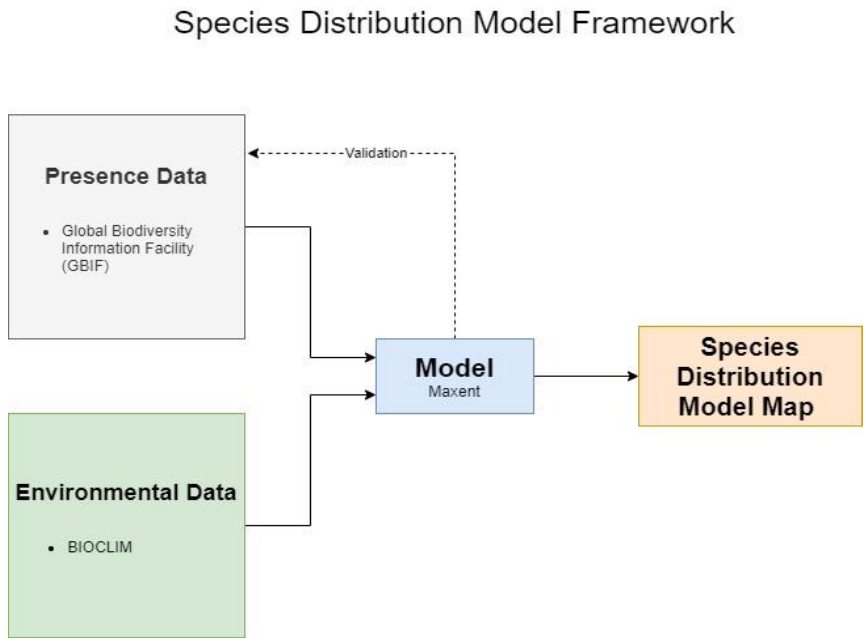

FIGURE 9: THE BASIC FRAMEWORK USED FOR CREATING SPECIES DISTRIBUTION MODELS FOR FOCAL INVASIVE SPECIES IN WASHINGTON STATE.

Model Evaluation

The performance of the species models was evaluated by applying a cumulative threshold. The cumulative threshold is a chosen threshold for which a species occurrence is considered a presence or absence. Currently there is no standardized rule for setting a threshold and thus it must be chosen by the researcher (Philips et al. 2006). Fixed cumulative thresholds of 1 and 5 for evaluation have been predominantly used in literature of species distribution models (Manel et al. 1999, Bailey et al. 2002, Phillips et al. 2006). However, the use of fixed cumulative thresholds has been shown to result in more false positives and negatives (cummings 2000, Liu et al. 2005). Researchers are currently evaluating Maxent to better understand the effectiveness of using different thresholds for predictive evaluations. Due to the limited rules, the sensitivity-specificity sum maximization (SSSM) approach for the threshold was utilized. The SSSM approach produces a threshold in Maxent that results in a better threshold for evaluating models than fixed thresholds (Manuel et al. 2001, Liu et al. 2005). Sensitivity is the measure that the test was able to correctly classify where a species does occur, and specificity is the measure that a test was able to classify where a species does not occur (Parikh et al. 2008). The SSSM allows the threshold to be determined by maximizing the sum of sensitive and specificity. This is equivalent to finding a point on the receiver operating characteristic (ROC) curve whose tangent slope is equal to 1 (Cantor et al. 1999). Once the cumulative threshold is chosen, it is used to produce the extrinsic omission rate (EOR), proportional predicted area (PPA), and p-value for a model. The EOR is the fraction of test locations which are predicted as not suitable for the species. The PPA is the fraction of pixels which are predicted as suitable for the given species. The p-value represents the null hypothesis, which states that the model performs randomly (Phillips et al. 2006). A low p-value corresponds to a non-random model. A one-tailed binomial test is applied to determine if the p-value is sufficient to disprove the null hypothesis. Lower EOR rates are needed for good model predictability (Anderson et al. 2002). Large PPA values may improve quality of species potential distribution models (Phillips et al. 2006).

Results

Ecological factors and thresholds for each species of interest that feed into MDS models were identified in the literature review (Table 3). SDM model results show that the most common variable among species models was elevation which was utilized in 7 of the 8 models (Table 4 & 5. Annual mean temperature was utilized in 4 of the 8 models (Table 4 & 5). Minimum temperature of coldest month was a shared variable for Chinese mystery snail, Brazilian elodea, and giant knotweed (Table 4 & 5). This variable is correlated with Annual Mean Temperature. All other environmental variables were used in 2 or less of the models.

Table 3: Environmental Factors

Species	Temperature Threshold	Desiccation	Water Depth Threshold	Salinity Threshold	Ph
New Zealand mudsnails *(Potamopyrgus antipodarum)*	0° C	48 Hrs. on dry substrates 50 days on wet substrate	≤ 25 m	Tolerant	
Bullfrog *(Lithobates catesbeianus)*	Vulnerable to freezing 15°C for egg development 38.2°C Maximum	Need Access to Water	Need shallow waters for tadpoles. Adults ≥ 1.5 m to escape predators.	Intolerant	≥4.3
Chinese mystery snail *(Cipangopaludina chinensis)*	45° C Maximum	Survive up to 4 weeks air exposure	0.2-3 m		6.5-8.4
Eurasian Watermilfoil *(Myriophyllum spicatum)*	0° C Lower threshold 15°C and 35°C needed for photosynthesis	Cannot survive desiccation	1 – 4 m typical 10 m recorded		
Brazilian elodea *(Egeria densa)*	3°C Lower threshold 16°C and 28°C needed for photosynthesis	Cannot survive desiccation	1-2 m 7 m recorded	Intolerant	
Flowering rush *(Butomus umbellatus)*	Can occur in USDA Zones 3-10	Cannot survive long term desiccation	6.1 m limit	Intolerant	
Japanese knotweed *(Fallopia japonica)* **&** **Giant knotweed** *(Polygonum sachalinese)*		Cannot survive long term desiccation		Tolerant	

Invasive aquatic animal species distribution models and maps

All aquatic animal species distribution models performed better than random and had a significant p-value less than 0.05 using the sensitivity-specificity sum maximization cumulative threshold (Table 4). The New Zealand mudsnail (*Potamopyrgus antipodarum*) model displayed a small p-value of 5.38E-13 and low EOR value of 0.00 (Table 4: Aquatic Animal Variables and Statistics.Table 4). The low p-value and small EOR value indicate a model that had good predictability for species distribution models. Regions with high predicted suitability can be seen along the Puget Sound and just north of Portland following the Columbian river (Figure 10).

The American Bullfrog (*Lithobates catebeianus*) model displayed a small p-value of 1.51E-53 and low EOR value of 0.077 (Table 4: Aquatic Animal Variables and Statistics.Table 4). The model shows a high predicted habitat suitability throughout the Puget Sound region and along the southern Washington Coastal region and following the Columbia river (Figure 11).

The Chinese Mystery Snail (*Cipangopaludina chinensisis*) model displayed a small p-value of 1.18E-3 and low EOR value of 0.000 (Table 4: Aquatic Animal Variables and Statistics.Table 4). This model utilized a small sample size of only 12 observations for presence data. The model shows a high predicted suitability throughout Western Washington into the Cascade Mountain range (Figure 12).

Invasive aquatic and terrestrial plant species distribution models and maps

All aquatic and terrestrial plant species distribution models performed better than random and had a significant p-value less than 0.05 using the sensitivity-specificity sum maximization cumulative threshold (Table 5). The model for Eurasian watermilfoil (*Myriophyllum spicatum*) had a small p-value of 6.11E-27 and low EOR value of 0.141 (Table 4: Aquatic Animal Variables and Statistics.Table 5). The low p-value and small EOR value indicate a model that had good predictability for species distribution models. The model predicted high suitability throughout Washington following major and minor river and stream systems (Figure 13).

The Brazilian elodea (*Egeria densa*) model displayed a small p-value of 1.24E-14 and low EOR value of 0.000 (Table 4: Aquatic Animal Variables and Statistics.Table 5). The model shows high predicted suitability along the Puget Sound and just north of Portland following the Columbian river (Figure 14).

The flowering rush (*Butomus umbellatus*) model displayed a small p-value of 2.76E-05 and low EOR value of 0.000 (Table 4: Aquatic Animal Variables and Statistics.Table 5). The model shows high predicted suitability throughout Washington following major and minor river and stream systems (Figure 15).

The Japanese knotweed (*Reynoutria japonica*) model displayed a small p-value of 1.40E-39 and low EOR value of 0.034 (Table 4: Aquatic Animal Variables and Statistics.Table 5). The model shows high predicted suitability locations primarily along the Puget Sound region and along the Columbia river (Figure 16).

The Giant knotweed (*Polygonum sachalinense)* model displayed a small p-value of 2.62E-2 and low EOR value of 0.000 (Table 4: Aquatic Animal Variables and Statistics.Table 5). This model utilities a small sample size of only 12 observations for presence data. The model shows high predicted suitability throughout Western Washington and along the Columbia River (Figure 17).

Table 4: Aquatic Animal Variables and Statistics.

SPECIES	# OF OBSERVATIONS	SELECTED VARIABLES UTILIZED IN MODEL	VARIABLE WEIGHT (% CONTRIBUTION)	STATISTICS		
				P value	EOR	PPA
New Zealand mudsnails (*Potamopyrgus antipodarum)*	n = 33	*Elevation*	80.6	5.38E-13	0.00	0.077
		Bio1: Annual Mean Temperature	7.5			
		Bio14: Precipitation of Driest Month	2.5			
Bullfrog (Lithobates catesbeianus)	n = 156	*Elevation*	55.3	1.51E-53	0.077	0.154
		Bio19: Precipitation of Coldest Quarter	13.3			
		Bio3: Isothermality	5.3			
Chinese mystery snail (*Cipangopaludina chinensis)*	n = 12	*Bio6: Minimum Temperature of Coldest Month*	67.4	1.18E-03	0.00	0.106
		Bio4: Temperature Seasonality	16.5			
		Bio12: Annual Precipitation	8.6			

Table 5: Aquatic Plant Variables and Statistics.

SPECIES	# OF OBSERVATIONS	SELECTED VARIABLES UTILIZED IN MODEL	VARIABLE WEIGHT (% CONTRIBUTION)	STATISTICS		
				P value	EOR	PPA
Eurasian Watermilfoil ***(Myriophyllum spicatum)***	n = 278	*Elevation*	48.2	6.11E-27	0.141	0.0.334
		Bio10: Mean Temperature of Warmest Quarter	6.2			
		Bio1: Annual Mean Temperature	5.2			
Brazilian elodea ***(Egeria densa)***	n = 48	*Elevation*	83	1.24E-14	0.000	0.118
		Bio6: Minimum Temperature of Coldest Month	5.2			
		Bio12: Annual Precipitation	3.1			
Flowering rush ***(Butomus umbellatus)***	n = 21	*Elevation*	31.4	2.76E-05	0.000	0.174
		Bio1: Annual Mean Temperature	15.3			
		Bio3: Isothermality	14.9			
Japanese knotweed ***(Fallopia japonica)***	n = 89	*Elevation*	50.3	1.40E-39	0.034	0.135
		Bio19: Precipitation of Coldest Quarter	11.8			
		Bio13: Precipitation Wettest Month	8.3			
Giant knotweed ***(Polygonum sachalinese)***	n = 12	*Bio6: Minimum Temperature of Coldest Month*	62.3	2.62E-02	0.000	0.297
		Elevation	*21.2*			
		Bio1: Annual Mean Temperature	*8.4*			

New Zealand mudsnail (Potamopyrgus antipodarum)

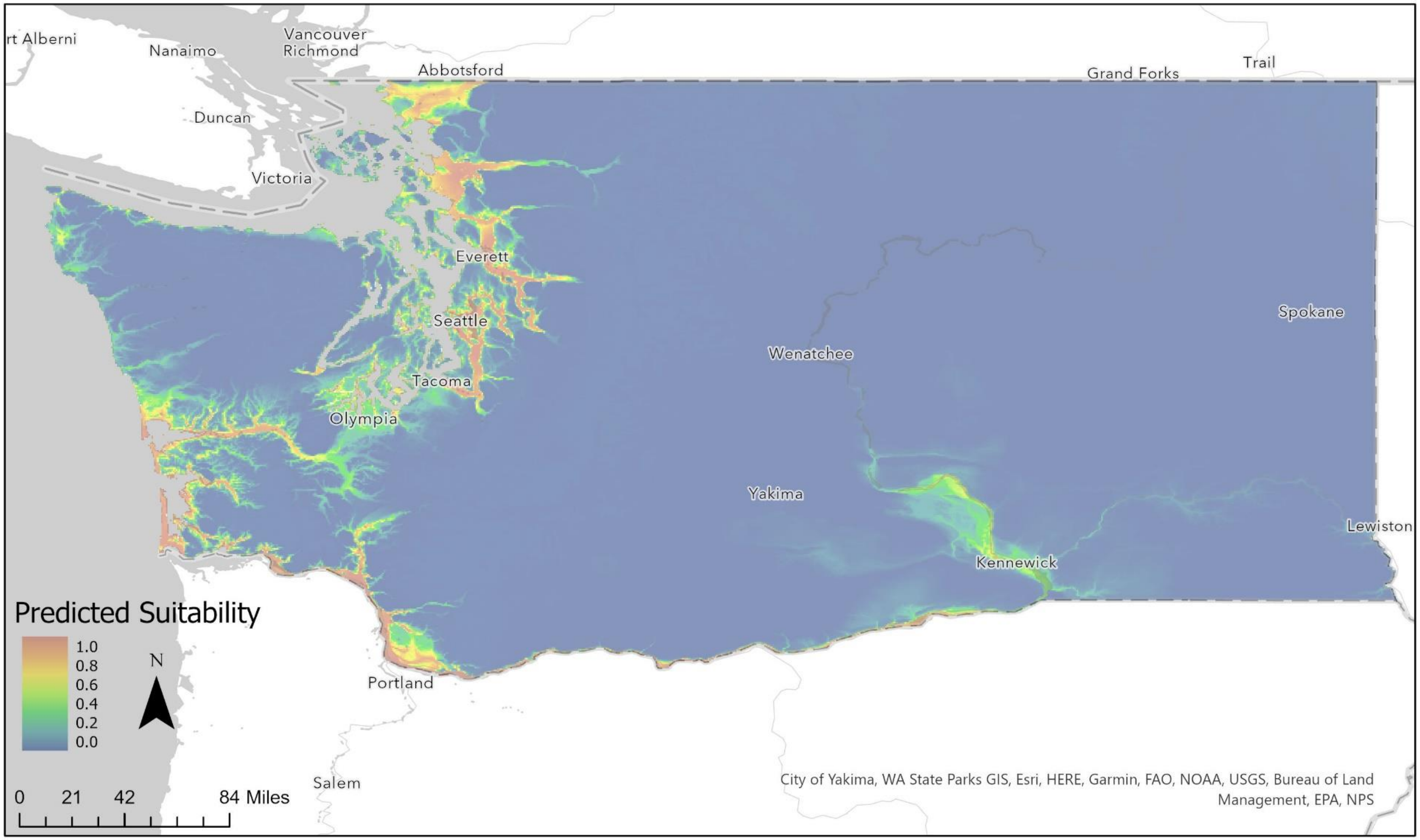

Figure 7: New Zealand mudsnail Species Distribution model.

American Bullfrog
(Lithobates catesbeianus)

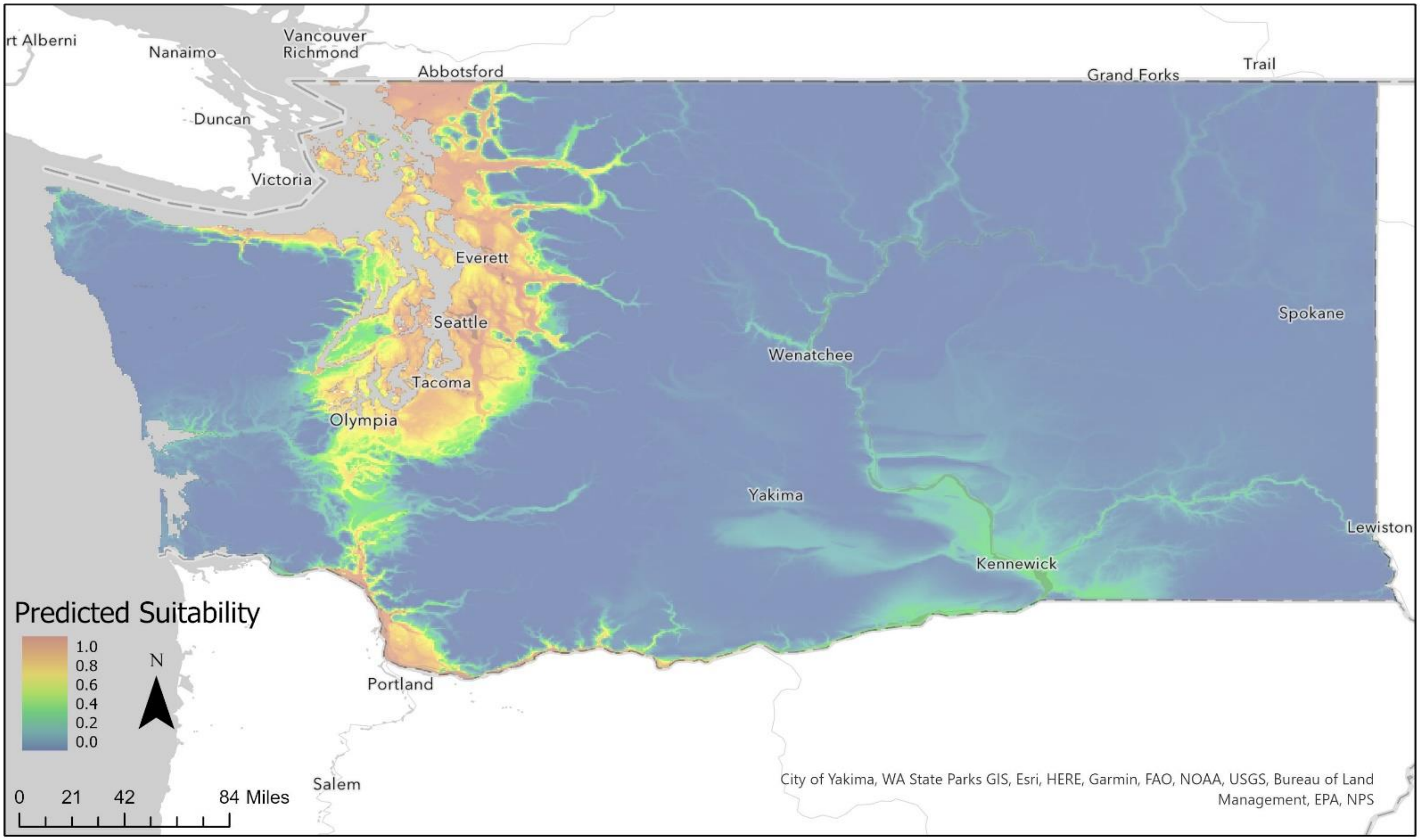

Figure 8: American Bullfrog Species distribution model

Chinese Mystery Snail (Cipangopaludina chinensis)

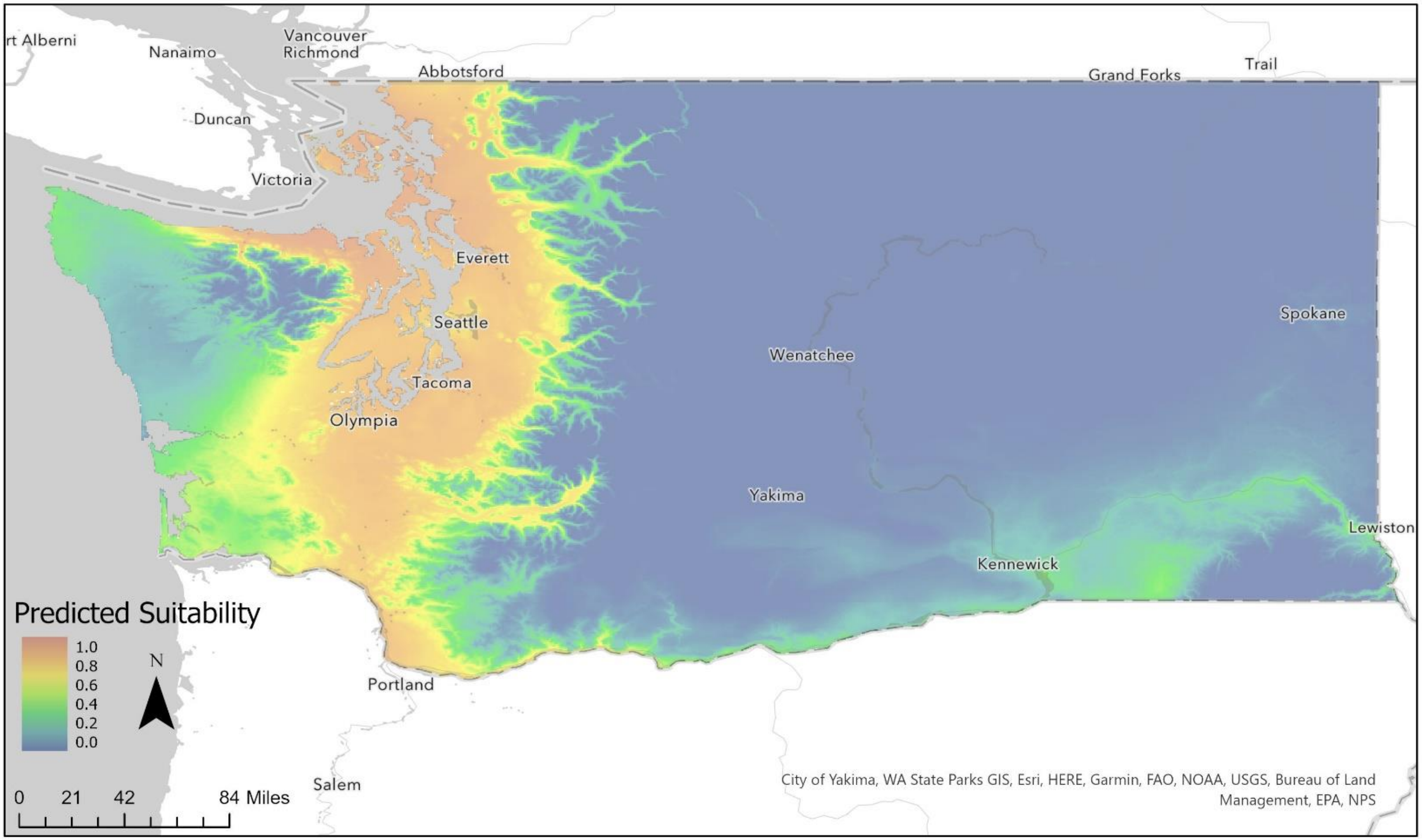

FIGURE 9: CHINESE MYSTERY SNAIL SPECIES DISTRIBUTION MODEL

Eurasian Watermilfoil (Myriophyllum spicatum)

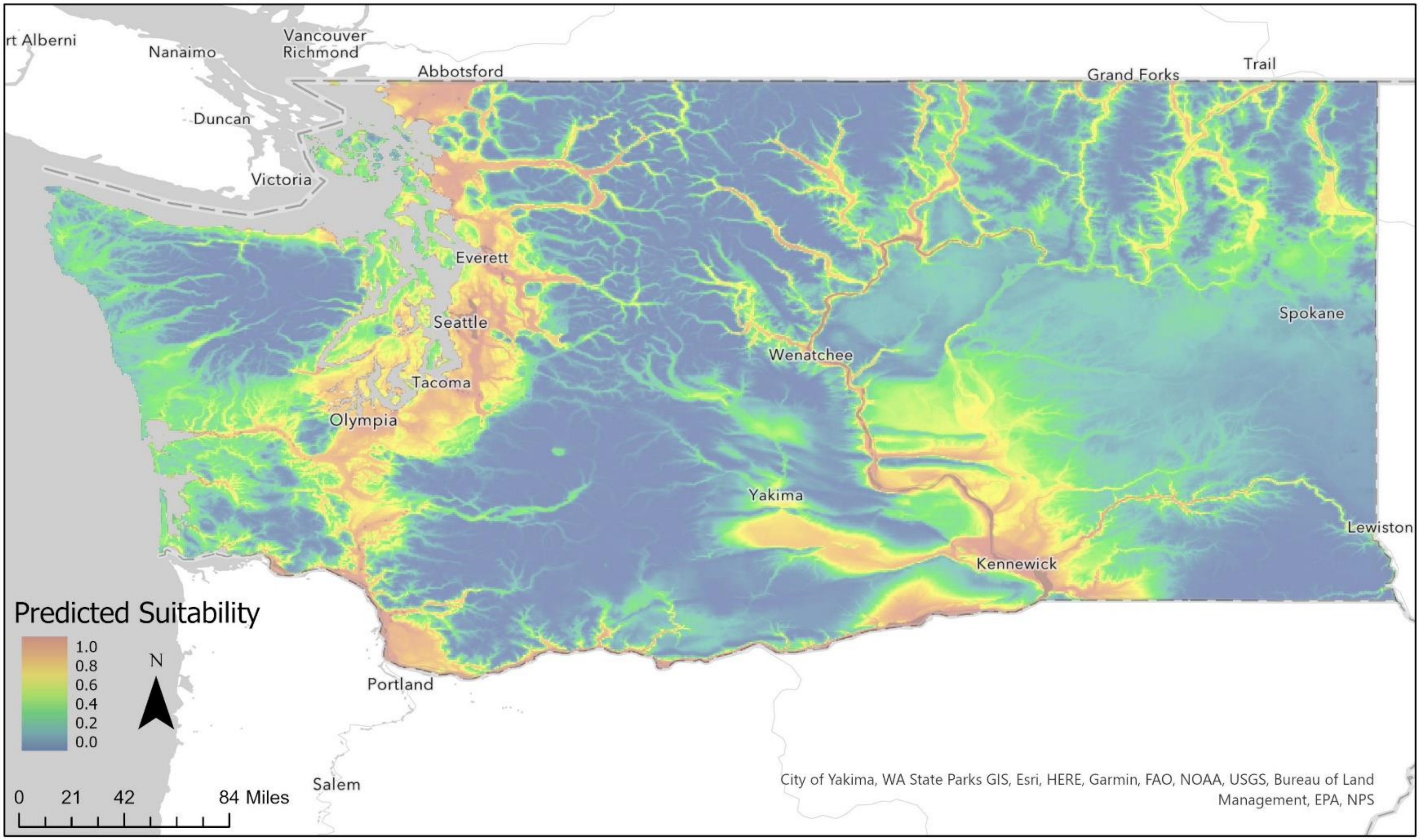

Figure 10: Eurasian Watermilfoil Species distribution model

Brazilian elodea
(Egeria densa)

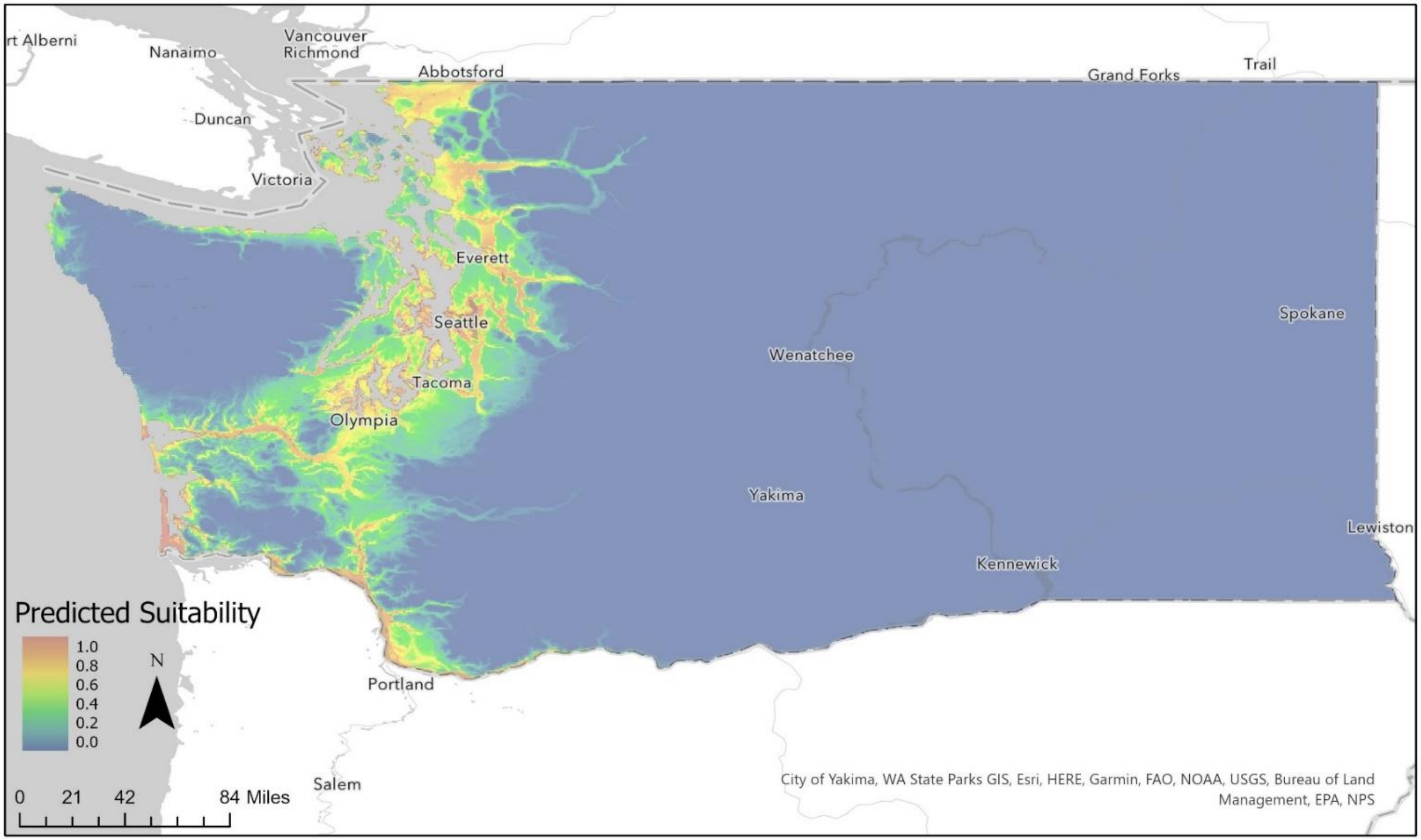

FIGURE 11: BRAZILIAN ELODEA SPECIES DISTRIBUTION MODEL

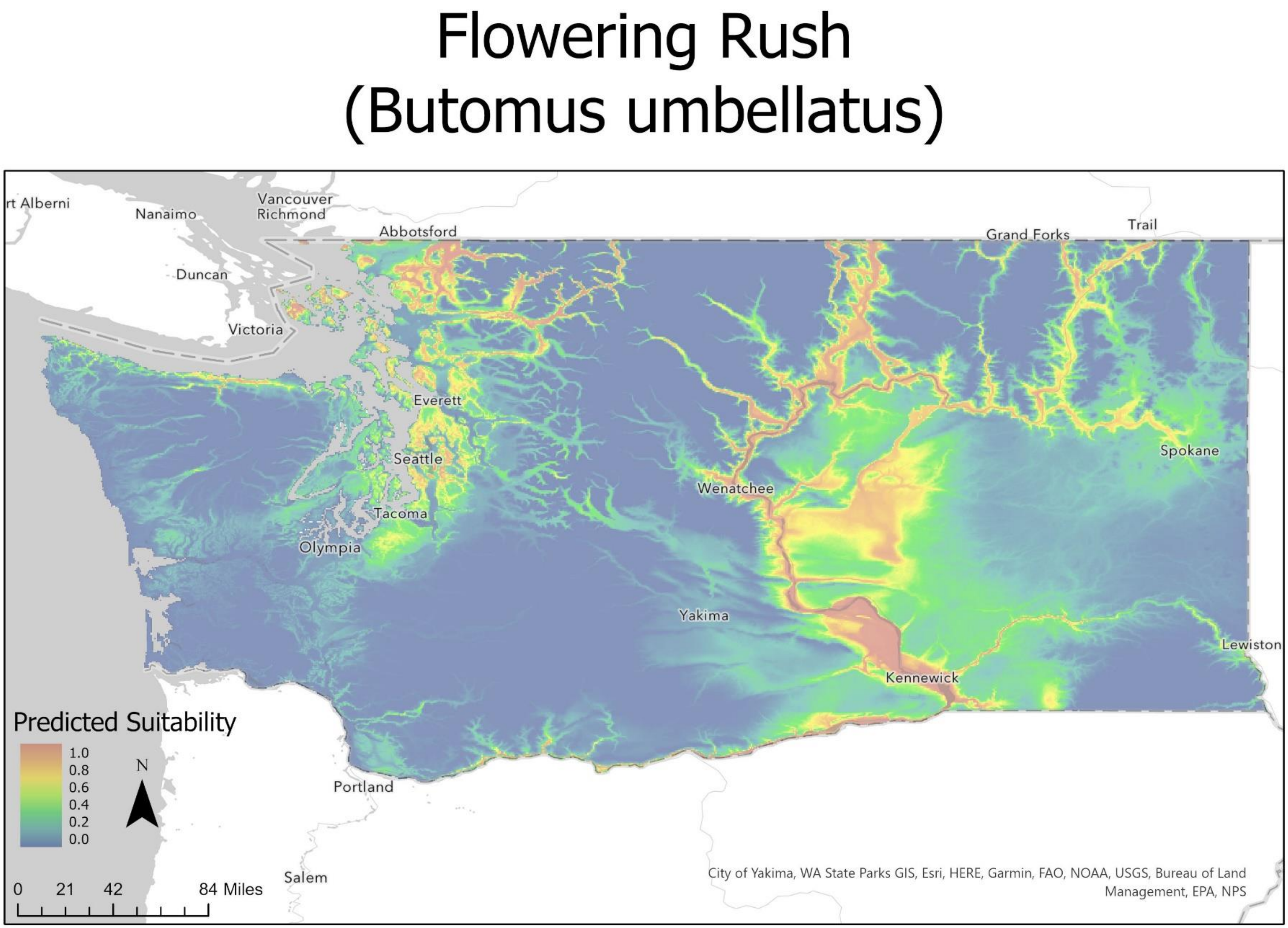

Figure 12: Flowering Rush Species Distribution model

Japanese Knotweed (Reynoutria japonica)

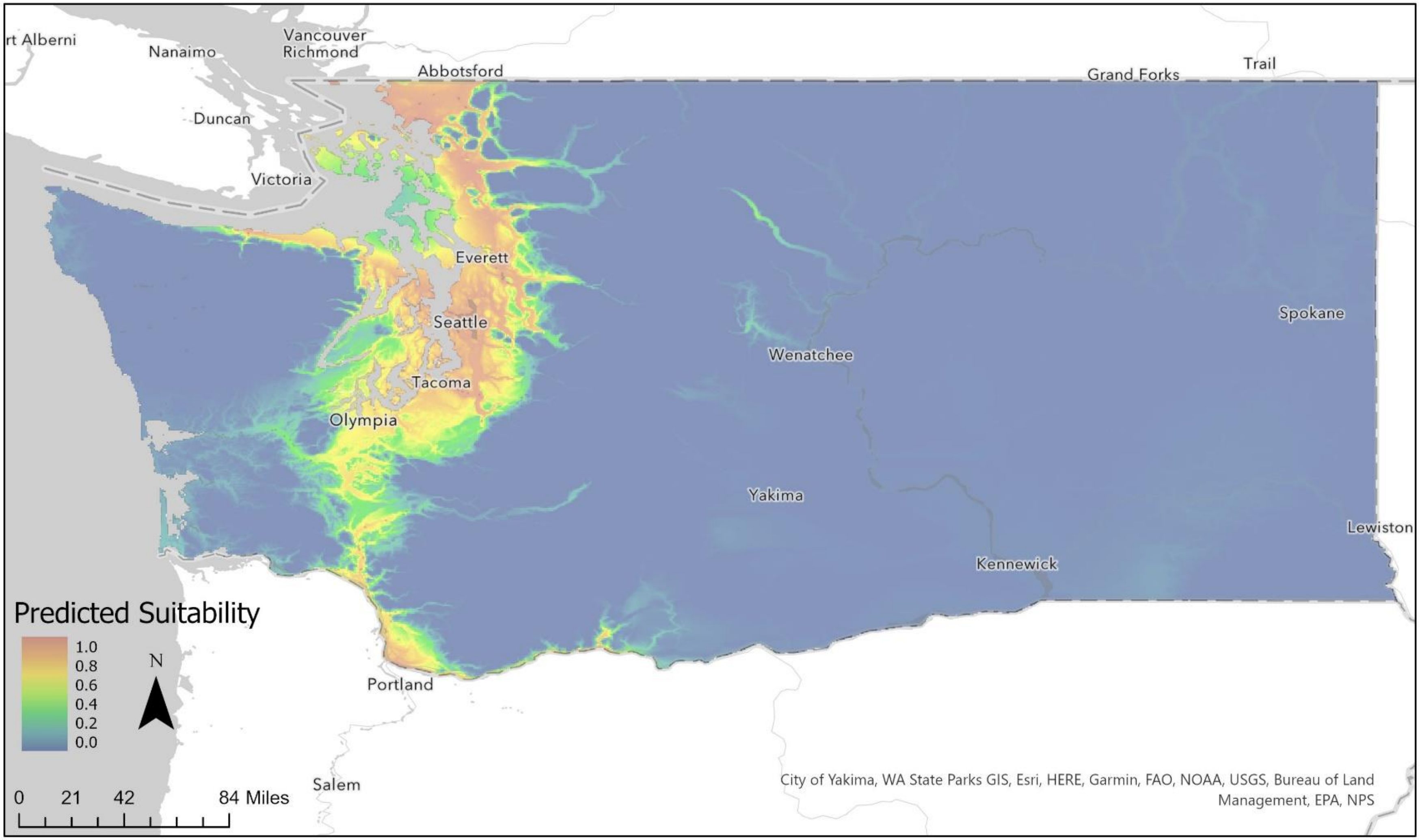

FIGURE 13: JAPANESE KNOTWEED SPECIES DISTRIBUTION MODEL

Giant Knotweed (Polygonum sachalinensis)

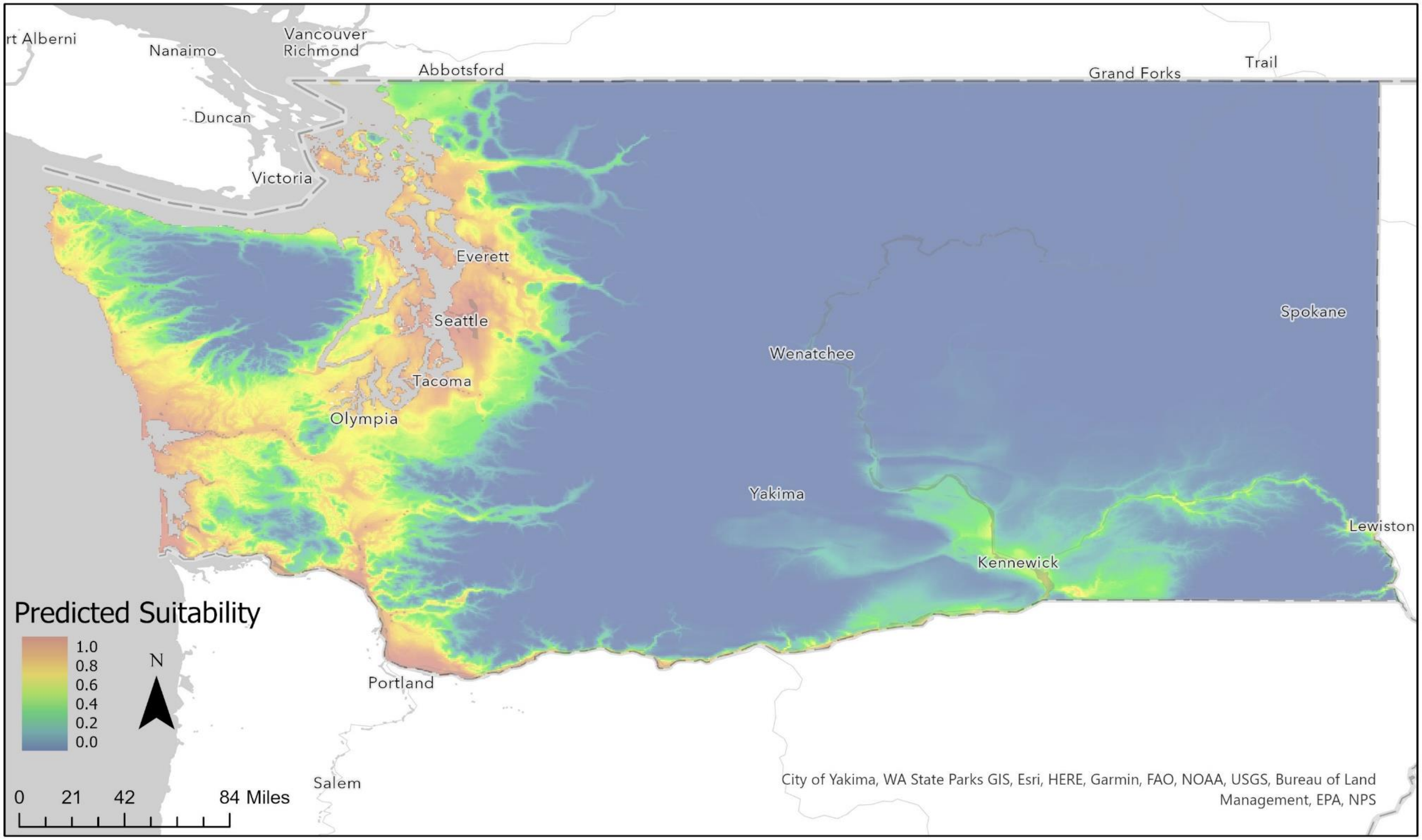

FIGURE 14: GIANT KNOTWEED SPECIES DISTRIBUTION MODEL

Discussion

Riparian forests are vulnerable to colonization by invasive plant and animal species that lead to degradation of such habitats. Early Detection and Rapid Response (EDRR) is vital for monitoring and managing these invasive species (Simberloff, 2013). By detecting species occurrences early when infestation is limited, eradication control measures can be more effective. The larger the population and distribution of an invasive species, the more difficult eradication efforts become (Simberloff 2003). Since EDRR programs often lack resources, it is important to be able to target potentially impacted regions. The use of SDM has been shown to help inform EDRR programs of high-risk regions for invasive species programs (Sofaer et al., 2019). By using SDM to identify risk regions managers are more likely to find previously undiscovered or new infestations. By identifying new infestations managers are better equipped to manage these infestations quickly and reduce the impacts the invasive species can have on the surrounding riparian forests.

In this study, all animal and plant models performed better than random when evaluated using the chosen sensitivity-specificity sum maximization cumulative threshold. Each model had p-values less than 0.05 and low EOR value which indicates the model had good predictability for species distribution models (Anderson et al. 2002). This indicates that this modeling approach shows promise to provide results that can contribute to monitoring designs.

Many of the variables that influenced both plant and animal models were related to temperature. This is important to understand as climate change will affect temperatures ranges in the future (Clelia et al. 2017). This change in climate will likely affect these models and can shift species distributions in the future. The species models that utilized annual mean temperature as a variable were flowering rush, Eurasian watermilfoil, New Zealand mudsnail, and giant knotweed. This corresponds to literature showing sensitivities to freezing and overall low temperatures as being factors for distribution of flowering rush, Eurasian watermilfoil, and New Zealand mudsnail (Lacoul & Freedman 2006, Hylleberg and Siegismund 1987, Moffitt and James 2012). Lower temperature thresholds are factors for the distribution of Brazilian elodea (Lacoul & Freedman 2006). Chinese mystery snails can tolerate low temperatures for extended periods of time (Burnett et al. 2018). These factors may be why minimum temperature of coldest month was selected in these species' models. Elevation was the most utilized variable. Elevation is a variable that can correlate with many factors such as temperature and precipitation. This could be the reason why it is utilized so often as a predictive variable.

All eight of the models showed high predicted suitability to invasion throughout the Puget Sound region. The north eastern region of the state showed lower susceptibility except for flowering rush and Eurasian water milfoil. Increased susceptibility around the Puget Sound could be due to several influencing factors including urbanization. Increased human population could act as an increased vector for the spread of invasive species and may influence the model due to sample bias where more species presence observations are made near regions of higher populations. Regions of higher populations may have more citizen science programs and invasive species surveys that allow for presence data to be better calculated than in regions with lower populations.

Species distribution models can help identify regions of the state that may have a higher susceptibility of invasive aquatic species. Narrowing down the susceptible regions could help better allocate resources for future surveys to identify where these species are occurring or where they are likely to spread. By narrowing the search, it allows for less time and money to be used on statewide surveys. For example, all species showed high predicted suitability in the Puget Sound and lower predicted suitability in the Northeastern portion of the state. This can help managers determine where best to allocate resources. Further species of interest in Washington State should be modeled to understand their potential susceptibility across the state.

Many of the species that were modeled in this project have literature discussing their distribution and impacts in Washington state. Some of the species modeled are already widely distributed in Washington state. This literature was reviewed to understand the correlations between current literature and the created models. A survey looking to understand the northern expansion of New Zealand mudsnails shows the mudsnails occurring in the Columbia river and north along the coast to Vancouver Island (Bersine et al., 2008, Davidson 2008). These locations correspond with high predicted suitability determined by the created model (Figure 10). The Washington Gap Analysis Project (WAGAP) utilized remote sensing land classification data and wildlife habitat relationship models to create distributions of terrestrial vertebrates including the American bullfrog (Dvornich et al. 1997). This study showed the predicted distribution along many riparian systems and lakes throughout Washington particularly in

Western Washington and along the Columbian river. This aligns with our results that show high predicted suitability in similar areas (Figure 11). A study in Washington looking at Chinese mystery snails surveyed Puget Sound lakes found Chinese mystery snail in many of these lakes (Twardochleb and Olden 2016). This corresponds with the high predicted suitability in the Puget Sound region determined in the SDM model (Figure 12). Eurasian water milfoil is wildly distributed throughout Washington as demonstrated in the literature. Many studies have looked at control and monitoring of Eurasian watermilfoil in Washington State (Parsons et al. 2004, Parsons et al., 2012, Tamayo et al., 2000) and correspond with the high predicted suitability in the SDM for Eurasian Water milfoil (Figure 13). Current distributions of Flowering rush are limited in Washington state (Madsen et al., 2016, Parsons et al. 2019). However, the SDM model shows high predicted suitability in the State showing high potential for this plant to spread and establish (Figure 15).

Giant knotweed and Japanese knotweed are both widespread in Western Washington. Giant knotweed is prevalent in Skagit County where is it been researched to understand effects on ecosystems and control efforts (Urgenson et al., 2009, Holman et al., 2010.) The SDM for Japanese knotweed and giant knotweed shows the Skagit river valley as being a region of high predicted suitability (Figure 16 and 17). This corresponds to the literature and control work showing the Skagit river region being a region with large populations of knotweed (Miller 2019). Other studies of knotweeds using Maxent have been effective to guide monitoring plans in southeastern Europe (Jovanovic et al., 2018) and Minnesota (Reinhardt and Russel 2019).

Caution should be used when using the Chinese mystery snail model and Giant knotweed model to make management decisions due to very small sample sizes utilized. Both models only utilized 12 observations of presence data. While the model statistics show significant predictability, a larger sample size would give greater strength for these models. Increased documented observation data from multiple agencies and citizen science platforms would enhance model training in the future.

One limitation in using Maxent to develop SDMs is the availability of complete environmental data. For the Maxent program, the data cannot contain any gaps in information which resulted in limited number of environmental inputs that could be used for the creation of the focal species models in Washington state. Limited data sets exist with complete environmental data at finer resolutions. Due to this limited resolution, finer scale predictions cannot be made at a more local scale. Accuracy of these models would benefit from future updates as more accurate and compete environmental data sources are made available and species occurrence datasets are updated. Another source of data for improving these models could be by overlaying mapping layers from USGS. This would allow managers to narrow down high probability regions in relation to lakes and rivers systems for species that require such environments.

Another improvement could be running the model with different environmental data to see if different environmental variables have better predictability for these selected species. Another challenge in creating SDM models is finding reliable presence data since different organizations and agencies often store data independently (Wallace et al., 2020). Some researchers recommend the development of a global information system for invasive species that works to make more information accessible on invasive species (Ricciardi et al., 2000).

Cultural considerations should also be assessed when developing monitoring and management strategies for invasive species. Native Americans have used the riparian habitats of the Pacific Northwest and managed lands for plants and animals for generations. Continued management needs to consider traditional practices and local knowledge from local tribes to help maintain biodiversity of the region and to better steward the land in conjunction with local tribes (Charnley et al. 2007).

Conclusions

Species Distribution models For Invasive Species Management

These models demonstrate that SDM models can be developed using existing environmental and presence datasets in Washington state for invasive plant and animal species of interest to forest managers. This supports using SDM models to help guide the focus of monitoring plans for early detection and rapid response. Using SDM models such as the ones developed for this project can help land managers know where to look for new infestations of specific invasive weeds and wildlife. Knowledge of higher risk regions can make monitoring plans more cost effective by narrowing the scope and accelerate eradication efforts. With swift eradication efforts managers can minimize the impact that invasive species have on riparian forests. This study results also supports a coordinated approach to monitoring and sharing data that enables for accessible high-quality datasets that improve model performance. A coordinated approach that links multiple databases would allow for sharing of information and data in a more time efficient way that could potentially benefit early detection of invasive species. By removing barriers to sharing invasive species data and utilizing modeling methods such as species distribution models, then EDRR efforts could be enhanced.

Communication Outreach

Sharing research and information is vital to ensuring that decisions on natural resource issues are made using the best and most recent available data. By sharing research, land managers are provided the tools they need to make decision that help benefit the state and local communities. To ensure that this information from this capstone project is shared with necessary decision makers in the state of Washington. Efforts will be made to contact the Washington State Invasive Species Council, King County Noxious Weeds, and the Mountains to Sound Greenway. Other local government agencies or non-profit organizations may be contacted in the future if appropriate. This document will be provided to these groups and, if interested, further communications and discussions will be explored. By sharing this document with these organizations, land managers can utilize and understand how species distribution models can be used to efficiently plan for invasive species monitoring on large scale efforts.

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