EXPLORING THE RELATIONSHIP BETWEEN THE NON-NATIVE ANNUAL GRASS RATTAIL FESCUE (VULPIA MYUROS) AND SOIL NUTRIENTS IN PUGET SOUND PRAIRIES

by

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ABSTRACT

Exploring the Relationship Between the Non-native Annual Grass Rattail fescue *(Vulpia myuros)* and soil nutrients in Puget Sound Prairies

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The South Puget Sound prairies of western Washington used to cover approximately 180,000 acres prior to European settlement but today that area has declined to 10% of that historic extent. Prairie restoration is necessary to conserve this rare ecosystem and recover threatened and endangered wildlife. Invasive vegetation poses a threat to restoration efforts by competing for valuable resources, such as nutrients and light. Rattail fescue *(Vulpia myuros)*, an invasive annual grass from the Mediterranean, has recently spread to prairie restoration sites, partly through contaminated native seed stock. Restoration managers are curious how land use history affects soils properties and if certain soil conditions can facilitate or impair rattail fescue spread. Rattail fescue research has explored control and nutrient use in agricultural settings, but no research has focused on prairie restoration sites. This study sampled soils at five invaded prairie restoration sites in the South Puget Sound with varying land use histories. Results indicate that rattail fescue overall has an inverse relationship with soil nitrate and an overwhelming positive relationship with soil iron. High soil nitrogen is not enough to impede the success of current management actions, and it is possible that soil amendments to reduce soil iron could be a future management action to control the spread of rattail fescue. More research is necessary to better understand the relationship between rattail fescue and iron, as well as if lowering soil iron is an effective control strategy either as a stand-alone action or part of an integrated management plan.

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1. Introduction

Dealing with invasive plants can be a major challenge for people and the environment. Both restoration managers and agricultural producers face difficulties in the field when dealing with invasive plants. For managers, invasive species compete with desired native plants, disturb vital ecosystem services, and are typically labor and cost intensive to control. For farmers and ranchers, invasive plants compete with crops for resources and reduce the resulting harvest's value. Rattail fescue (*Vulpia myuros*) is an invasive annual grass that has a history of infesting agricultural communities in the arid west of the United States as well as Australian farms. It has now begun to spread into restoration sites, partly due to contaminated seed stock. Through research conducted in Australian agriculture since the 1950s, and more recent studies conducted in agricultural crop fields of the arid west, rattail fescue is known to respond poorly to typical control methods such as grazing and chemical control (Ball et al., 2007; Lyon et al., 2018). The challenge of controlling rattail fescue exists partially due to the lack of research exploring growth and control of rattail fescue in restoration settings.

Most restoration practices involve the reintroduction of native plants via seed or plugs. In the Pacific Northwest, prairie restoration managers face the challenge of seed stock contaminated with rattail fescue but uncertainty of what growing conditions will encourage or discourage rattail fescue growth. Prairie managers often use native seeding as a method to quickly and efficiently re-introduce native species to sites, but in the past decade the stock typically used has become contaminated with rattail fescue (Alderman et al., 2011). This poses the problem of being unsure at the time of planting what level of invasion of rattail fescue is possible, making it difficult for managers to make informed decisions about where to risk planting contaminated seed stock, as well as to create informed control plans. Prairies are critical habitats for a variety of endangered plants and wildlife, and research exploring how to minimize rattail fescue establishment in the first place will support efforts to restore native prairie habitat.

Prairies provide important habitat to a group of endangered plants and animals and carry cultural significance for indigenous people. Historically in Washington, prairies were a larger part of the ecosystem. They were actively maintained by indigenous people via cultural burning that prevented encroachment of trees and forest habitat. These areas provided important locations for community gatherings and resource gathering. As colonization of the west occurred, the people who had long cared for these prairies were systematically oppressed and removed from their lands. Prairies began to disappear from the landscape as the people who maintained them were removed and European colonizers developed prairies into agricultural areas. Now historically widespread species such as Taylor's checkerspot butterfly (*Euphydryas editha taylori*) and golden paintbrush (*Castilleja levisecta*) are either endangered or threatened due to habitat loss and degradation (Kronland & Martin, 2015). Rattail fescue poses a threat to the survival of these species as well as tribal cultural practices because they all rely on the quality and quantity of prairie habitat.

Restoration managers can increase existing prairie quality and even help reconvert prairies back from agricultural use. Given the limited resources available to managers, and the urgent need to waste no resources or time in recovery, any hurdle to restoring native habitat is an issue. Managers' ability to easily spread native seed stock increases their ability to effectively restore native habitat. It is a practice that can be done easily by few people and is less expensive than direct planting. Contaminated seed stock poses a stress and risk to restoration plans, as it means restorationists could unintentionally introduce a new invasive species to their sites. A major issue with rattail fescue contaminated seed stock is the lack of knowledge and research understanding how site conditions can influence its growth and establishment.

Variations in soil conditions influence the type of vegetation and how well plants establish themselves (Baer et al., 2004; Gornish & Ambrozio dos Santos, 2016). These observations have facilitated a curiosity in how varying prairie soil conditions could influence the establishment of rattail fescue from contaminated seed. Because rattail fescue has shown some resistance to common control methods such as chemical control and grazing (Ball et al., 2007), managers are looking to make more informed decisions about where they could risk spreading contaminated seed so they would have an easier time managing for rattail fescue down the road. While the research to inform their decision making is somewhat lacking, a recent project local to Olympia, WA has presented a unique study opportunity to explore how soil conditions at different prairie sites may have influenced the establishment of rattail fescue.

The goal of this project is to identify what soil factors contribute to rattail fescue establishment and growth, thereby providing important information to restoration and management of prairie restoration sites. To do this, soil was sampled and vegetative cover recorded at five prairie restoration sites with varied land use history and restoration status. Following this introduction is a literature review that focuses on the life cycle and habitat requirements of rattail fescue, control methods, soil nutrients, and rattail fescue impacts in agricultural and natural habitats. Then the methods used in this study are described, including experimental design, field sampling, sample processing, and data analysis. Results are then presented followed by a discussion that includes a breakdown of results by site. Finally, the thesis ends with a conclusion that presents next steps in rattail fescue research and management.

2. Literature Review

2.1 Introduction

This literature review begins with an overview of rattail fescue biology, including its lifecycle and habitat requirements. Following is a section focused on rattail fescue and soil nutrients, primary Phosphorous (P) and Nitrogen (N). Next is a section on control and management of rattail fescue. Two main topics discussed here are herbicide application and integrated management. This is followed by a brief section on the impacts of rattail fescue in agriculture and grassland settings, including potential allelopathic effects. The literature review ends with a short summary, including the direction it provides for this study.

2.2 Biology

2.2.1 Lifecycle & Description

Rattail fescue is a winter annual grass that is native to central and southern Europe and the Mediterranean (Wallace, 1997). Fall weather conditions (lower temperatures and increased rainfall) stimulate seed germination following a necessary dormancy period of 2-3 months (Dillon & Forcella, 1984). Seedlings then emerge in late winter to early spring after a 2–3 month germination period. Seedlings are 5-15 cm tall while adults range from 0.3-0.6 m tall (Lyon et al., 2018). Plants grow throughout winter and spring, and in mid to late spring they reach their adult stage and begin producing flowers. Rattail fescue is self-pollinating, relying solely on seeds for reproduction, and goes to seed in late spring to early summer (Lyon et al., 2018). These seeds remain in the top 0-5 cm of soil if the soil is left undisturbed and go through an after ripening period that prepares them for the germination stage (Dillon & Forcella, 1984; Lyon et al., 2018).

Büchi et al. (2021) reviewed available literature on rattail fescue's growth and management and found that while many papers cite the plant's high seed production and shallow root growth, these papers are relying on a few, older pieces of literature. For example, a paper from Australia in the 1960's is often cited as evidence of rattail fescue's shallow root growth and there is no study that has provided direct evidence of its seed production (Büchi et al., 2021). The authors suggest that further research avenues should explore how rattail fescue's growth could vary in different locations and climates and confirm these characteristics.

2.2.2 Habitat requirements

Typical cold and moist winter conditions of the PNW create an ideal climate for the germination and emergence of rattail fescue. Average daytime and nighttime temperatures between October-April are 60°F and 42°F, respectively. Average monthly rainfall during the same timeframe is 17.8 cm. Research has shown a trend with cooler temperatures leading to a greater number of seeds germinating (Dillon & Forcella, 1984). Rattail fescue has greater success establishing itself in soils that are left untilled or undisturbed and it's seed germination and establishment success is greatest at 0-1 cm depth, becomes limited between 1-5 cm, and is nearly non-existent below 5 cm (Dillon & Forcella, 1984). Research has shown that tillage farming is related to either reduced presence or no presence of rattail fescue, and this trend is attributed to the continued turnover of the soil, preventing the grass from establishing itself (i.e., if seeds are present, they are buried too deep to germinate and emerge) (Lyon et al., 2018). In a survey of rattail fescue growth in the Australian countryside, McIntyre & Whalley (1990) found Vulpia spp. at 88% of sites, indicating its tolerance for a variety of habitats. These habitat types included ruderal, pasture, natural pasture, sown pasture, and sheep pastures.

2.3 Soil and Rattail Fescue

The effects of soil characteristics on rattail fescue's growth have been researched to some extent and created an exciting array of established work. Studies vary from researching direct relationships between rattail fescue and nutrient application (Hill et al., 2006; Jones et al., 1961), effects of a variety of herbicides (Akhter et al., 2020; Lawrence & Burke, 2014), and allelopathic effects (An, Pratley, Haig, et al., 1997; Kato-Noguchi et al., 2010). These studies provide some insight into ideal soil conditions for rattail fescue's establishment and growth. Overall, rattail fescue has shown an ability to reach maximum growth in low nutrient and fertility situations in agricultural lands (Hill et al., 2006; Jones et al., 1961; Rossiter, 1964), giving it a potential competitive advantage over other annual grasses and perennial grasses in degraded soils.

2.3.1 Soil Nutrients

2.3.1.1 Phosphorous

Much of the research points to rattail fescue's ability to make the most out of low fertility soils and reach maximum growth at lower concentrations of phosphorous compared to other grasses and vegetation (Asher & Loneragan, 1967; Hill et al., 2005; Rossiter, 1964). Rattail fescue also does not seem to be benefit from increasing applications of P fertilizer, and in studies that compared its growth to other plants with increasing P applications, rattail fescue's coverage tended to decrease with increasing P applications (Asher & Loneragan, 1967).

Rossiter (1964) also observed a general inverse trend between rattail fescue growth and phosphorous addition in two separate experiments. In the first, they experimented with adding increasing superphosphate concentrations over a 13yr period. In the second, they experimented with a different series of increased superphosphate concentrations over a 10yr period. Here, rattail fescue percent coverage decreased with increasing superphosphate concentration application. The author observed decreasing percent contribution to the species community with increasing superphosphate applications, although this trend was not statistically significant. In the second experiment, rattail fescue was grouped together with other annual grasses, notably barley grass. In the first half of this experiment rattail fescue dominated the annual grass community composition, and annual grasses did not respond to increased P concentration fertilizer applications. However, in the second half of the experiment, barley grass began to dominate the annual grass community composition after which the annual grass community as a whole began to respond to increased P concentration fertilizer applications.

Rattail fescue's ability to grow in low phosphorous environments is likely related to its nutrient requirements. Hill et al. (2005) showed that rattail fescue had a lower critical P requirement compared to other similar annual grasses. Authors used Relative Growth Rate (RGR) as a measure for comparison between species included in the study because it is a physical process related to nutrient acquisition and species competition. Rattail fescue hit a higher RGR at low P applications compared to the other plants in the study, and the RGR rose only 15% from the lowest to the highest P applications while *Hordeum leporinum* doubled its rate (Hill et al., 2005). Rattail fescue was 1 of 4 species with the lowest critical external P requirements, described as "the concentration of nutrient in plant tissue corresponding to near-maximum growth rate" based on the definition by Smith & Loneragan (1997) and as cited in (Hill et al., 2005).

2.3.1.2 Nitrogen

Rattail fescue also expresses the ability to grow in low nitrogen environments. Jones (1961) surveyed how communities composed of desirable and undesirable grasses responded to a variety of previous nitrogen fertilizer application regimes. Sampling sites were previously grazed rangeland and included both fertilized and unfertilized sites. Rattail fescue, grouped in the undesirable classification, was found at 7 of 11 study locations. An inverse relationship between rattail fescue coverage and fertilizer application was observed at 5 of 11 study locations. One potential explanation for this observation could be related to the effect of rattail fescue density on its response to additional N.

Rattail fescue stand density impacts both its response to added N and the N content of the plant's dry weight. At low density rattail fescue's response to increasing fertilizer application regimes was relatively low (Cocks, 1974). In Cocks (1974) study, medium density for rattail fescue was defined as 2.9 plants per dm^2, low density defined as 1/50th of this, and high density defined as 50 times the medium density. After 9 weeks of growth, rattail fescue had absorbed similar amounts of nitrogen at the low and high densities (1.7 and 2.0mg/plant respectively) but this diverged greatly after 15 weeks of growth. Rattail fescue in the low-density group absorbed 10.2mg/plant while rattail fescue in the high-density group absorbed 29.5mg/plant, nearly 3 times greater than the low-density value. At high density the N content was lower across all N application regimes when compared to the low densities, but rattail fescue's N content grew the greatest from the lowest to the highest fertilizer applications. At medium density, rattail fescue had similar N content values to the low-density results, but expressed a response trend like the high-density response and in fact showed a slightly greater difference of N content values between the lowest and highest fertilizer applications. Rattail fescue's response to increasing fertilizer applications potentially stagnates after the community's density reaches a certain point. The high-density community's high N absorption but lower N content could indicate that rattail fescue can "make up" for starting with less N by increasing its uptake rate, but that at some point the density of the community causes this value to stagnate.

It's possible that the density-based response and reduced overall N content is related to rattail fescue's requirement for N. Hill et al. (2005) observed that rattail fescue's critical N requirement fell in the middle of the range, leaning towards the higher side. Rattail fescue also had one of the lowest RGR at both low and high N. This is similar to the other annual grasses grown in Cocks (1974) study, where *Lolium rigidum* and *Hordeum leporinum* at 15 weeks of growth had absorbed 2 and 7 times (respectively) more N in the low-density group and 4 times (for both) more N than rattail fescue in the high-density group. Rattail fescue's low RGR response to N is similar to its relationship with P, where it also has a low RGR response (Hill et al., 2005), but its requirement for N is greater than its need for P.

Rattail fescue's ability to grow in low nitrogen environments is evident when soils from disturbed and undisturbed land are compared. Stylinski & Allen (1999) evaluated the relationship between the vegetation community and soil variables from different kinds of unnatural disturbance: construction, heavy-vehicle activity, landfill operations, and soil excavation and tillage. These relationships were compared to those at undisturbed sites. While rattail fescue was one of the dominant exotic grasses found on disturbed sites, its cover did not vary significantly between disturbed and undisturbed sites. Native shrub cover was however significantly lower on disturbed sites. Total soil nitrogen and percent organic matter were also significantly lower on disturbed sites compared to undisturbed sites. Rattail fescue did not take advantage of the additional N at undisturbed sites and was unaffected by the lower availability of N at the disturbed sites, allowing it to dominate the exotic grass community.

2.3.1.3 Potassium

Rattail fescue seed germination and root penetration respond to soil potassium. Ozanne & Asher (1965) conducted a two-fold experiment evaluating rattail fescue response to potassium.

The first quantified rattail fescue seed weight and potassium content. The second explored the relationship between seed potassium content and root depth penetration in a potassium deficient soil. The authors found rattail fescue to have smaller seeds with a low level of in-house potassium. Seedling emergence and root penetration depth were affected by soil potassium deficiencies and there was a significant, positive correlation between root penetration depth and seed potassium. Amending the soil with potassium increased root penetration depth from approximately 1-3 cm to ~15 cm. The study did not define the upper and lower extents of rattail fescue's potassium requirements unlike how previous studies did for phosphorous and nitrogen.

2.3.2 Control & Management

Several forms of control have been explored over the last few decades. Tilling has been identified as the most effective way to control rattail fescue because it distributes the seed stock to a depth that isn't conducive to rattail fescue seed germination (Lyon et al., 2018). However, this is not a feasible approach for prairie management. Livestock grazing is not considered a viable option for control, at least on its own. It has been shown to be an ineffective form of control, although timing does matter (Milchalk & Dowling, 1996). Rattail fescue is also considered a poor forage for livestock due to sharp awns that livestock will actively avoid (Lyon et al., 2018). Prescribed burning is also potentially ineffective as a single treatment (Schillinger et al., 2010). A 2010 study explored no-till crop rotation combined with several different crop residue management approaches (Schillinger et al., 2010). Rattail fescue was present throughout the study but was not specifically part of the study. The authors did not observe a notable difference in rattail fescue cover following burning, regardless of herbicide application, and noted that the seed bank was likely enough to support resprouting in seasons following various management activities, including fire (Schillinger et al., 2010).

Chemical control has been found to have the greatest potential for successful control. The timing and type of herbicide application determines the effectiveness on control of rattail fescue. Pre-emergent and post-emergent herbicides have been explored, and the timing of application and type of herbicide plays a significant role in successful control of rattail fescue. Overall, early and consistent intervention has shown to be an effective control regime (Akhter et al., 2020, 2021; Ball et al., 2007; Forcella, 1986; Jemmett et al., 2008; Leys et al., 1991). Glyphosate and paraquat, both non-selective post-emergent herbicides, were explored early on by Leys et al. (1991). The authors found early application and multiple applications of either herbicide was crucial for effective control. Glyphosate was found most effective either when the seed heads were emerging or when rattail fescue was flowering; paraquat was most successful when rattail fescue was flowering and had more success than glyphosate at later applications (Leys et al., 1991). Ball et al. (2007) observed and recorded the effects of several herbicides on rattail fescue control within crops of winter wheat. Application of the pre-emergent flufenacet alone or in combination with a post-emergent herbicides sulfosulfuron, mesosulfuron, diuron, or imazamox provided consistent control across a wide range of PNW dryland conditions, and winter wheat yields were improved in plots with this application regime. In another study, pre-emergent herbicides tended to be even more effective than early and late post-emergent applications (Lawrence & Burke, 2014). The authors studied the effectiveness pyrosulam, mesosulfuron, and flufenacet. Herbicide treatments were applied either in early or late spring, or a fall application succeeded by another application the following spring. Lawrence & Burke (2014) did not find pyrosulam or mesosulfuron alone effective, but effectiveness increased when used either in conjunction with each other or with flufenacet. Ultimately the most effective treatments always used flufenacet, and the pre-emergent could be used alone (Lawrence & Burke, 2014). The use of the pre-emergent prosulfocarb was also shown to be the most effective treatment compared to a combined mesosulfuron and iodosulfuron treatment, however the same study found that rattail fescue had some tolerance to the standard application volume (Akhter et al., 2021). The use of pre-emergent herbicide and the appropriate timing of post-emergent herbicide applications were found to have the most success.

The timing of herbicide application also mattered when used in conjunction with other pasture management tools. Glyphosate was applied to pastures in fallow in a study by (Jemmett et al., 2008). The authors found that two sequential applications of glyphosate following emergence was the most effective treatment at 9 sites across three states (Washington, Idaho, and Oregon). The false seed bed technique combined with glyphosate applications has also shown success (Akhter et al., 2020). The false seed bed technique involves delaying crop sowing in prepped fields to allow rattail fescue to emerge, allowing land managers to manage for it before it adversely affects desired crops. Both approaches required multiple phases of management and were successful in settings where land was used for crop production. Another study found the false seed bed technique effectively reduced rattail fescue seed by 80% (Jensen, 2019). An earlier study by (Dowling et al., 1997) explored the use of herbicide alongside seeding of a subterranean clover and P fertilizer application. They found that herbicide application alone did not prevent rattail fescue regeneration, but with the addition of clover and P fertilizer, the clover was able to establish and prevent significant regrowth of rattail fescue.

2.3.3 Allelopathy

Rattail fescue has allelopathic effects that hinder germination and seedling growth of pasture and crops species. Dead tissues left on the surface leach allelopathic chemicals into the soil and ultraviolet light and moisture increase the effects (Pratley & Ingrey, 1990). Pratley &

Ingrey (1990) tested for the allelopathic effects by exposing potted soil to four different treatments: 1) one with no rattail fescue residue, 2) one with just residue, 3) one combining residue with UV light, and 3) one with residue, UV light, and moisture. Following these treatments, four pasture species were seeded. Rattail fescue's allelopathic effects reduced the germination of three species, reduced foliage production in all four species, and reduced root growth in three species. The authors of this study speculated that UV light worked to break down the residues, making it easier for chemicals to leach into the soil when moisture is introduced. Later research showed that late-stage decomposition of rattail fescue residues increased the allelopathic effects. Aqueous extracts were created by soaking decomposing rattail fescue residues between 2-110 days (An et al., 1997a). The length of decomposition determined the extent of allelopathic effects on winter wheat seed germination. With increased decomposition and extraction times, germination delay was extended, inhibition increased, and seed recovery became less likely (An et al., 1997a). Plant species and cultivars within species also impact the extent of seed germination inhibition and seedling development (An et al., 1997b). Later research also identified two allelopathic substances contained with rattail fescue, and again confirmed the effects of these chemicals on root and shoot production with a different group of pastures species (Kato-Noguchi et al., 2010). More recent research explored the use of powdered rattail fescue residues for weed management and the authors found rattail fescue is still effective at reducing root and shoot growth in a powdered form (Yamamoto & Kato-Noguchi, 2015). However, rattail fescue's allelopathic effects are reduced when the chemicals are diluted with soil. An et al. (1993) found that the ratio of soil to residue affected the phytotoxicity of the allelopathic chemicals. Soil added to aqueous extracts of rattail fescue worked to diminish the allelopathic effects. Building on these findings, a later study that incorporated rattail fescue residue into the soil (via tilling) minimized the allelopathic effect (An et al., 1996). If rattail fescue residue is left on the surface to break down it will leach allelopathic chemicals into the soil but removing it before this process occurs is sufficient to avoid the effects. Seeds of pasture species and crops exposed to concentrated rattail fescue residues, whether powdered or aqueous, experience adverse effects and reduced growth, but mixing residues with soil both dilutes the chemicals and inhibits the processes that generate allelopathic chemicals.

2.4 Summary

Rattail fescue, as an annual grass, has an advantage over native vegetation because its growth cycle starts before the perennial vegetation native to prairies. It has become more prevalent in agriculture settings due to adoption of no-till methods (Lyon et al., 2018) and more recently has spread via contaminated native seed stock used in prairie restoration (Alderman et al., 2011). It has a low requirement for Phosphorous and a medium requirement for Nitrate (Hill et al., 2005), and does not react strongly to added nutrients (Asher & Loneragan, 1967; Hill et al., 2005; Jones et al., 1961; Rossiter, 1964). Success with herbicide depends on timing and frequency of applications (Dowling et al., 1997; Jemmett et al., 2008; Lawrence & Burke, 2014; Leys et al., 1991), and some integrated methods have shown promise (Akhter et al., 2020; Jensen, 2019; Tozer et al., 2009). Rattail fescue also has alleopathic chemicals that can impede germination and establishment of pasture species (An et al., 1997a; An et al., 1997b; Kato-Noguchi et al., 2010; Pratley & Ingrey, 1990) and have even been explored as a weed management tool (Yamamoto & Kato-Noguchi, 2015). Control of rattail fescue in prairie restoration settings is challenging due to its presence within the seed stock and limited success with herbicide use. This study will build primarily on research focused on rattail fescue and its nutrient use and requirements, and it will bring insight to rattail fescue’s relationship with soil nutrients in restoration settings.

3. Methods

3.1 Site Background and Overview

This study focused on five prairie restoration sites in South Puget Sound (Figure 1). Each had varying levels of rattail fescue invasion and differing land use histories. All five sites have been managed for prairie restoration for varying lengths of time.

Figure 1.

South Sound Sample Sites

Note. Map showing location of sample sites in Thurston County, WA with an inset map showing location within the state.

3.1.1 Johnson

Johnson Prairie is in the southwest corner of the Joint Base Lewis-McChord military base, located between Tacoma and Olympia, Washington. The soils at Johnson are primarily

Spanaway gravelly sandy loam (Soil Survey Staff, NRCS, USDA, n.d.). This prairie has been co-managed by the military and the Center for Natural Lands Management (CNLM) for more than 20 years. The goal of this collaboration is to preserve and restore prairies on the base and maintain habitat for several federally endangered and threatened species, including the Taylor's checkerspot butterfly and the Mazama pocket gopher (Kronland & Martin, 2015). JBLM is home to approximately 95% of the remaining prairie habitat in the region primarily due to historical stewardship by Indigenous communities, and then military activities on the base since its establishment in 1917 (https://home.army.mil/lewis-mcchord/about/history). This gives Johnson a unique history compared to the other four sites for two reasons. First, it is the only one whose land use history does not include housing livestock or farming and so has not experienced the same level of nutrient inputs that occurred at the other four sites. Second, it has had the most consistent land use over the last century since the base was first established in 1917. Once under co-management by JBLM and CNLM, the site has shared similar management histories as the other sites in this study. Over the last 20 years or so, herbicide application, prescribed fire, and direct seeding have been implemented on the prairie to restore vegetation native to Puget Sound prairies that are vital for endangered and threatened wildlife populations.

3.1.2 Violet

Violet Prairie historically was used as a dairy farm. Nutrient inputs were primarily sourced from livestock waste, and possibly fertilizer additions to help maintain grazing conditions. Soils at Violet are primarily Spanaway gravelly sandy loam (Soil Survey Staff, NRCS, USDA, n.d.). Acquired by the Center for Natural Lands Management (CNLM) in 2013 for conservation, this prairie has now been managed for prairie habitat restoration for a decade. Two prescribed burns have occurred at the site where I sampled, followed by applications of pre-emergent herbicide and eventually direct seeding. In non-burn years the site is inspected, and an herbicide application plan is implemented based on site needs. Earlier on in the restoration process, the site received more broadcast applications of herbicide, but as direct seeding has led to native plant establishment, management has shifted to spot spraying invasives. Management activities have also varied between different parts of the site, with the south side of the prairie receiving more intensive management than the north side of the prairie.

3.1.3 Glacial Heritage

Glacial Heritage Preserve historically was maintained as open prairie by Indigenous people and then used for livestock grazing starting in the 1800s. Nutrient inputs were primarily sourced from livestock waste, and possibly fertilizer additions to help maintain grazing conditions. Soils at Glacial are primarily Spanaway-Nisqually soils consisting of gravelly sandy loam in the top 15cm with gravelly-ness increasing with increased depth (Soil Survey Staff, NRCS, USDA, n.d.). Glacial's restoration management history is the longest of all five prairies, extending to the early 1990s. After livestock were removed from the site in the mid-1900s, the site was heavily invaded by scotch broom and was the most heavily invaded by this invasive species of any of the 5 sites. The most recent burns at this site were in 2013 and in 2017. Early on in its management history, restoration activities focused on mowing, broadcast herbicide application and manual removal of scotch broom. As the invasive was cleared, more direct native seeding occurred. As native seeds established themselves, herbicide application became more targeted to focus on residual invasives that were competing with native establishment. This management style continues today, along with the manual removal of scotch broom and other invasives at the site. Historically, the site experienced grass-specific herbicide applications in the spring followed by a burn in the late summer/early fall which was followed by a post-burn broad spectrum herbicide application and then native seeding. This approach was used across most PNW prairie restoration sites for at least a decade (Stanley et al., 2011).

3.1.4 Tenalquot

Tenalquot Prairie historically housed a horse farm. Like previous sites, nutrient inputs would have primarily been from livestock waste and likely fertilizer applications to maintain grazing conditions. Soils at Tenalquot are also Spanaway gravelly sandy loam (Soil Survey Staff, NRCS, USDA, n.d.). Tenalquot was acquired by The Nature Conservancy in 2006 and transferred to CNLM in 2014 and has been managed for prairie habitat restoration for 17 years. Of the 5 sites, Tenalquot has had the most prescribed burns in the area I sampled in the past 15 years, with 4 separate prescribed burns with a fire return interval of 2-4 years. Typically following these burns, a combination of spot spraying herbicide and direct seeding was used to help establish native plants at the site. From year-to-year, management activities have included hand pulling scotch broom and spot-spraying non-native perennial grasses and forbs, depending on site needs.

3.1.5 Deschutes

Deschutes Prairie Preserve historically also housed a horse farm, and nutrient inputs would have been from similar sources (livestock waste, fertilizer applications). Like the previous prairies described, the primary soils at Deschutes are Spanaway gravelly sandy loam (Soil Survey Staff, NRCS, USDA, n.d.). CNLM has managed Deschutes for the shortest length of time of all sites as it was acquired in 2014 and so has a nine-year restoration management history. In the time there has been one prescribed burn along with annual herbicide and hand-removal of invasive vegetation. A unique management action at this prairie, same as Violet, is the use of pre-emergent herbicide following the burn at the site. A horse farm is still located adjacent to the site, and a paved, public hiking trail passes through the middle of the site.

Table 1.

Prairie Site Management History

Site	Soil Type	Land Use History	Length of Time Managed	Prescribed Burns Since 2005	Herbicide	Native Seeding
Johnson	Everett-Spanaway complex & Spanaway gravelly-sandy loam	Artillery practice	>20 years	1-4	Broadcast application of glyphosate; spot spraying of grass- and forb-specific herbicide	Yes
Violet	Spanaway gravelly-sandy loam	Livestock grazing	10 years	2	Fall Pre-Emergent; Broadcast application of glyphosate; spot spraying of grass- and forb-specific herbicide	Yes
Glacial	Spanaway-Nisqually complex	Livestock grazing	>30 years	2	Broadcast application of glyphosate; spot spraying of grass- and forb-specific herbicide	Yes
Tenalquot	Spanaway gravelly-sandy loam	Horse farm	17 years	4	Broadcast application of glyphosate; spot spraying of grass- and forb-specific herbicide	Yes
Deschutes	Spanaway stony sandy loam & Spanaway gravelly sandy loam	Horse farm	9 years	1	Fall Pre-Emergent, Broadcast application of glyphosate; spot spraying of grass- and forb-specific herbicide	Yes

Note. Prescribed burn data prior to 2005 was unavailable.

3.2 Field Methods

3.2.1 Plot selection

At each of the five sites, areas of low- moderate-, and high-levels of rattail fescue infestation were qualitatively identified, and three plots were sampled each of the areas for a total of 9 plots per site. This approach was used to capture soil conditions under the various rattail fescue coverage unique to each site. These observations also ensured that there was an informed selection method that helped capture the true variation in coverage rather than sampling at the first spots where rattail fescue was observed. Levels of infestation were then determined quantitatively using the point-intercept method, explained below. A PVC 1 meter x 1 meter quadrat was placed selectively to ensure capture of soil conditions in various states of rattail fescue infestation. The overall goal was to capture a range of the variability of rattail fescue and the related soil conditions at each site. Comparisons were done within site and across sites. Plots were placed at least 3 meters apart.

3.2.2 Vegetative cover

Vegetative cover was measured using the point-intercept method. The PVC 1 meter x 1 meter quadrat was augmented with 8 pieces of twine, 4 evenly spaced along the horizontal axis and another 4 evenly spaced along the vertical axis. These created 16 intersecting points. A metal rod with a 5-millimeter circumference was placed at each intersecting point and lowered to the ground. Vegetation and ground conditions (bare ground, moss, wood, or rock) touching the metal rod were recorded in the quadrat for a total possible 16 observations per sample plot. For data analysis, the number of recorded observations for rattail fescue was divided by the total number of possible observations and multiplied by 100 to convert to percent cover.

3.2.3 Soil cores for Soil Nutrient Analysis

All soil cores were collected using a 5cm diameter, 14cm tall PVC pipe hammered to a maximum depth of 14cm. Rattail fescue roots can grow up to 15-23cm depending on the soil type and topsoil layer depth (Lyon et al., 2018). One sample was collected at each corner of a sample plot (with some exceptions when there were too many rocks to sample on the corners). Cores from a single plot were mixed to create a homogenous composite sample from which approximately 2 cups of soil were collected into paper sample bags with an interior plastic coating to be sent to Midwest Laboratories for testing.

3.2.4 Soil cores for Bulk Density

A single, separate core was collected from the middle of each plot for bulk density testing. The standard depth used to collect these soil cores was 14cm. The core was placed into a labelled Ziploc bag. Each bag was then placed into a backpack with other samples to be processed later the same day. Bulk density tests were performed by me in a lab at The Evergreen State College.

3.3 Sample Processing

3.3.1 Bulk Density

Bulk density samples were transported to the lab and deposited into aluminum bread loaf baking tins for drying and weighing. Prior to drying, vegetative material and large rocks were removed from the sample. All soils were dried for 12-24hrs before being weighed with a standard scale (not analytical scale). After the weight was collected, the soil was removed and the container brushed and wiped cleaned. Then the container was weighed separately so its weight could be subtracted from the weight of the dried soil sample and tin combined.

3.3.2 Soil moisture

Soil samples for soil moisture tested were taken from the composite sample created initially for the soil nutrient analysis. Approximately ¼ cup of soil was gathered and stored in a labeled Ziploc bag with all air removed. These samples were placed into a backpack with other samples to be processed later the same day. Soil moisture tests were performed by me in a lab at The Evergreen State College.

Soil moisture was measured using the Oven Drying Method. A ceramic crucible was marked with the sample ID and weighed using an analytical scale. This weight was recorded and the scale was tared. Using a metal scoop, soil was transferred from the Ziploc bag to the crucible. Vegetative material was removed during the transfer process. The crucible with soil was weighed again and this weight was recorded. Samples were then lightly covered with aluminum foil to minimize spillage. After a period of 24hrs in the oven at 110°C each sample was weighed again using the analytical scale with the foil removed. This weight was recorded, and the crucible weight recorded at the beginning of the process was subtracted to find the true dry weight of the soil.

3.3.3 Soil nutrients

Soil samples were sent to Midwest Laboratories for nutrient testing. Table 2 summarizes the protocols used for each of the tests completed.

Table 2.

Midwest Laboratories Testing Methodology

Variable Tested	**Method**	**Reference**
Potassium, Magnesium, Calcium, Sodium, CEC	Ammonium Acetate Extraction / ICP-AES Analysis	NCR, Chapter 7 (Cations) & SERA, Chapter 4.6 (Sulfur) / EPA 6010B
Sulfur, Zinc, Manganese, Iron, Copper, Boron	Mehlich 3 Extraction / ICP-AES Analysis	SERA, Chapter 4.3 / EPA 6010B
Nitrate	Potassium Chloride Extraction / Automated Cadmium Reduction	NCR, Chapter 5 / EPA 353.2
pH	pH 1:1 (Soil:Water), pH 1:2 (Soil:Water)	NCR, Chapter 4
Phosphorous	Weak Bray Extraction (1:7) / Colorimetric	NCR, Chapter 6
Organic Matter	Gravimetric Determination with High Temperature Oxidation	NCR, Chapter 12
Salts	EC 1:1 (Soil:Water) EC 1:2 (Soil:Water)	NCR, Chapter 13

Reference: Midwest Laboratories (n.d.). Soil Testing Methods sheet is available from Midwest Laboraties by request.

3.4 Data Analysis

Data were checked for linear relationships between the dependent and independent variables. The backwards stepwise regression uses the Akaike information criterion (AIC) to determine if a variable should be retained or removed. Following that was a test for multicollinearity that used Variance Inflation Factor (VIF) to determine if variables retained in the suggested model from backwards stepwise regression had multicollinearity issues. After ensuring no issues, the final suggested independent variables were used in a new multivariate linear regression model to determine which factors were significant using a P-value of 0.05. Significant factors were used to create the final model formula for a mixed effects model that used site as a random factor and significant soil metrics as fixed effects. The model tested whether site had a significant effect on the relationships between rattail fescue percent coverage and the final retained significant independent variables. The version of RStudio used was R-4.3.2 and the following packages: tidyverse, caret, olsrr, leaps, AER, plm, lmerTest, lme4, afex, effects, car, ggplot2, and viridis (Posit Team, 2023).

4. Results

Average rattail fescue percent cover ranged from 35% at Violet to 67% at Glacial (see Table 3). Violet was also the only site with less than 50% percent cover. Average nutrient values (in ppm) also tended to be higher at Violet than the other 4 sites. This included Nitrate, however Iron content was similar to all other sites besides Glacial. Tenalquot and Deschutes both had 56% average rattail fescue cover, but differed slightly in their average Nitrate content (Tenalquot = 1.9ppm, Deschutes = 2.3ppm) and average Iron content (Tenalquot = 46.3ppm, Deschutes = 38.1ppm).

The backwards stepwise regression model retained Nitrate, Iron, Sulfur, and Boron in the final suggested formula, starting from an AIC= -117.55 and ending with an AIC = -138.13 (Table 3). The VIF scores came back as all less than 5. Values at 5 and greater are cause for concern and the higher scores indicate higher multicollinearity (James et al., 2013).

Four variables were retained by the stepwise regression and suggested for use in a multivariate linear regression model: Nitrate, Iron, Sulfur, and Boron. Nitrate and Iron remained statistically significant, and Sulfur and Boron were no longer significant at the $P < 0.05$ level (Table 3). Following this, a mixed effects model was created using Iron and Nitrate as fixed effects with site as a random effect to see how the relationship between these variables and rattail fescue percent coverage varied by site.

Table 3.

Summary of Raw Data

	Johnson		Violet		Glacial		Tenalquot		Deschutes	
Variable	**Avg**	**STDEV**	**Avg**	**STDEV**	**Avg**	**STDEV**	**Avg**	**STDEV**	**Avg**	**STDEV**
Rattail Percent Cover	60%	±11%	35%	±20%	67%	±23%	56%	±30%	56%	±32%
Phosphorous	19.2	±5.0	136.9	±48.5	27.0	±10.2	14.4	±6.0	17.7	±7.7
Nitrate	2.8	±1.0	5.4	±2.2	2.1	±1.2	1.9	±0.6	2.3	±1.1
Sulfur	39.0	±6.9	25.3	±13.0	38.0	±9.4	39.9	±10.1	29.8	±16.9
Potassium	82.9	±18.5	138.1	±67.3	71.9	±14.5	74.2	±39.3	70.7	±23.0
Magnesium	58.1	±9.9	156.0	±31.2	70.1	±37.2	54.0	±13.4	40.1	±10.8
Calcium	419.4	±89.4	1550.8	±267.2	479.1	±322.9	373.0	±101.0	514.4	±219.0
Sodium	13.7	±1.3	14.1	±2.2	24.0	±12.5	15.6	±2.4	14.2	±2.3
pH	5.3	±0.1	5.8	±0.2	5.4	±0.4	5.3	±0.1	5.5	±0.3
Organic Matter	18.5	±2.2	11.7	±2.7	19.3	±3.8	13.4	±2.1	13.2	±8.0
CEC	4.2	±0.8	11.9	±1.7	4.4	±2.0	3.7	±0.8	4.2	±1.3
Salts	0.1	±0.1	0.2	±0.1	0.2	±0.0	0.1	±0.0	0.1	±0.0
Percent Soil Moisture	28%	±5%	30%	±3%	27%	±4%	22%	±4%	21%	±5%
Bulk Density	25.5	±4.8	24.0	±4.5	27.5	±6.3	24.0	±3.6	29.4	±7.5
Zinc	10.5	±16.2	18.7	±5.5	1.3	±0.4	0.9	±0.3	0.9	±0.7
Managense	23.3	±4.7	21.6	±2.7	26.7	±8.5	24.0	±7.8	13.1	±8.0
Iron	44.3	±19.1	46.1	±14.5	61.4	±13.7	46.3	±11.9	38.1	±20.6
Copper	1.4	±1.3	10.1	±6.4	0.4	±0.1	0.3	±0.0	0.4	±0.2
Boron	0.2	±0.1	0.2	±0.0	0.2	±0.0	0.2	±0.1	0.2	±0.1

Note. Summary of raw data for all independent variables, and Rattail Percent Cover, for each site. Values from the 9 plots per site were averaged and standard deviation calculated. All variables are in ppm unless otherwise noted.

Table 4.

Results of Initial Model Building

Variable	**Initial Linear Regression P-value**	**Initial Linear Regression AIC**	**Backwards Stepwise Regression Final Formula AIC**	**VIF score**	**Linear Regression P-value**
Organic matter	0.40	-118.30	NA	NA	NA
Phosphorous	0.48	-118.68	NA	NA	NA
Potassium	0.45	-119.53	NA	NA	NA
Magnesium	0.42	-118.42	NA	NA	NA
Calcium	0.97	-119.54	NA	NA	NA
Sodium	0.47	-118.61	NA	NA	NA
pH	0.89	-119.52	NA	NA	NA
CEC	0.81	-119.45	NA	NA	NA
Zinc	0.83	-119.47	NA	NA	NA
Manganese	0.61	-119.10	NA	NA	NA
Copper	0.98	-119.55	NA	NA	NA
Salts	0.68	-119.26	NA	NA	NA
Percent Soil Moisture	0.15	-115.85	NA	NA	NA
Bulk Density	0.74	-119.36	NA	NA	NA
Sulfur	0.23	-116.99	-136.74	1.32	**0.08 .**
Boron	0.25	-113.96	-136.18	1.72	**0.06 .**
Iron	0.08	-117.18	-131.21	1.74	**0.01***
Nitrate	0.32	-117.78	-125.44	1.29	**<0.01*****

*Note. Significance codes: ‘***’<0.001 ‘**’<0.01 ‘*’<0.05 ‘.’<0.1. Initial Linear Regression AIC value = -115.55. Backwards Stepwise Regression Final Formula AIC value = -138.1. Variables carried over into the mixed effects model are bold type.*

In the mixed effects model, there was an inverse relationship between soil nitrogen and rattail fescue cover at Violet, Glacial, and Deschutes and a positive relationship at Johnson and Tenalquot (Figure 2). Violet Prairie expressed the strongest inverse relationship of all the sites and was the only site with nitrate values greater than 5ppm. Most of the predicted values are concentrated in the upper left corner of the graph (low nitrogen, high rattail fescue cover) and the number of data points declines as nitrate increases, and above the 5-ppm nitrate mark all data points are from Violet Prairie.

Soil iron and rattail fescue had an overall positive relationship (Figure 3). Deschutes was the only site to have an inverse relationship between iron and rattail fescue. Predicted iron varied somewhat between sites. Notably, Violet had the lowest predicted values although the sample average value was similar to other sites. Tenalquot, Glacial, and Johnson all had similar amounts of predicted soil iron, although Glacial had the highest observed sample average, 61.4ppm compared to 46.3ppm at Tenalquot and 44.3ppm at Johnson. This is strikingly different from the rattail fescue coverage/nitrate relationship.

Figure 2.

Predicted Vulpia Coverage & Nitrogen

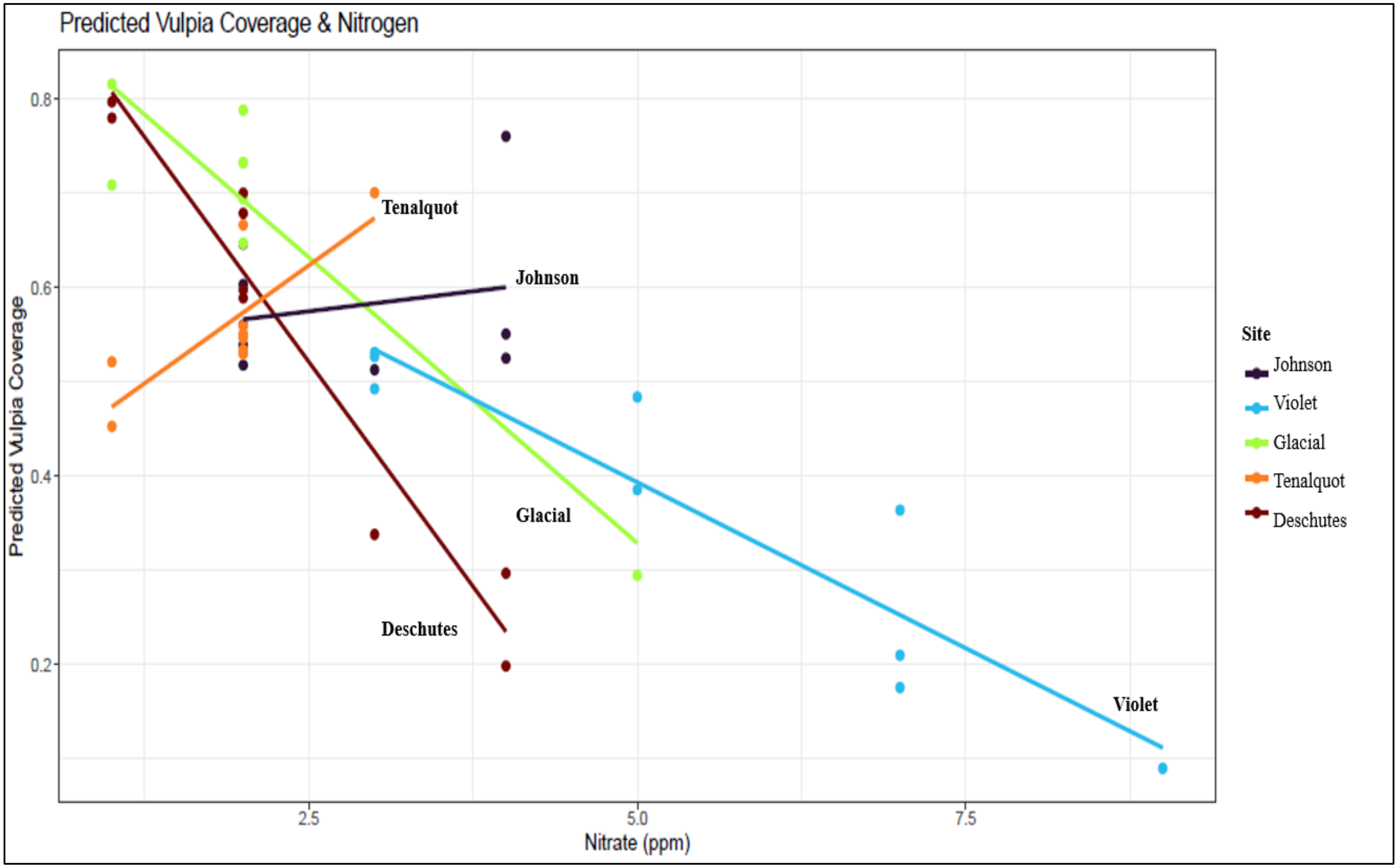
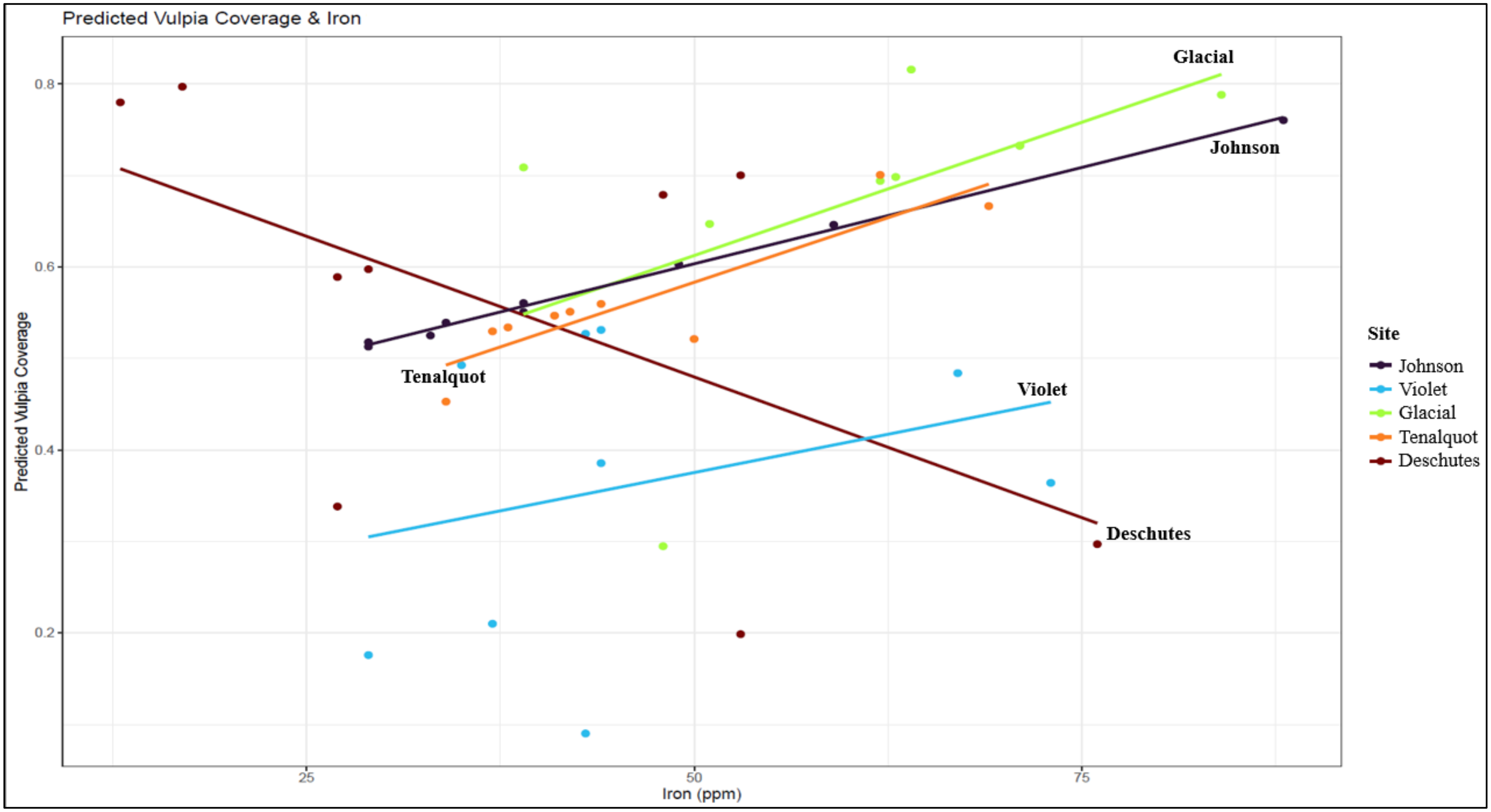


Figure 3.

Predicted Vulpia Coverage & Iron



5. Discussion

Rattail fescue *(Vulpia myuros)* has become increasingly problematic over the last few decades within the Pacific Northwest. The invasive annual grass began causing issues for crop producers and proved difficult to manage with herbicide alone. More recently, rattail fescue has spread to more non-agricultural settings including South Puget Sound prairies managed for restoration. Prairies naturally have low nutrient soils but land use activities such as farming and livestock grazing increase soil nutrient availability. Both of these land use activities are part of the history of prairies in the area that are now undergoing restoration, and increased nutrient availability (primarily nitrogen) has made them more susceptible to non-native species invasions (Dennehey et al. 2011). This study explored what kind of relationship exists between rattail fescue and prairie soils with these land use histories. The overarching goal was to provide land managers with data to support their restoration efforts.

5.1 Nitrogen

In this study, nitrogen had an inverse relationship with rattail fescue, which aligns with previous work (Cocks, 1974; Hill et al., 2005; Jones et al., 1961). When comparing the presence of desirable or non-desirable grasses with the amount of nitrogen fertilizer applied over a period of years, Jones (1961) found rattail fescue at 7 of the 11 sample locations and 5 of these showed an inverse relationship between rattail fescue and nitrogen. These results were not statistically significant, but they do show a similar inverse trending relationship between the variables. On the other hand, a more recent study performed by Stylinski & Allen (1999) found that variation in nitrogen levels between sites did not explain variations in rattail fescue levels, even when nitrogen variation between sites was statistically significant.

This study was also a chance to understand the impact of land use history and management activities on the rattail fescue and soil nutrient relationship. Two of the inverse relationships were at sites where a pre-emergent herbicide was used, Deschutes and Violet, and both sites have the shortest management history. Pre-emergent herbicide has been identified as one of the most effective methods for controlling rattail fescue (Ball et al., 2007; Dowling et al., 1997; Jemmett et al., 2008; Lawrence & Burke, 2014). Pre-emergent was not used at Glacial, the third site with an inverse relationship, but this site does have the longest management history of all five prairie sites. While the rattail fescue challenge began relatively recently within Glacial's management history, the site has had the longest time to allow native vegetation to establish. Tenalquot and Johnson had weak positive relationships between rattail fescue and soil nitrogen content even though these sites have received similar treatments to Glacial. Overall, higher soil nitrogen content at recently converted sites has not been enough to impede the success of restoration activities.

Rattail fescue's low nitrogen requirement lends to the successful management at these sites. A study exploring the growth of rattail fescue in response to nitrogen and phosphorous applications found that rattail fescue was one of three species that had the lowest relative growth rate at both high and low N applications (Hill et al., 2005). This finding helps explain why soils with higher levels of nitrogen present did not necessarily have higher rattail fescue coverage. While previous studies have shown rattail fescue's overall inverse relationship with nitrogen, my study highlights the effects of vegetation management activities on rattail fescue's ability to grow in soils with differing nitrogen levels.

5.2 Iron

This is the first study to show a statistically significant relationship between rattail fescue coverage and soil iron content. No previous studies have focused on or reported iron in their results. Interestingly, all sites except for Deschutes showed a strong positive relationship between the two variables. Iron is a micronutrient that plants need in small amounts to aid in the synthesis of chlorophyll (Rout & Sahoo, 2015). Rattail fescue's overall positive relationship with iron could possibly be due to the soil iron content range remaining below an unknown upper limit of rattail fescue's need for iron. Research has shown the upper limit of rattail fescue's need for phosphorous: it reached its maximum growth at 1 micromole P while other grasses in the study required higher P concentrations to achieve maximum growth (Asher & Loneragan, 1967). Rattail fescue has also been shown to have a low requirement for nitrate (Hill et al., 2005). Perhaps rattail fescue has a greater use or need for iron than these macronutrients, or higher levels of soil iron are required before rattail fescue experiences adverse effects.

5.3 Site Effects

5.3.1 Johnson

Johnson showed a slight positive relationship between predicted percent rattail fescue coverage and soil Nitrate. Sample plots at this site were relatively uniform with similar sun exposure, ground cover, and thatch conditions. Johnson has also been managed for over 20 years in conjunction with military training by JBLM. It is interesting that this site had a slight positive relationship between nitrate and rattail fescue cover, considering it had the least amount of nutrient input compared to the other four sites that were previously used either for livestock grazing or as a horse farm, both of which would have some level of manure input.

Johnson was one of four sites to show a strong positive relationship between soil iron content and rattail fescue coverage. It is unclear why the site has the levels of soil iron that it does. Again, these plots had relatively uniform environmental conditions, and it is interesting that while nitrate values were also fairly uniform, the iron values varied enough to have a much stronger relationship.

5.3.2 Violet

Land use at Violet prior to management by CNLM was livestock grazing and use as a dairy farm. Areas of this site have been heavily managed to control invasive plant species, prior to and in response to the invasion of rattail fescue. These management activities have likely had an impact on the amount of rattail fescue present at the site and within sample plots. Plots with the highest soil nitrate concentrations also had very high thatch levels. Violet plot conditions varied more widely than at other sample sites, both in management history and current habitat conditions. There are not enough data points alone here at this site to directly attribute the thatch cover or soil nitrate as elements that can explain rattail fescue percent cover, however it does suggest that rattail fescue's success in high nitrogen environments can be impeded by shade. This, along with the difference in previous herbicide treatments across the plots, could help explain the difference in rattail fescue percent cover in the presence of high or low values of nitrogen.

Violet was one of four sites to have a strong positive relationship between rattail fescue cover and iron, although Violet also had the least amount of iron of all 5 sites. Manure is a source of iron (Schulte, n.d.) so perhaps the previous land use is a contributing factor to the amount and distribution of soil iron at this site.

5.3.3 Glacial

Glacial has been under prairie restoration management longer than any of the other sites, which could explain the overall low nitrogen content of the soil. Of the three sites with an inverse relationship, Glacial was the only one that did not receive an application of pre-emergent herbicide. Historically, the site did experience grass-specific herbicide applications in the spring and a broad-spectrum herbicide in the fall following prescribed burns. It has also been over a decade since the removal of dense scotch broom growth in the sampled areas but sparse individual plants remained. Scotch broom has also been shown to have allelopathic effects and can have negative legacy effects on soil even after its removal (Slesak et al., 2022). Even 4 years post removal, plots where scotch broom was removed had worse soil conditions for native plant species recovery than did areas where scotch broom had never grown (Slesak et al., 2022). Perhaps at Glacial, the history of extensive scotch broom invasion created pockets of high nitrogen in the soil and thus when the invasive annual rattail fescue was introduced, it spread to soil that still hadn't fully recovered from a previous invasive plant community. It is interesting though that of the three sites with inverse relationships, Glacial had some of the highest percent cover of rattail fescue in the monitoring plots. The highest percent cover of rattail fescue at Glacial occurred in conditions that were like Deschutes: plots located on the southeast side of Douglas fir trees. The high percent cover of rattail fescue at Glacial could be due to the local effect of this conifer species, such as impacts to soil properties and protection from the elements like sunlight, wind, and rain, instead of the low nitrogen content of those plots. Similar patterns have been found in grassland ecosystems where conditions created by conifers favor non-native species (Metlen et al., 2013). The previous management activities where the rest of the sample plots were located may have confounded the findings of higher nitrogen levels negatively impacting the success of rattail fescue growth.

Glacial was one of four sites that had a strong positive relationship between iron and rattail fescue coverage. The reason for this relationship is unclear because of the lack of research on rattail fescue's use of iron. It's also unclear why this site is has the highest iron of the five sites. Given that this site has been under management the longest, perhaps it suggests that native prairie vegetation has a relatively low requirement for iron.

5.3.4 Tenalquot

Rattail fescue percent coverage at Tenalquot revealed the strongest positive trend of all five sites. This site was previously a horse farm and has been managed by The Nature Conservancy and then CNLM for the past 17 years. Since 2007 the area I sampled has seen four prescribed burns that were followed by direct seeding. Pre-emergent herbicide has not been applied at this site which is one major difference between Tenalquot and the two prairies (Deschutes and Violet) that did receive treatments. The relationship expressed at Tenalquot site could be partly attributed to this different management approach.

Another major management difference at Tenalquot is more frequent prescribed burns. It is difficult to say to what extent burning could have impacted rattail fescue coverage since fire effects on soil and vegetation on these sites have not been directly studied. However, soil nitrate increased post burn in Columbia Basin sagebrush shrubsteppe ecosystems (Nichols et al., 2021) and in grasslands in the southwest United States (Fultz et al., 2016). Increased resource availability could make an ecosystem more susceptible to invasion (Nichols et al., 2021), however the increase is relatively short lived, lasting 2-6 months in southwest grasslands (Fultz et al., 2016). Managers at Tenalquot have followed prescribed burns with native seeding and, given that Tenalquot has the most fire activity of the 5 sites, these actions could have led to increased spread of rattail fescue. Fire clears vegetation and debris, reducing shade and increasing space and nutrient availability, particularly for early season annual species. This pattern has been well established for cheatgrass (*Bromus tectorum*), an invasive annual grass species that has invaded millions of acres of the intermountain West (Knapp 1996). More research on rattail fescue's response to shading and fire would be necessary to make a definitive conclusion.

5.3.5 Deschutes

Deschutes is one of three sites that expressed a strong inverse trend between predicted rattail fescue coverage and nitrate. Management history following its time as a horse farm includes one prescribed burn, the application of pre-emergent herbicide, and native seeding. As discussed previously, the use of pre-emergent at this prairie could have contributed to the inverse relationship observed between rattail fescue coverage and nitrate. Of all sites sampled, this one has experienced the least prescribed burning compared to other sites.

Deschutes is the only site to express an inverse relationship between soil iron and rattail fescue coverage. It is unclear why Deschutes had the lowest averagee iron values of the 5 sites, and why it is the only one to have inverse relationships for both nitrate and iron with rattail fescue coverage. Tenalquot was also used previously as a horse farm, but it had positive relationships for both nitrate and iron. Deschutes has the shortest management history of all sites, so perhaps management activities at other sites are influencing this relationship.

5.4 Areas of future research and implications for land management

Several avenues are available for future research opportunities. First, it would be valuable to explore how soil iron varies among prairie sites and the effect of manipulating iron with soil amendments on rattail fescue coverage. Future management actions could include lime applications to reduce soil iron to potentially limit the spread of rattail fescue. Second, studying the direct relationship between iron and rattail fescue (similar to the nitrate and phosphorous studies) would provide valuable information to better understand exactly how rattail fescue responds to varying iron levels. Finally, it is worth exploring the effects of conifers on rattail fescue spread. This should include comparing open prairie soils to soil under conifers to understand the effect of conifers on soil properties. This should also include the environmental conditions within the vicinity of conifers that could influence rattail fescue spread, such as the effect of shading.

6. Conclusion

This study took advantage of a unique opportunity to contribute to a local restoration issue that lacks the research necessary to make informed decisions. Previous research exploring rattail fescue infestations did not include infestations in restoration settings, let alone prairie habitats. Through this work, I was able to bring together the previous literature and explore the relationship between rattail fescue and soil in a new way. Synthesizing this research in a prairie restoration setting is new and necessary for local site managers to successfully restore prairies while preventing the establishment of yet another invasive species. Previous research had shown some promising data trends, but were not conclusive enough to paint a definitive picture of how soil conditions influence rattail fescue growth in a restoration context. This study aimed to explore rattail fescue in a new setting and hopefully result in management suggestions.

Previous literature tended to report an inverse relationship between rattail fescue and soil fertility. Repeatedly, rattail fescue seedlings responded poorly to increased nutrient applications, primarily in phosphorous studies, but also within the few nitrogen studies. Studies exploring rattail fescue's nutrient needs tended to report an ability to grow in low nutrient environments, somehow able to extract phosphorous effectively in settings where other vegetation struggled, potentially explaining why, when more nutrients are present, rattail fescue does not suddenly explode like we see with other invasives. When it did have a positive relationship with nutrient content, the relationship was weak. It is possible that rattail fescue simply is well equipped to grow in low nutrient environments, but once more nutrients are introduced, other plants have the resources they need to increase their coverage while rattail fescue's coverage declines. If this is the case, it could have implications for management at these sites.

Integrated pest management is already employed at the sites evaluated in this study. Managers use a mix of targeted herbicide and burning to remove invasives. Burning also has the benefit of being a historic cultural practice influencing prairie ecosystem dynamics. Managers are seeking possible soil amendment treatments to help combat rattail fescue. Lime amendments could be a potential management action to reduce soil iron and potentially limit rattail fescue's ability to spread. It is possible that over the course of several years, a combination of planting, herbicide application, and lime amendments could produce the conditions that are of greater benefit to desired vegetation than that of rattail fescue. If managers decide to test this theory out, it would be worth documenting their efforts to evaluate the effects of these methods over the management period. Hopefully this suggestion can lead to improved management of rattail fescue on local native prairie sites, as they are important both ecologically and culturally.

As invasive species continue to spread and impede restoration efforts, we race to understand both the species and how to manage them. All too often invasive management is held back by a lack of information, and managers face constant trial and error to explore what will work on their sites. While this study does not remove the need for trial and error, hopefully it leads to better informed management attempts that could lead to improved results in the years to come. Rattail fescue suddenly showed up on these restoration sites in the last 6-7 years, and hopefully it's not too late to do something about it. Based on the previous research and this study, I am hopeful that with continued integrated pest management practices, these sites will see a decline of rattail fescue, even as potentially contaminated seed stock continues to be spread. Hopefully this study helped to uncover another piece to the puzzle of rattail fescue management, no matter the setting.

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