Revegetation as a method for dust mitigation along reservoir drawdown zones

by

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B.Sc., University of Northern British Columbia, 2021

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Abstract

Large-scale industrial development, such as construction of hydroelectric dams and reservoirs, can have long-lasting environmental and social impacts on communities and surrounding ecosystems. Williston Reservoir, located in northern British Columbia, is one example where intense wind erosion and fugitive dust impacts the local community of Tsay Keh Dene and surrounding area. To try and address the dust impacts, BC Hydro, the public utility that operates the reservoir, and Tsay Keh Dene Nation, have established the Williston Dust Mitigation program with the goal of reducing fugitive dust emissions along the reservoir. Dust mitigation trials have been implemented for over three decades, but efforts have struggled to scale due to factors like remoteness, challenging reservoir environment conditions, cost, and the capacity to scale mitigation solutions. To help inform the WDMP's efforts, I investigated how vegetation may be used to mitigate dust at the necessary scale to address the issue. My first study involved conducting greenhouse and field experiments to select plant species suitable for revegetation efforts, which found cover crop species, like *Secale cereale* and *Avena sativa*, to be best suited for annual seeding in regions of the drawdown zone that flood every year, while some native grasses like *Elymus trachycaulus* and *Elymus lanceolatus* may be good candidates for higher elevation regions that do not flood every year. The second study investigated seeding rates and the application of fertilizer, along with measuring dust emissions across a 120-hectare beach to determine how varying treatments influenced total vegetation cover, and how vegetation cover impacted fugitive dust emissions. Vegetation cover was found to significantly reduce fugitive dust emissions and the application of fertilizer significantly increased vegetation cover. This suggests that fertilizer should be applied in moderation with cover crop planting to bolster early plant growth, but that the application be properly calculated so that excess nutrients do not leach to into the reservoir environment and costs are reduced. Overall, using cover crops in annually flooded areas of Williston Reservoir appears to be the most cost-effective dust mitigation treatment, while restoration efforts in higher drawdown zone areas using native plants should be explored further.

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1 Introduction

1.1 Hydroelectric Generation in British Columbia and the Challenges of Mitigating the Impacts

Large-scale industrial activities that reshape landscapes, such as the construction of hydroelectric reservoirs, can result in profound alterations to ecosystems and surrounding communities. These changes can have significant consequences on ecosystem health, such as a loss in biodiversity, a decrease in water quality, and loss of wildlife habitat. Local communities can be impacted through the disruption to livelihoods, recreational opportunities, and cultural and spiritual connections with the land. For large-scale hydroelectric projects, comprehensive planning and consultation must be done prior to construction, and a plan for proper compensation, mitigation, and restoration must be established to address both the short and long-term impacts (Egre & Milewski, 2002; Wang et al., 2014). Unfortunately, many hydroelectric projects, such as those built in the province of British Columbia, were constructed before comprehensive environmental impact assessments were required by law. Thus, there are many long-lasting impacts that never had proper management plans created to address them.

In British Columbia, hydroelectric facilities have been used to produce power since the late 1890's, when facilities such as Bonnington Falls were constructed and operated for local power production by West Kootenay Power (Canadian Hydropower Association, 2008). In the early 1900's additional facilities were constructed near Vancouver to support the cities growing electricity demand, while larger facilities, like Brilliant Dam on Kootenay River and Kenney Dam on the upper Nechako River were built in the 1940's and 1950's to support energy intensive smelting activities (Bradford, 2022; Columbia Power, 2013). In the 1960's the Provincial Government implemented the "Two Rivers Policy", led by then Premier W. A. C. Bennett, which resulted in the construction of several large hydroelectric facilities along both the Peace and Columbia River systems with the goal of increasing the provincial hydroelectric capacity to support industrial development in the province (Tomblin, 1990). The dams constructed during the Two Rivers Policy era make up the backbone of British Columbia's current hydroelectric generating capacity, but these dams and reservoirs were constructed prior to any environmental impact assessment policy or legislation. These came later in 1973 through the Federal Government's Environmental Assessment and Review Process and provincially in 1995 through the Environmental Assessment Act (Government of Canada, 2023; Haddock, 2010). The lack of proper impact assessment prior to construction, along with the sheer scale of the projects, such as the W.A.C. Bennett Dam and Williston Reservoir on the Peace River system, have resulted in large and long-lasting environmental impacts that require ongoing mitigation measures decades after completion.

A major challenge for implementing mitigation projects around hydroelectric reservoir is often their remoteness (McAnulty & Baroudi, 2010). Developing the necessary infrastructure to support a project can be challenging in remote areas (Hay et al., 2017; Sidawi, 2012). Establishing road access, riparian crossings, and maintaining transportation networks to access an area may be expensive, environmentally disruptive, and can cause cumulative and unintended effects. Transporting equipment, materials, and supplies can be difficult, add extra costs, and a lack of established supply chains can lead to delays that impact logistics. Finding a skilled workforce can be a challenge in remote locations due to low population numbers, a lack of training and experience, and few social and healthcare amenities (Hay et al., 2017). Indigenous communities often have unique cultural, social, and economic considerations in remote regions (Anaya, 2005; Papillon & Rodon, 2017). Engaging with these communities, understanding the responsibility of all parties involved, and involving them in all the steps of a project is vital for obtaining social license, minimizing project conflicts, and maximizing the co-benefits (Angell & Parkins, 2011; Brock et al., 2021). All these factors are important to consider when implementing projects to mitigate or restore landscape level impacts from projects such as hydroelectric dams and reservoirs.

Efforts to mitigate negative effects around hydroelectric reservoirs must also be approached with the understanding that ongoing annual interventions may be necessary (Allen & Klimas, 1986; Burton, 2010; Nilsson & Keddy, 1988; Vilmundardóttir et al., 2010). Reservoirs are dynamic systems affected by factors such as sediment deposition, water flow, and changing climate conditions (Men et al., 2019; Şen, 2021). A long-term commitment is required for monitoring, maintenance, and adaptation to ensure that mitigation strategies remain effective. Reservoirs may require approaches that would typically be viewed as unorthodox, costly, or temporary, such as annual seeding of agricultural cover crops to address erosion in areas that become flooded or comprised on a cyclical basis or adding nutrients in the form of liquid fertilizers to boost aquatic productivity (Persson et al., 2008; Schindler et al., 2020). While the need for regular work can increase costs and complexities, it underscores the importance of continuous management in mitigating the impacts of landscape-changing projects and the need for robust planning to achieve sustainable outcomes for both ecosystems and the communities that rely on them.

1.2 Historic Impacts of Large-scale Hydroelectric Development on Canada's Indigenous Peoples

Large hydroelectric developments have had an outsized impact on Indigenous Peoples in Canada due to historical marginalization and systemic inequalities (Papillon & Rodon, 2017). Many Indigenous communities reside in remote, resource-rich regions where development is prioritized, but have lacked the opportunity for meaningful involvement in the decision-making process and in benefit sharing regarding new hydroelectric developments (Hendriks et al., 2017). Large-scale hydroelectric projects in their very nature alter entire landscapes, and these landscape level changes have impact local Indigenous Peoples in a variety of ways, such as relocation, a loss of traditional burial and cultural sites, and disruptions to entire ecosystems that were relied upon for nourishment and livelihoods (Rosenberg et al., 1995).

In cases such as WAC Bennett Dam along the Peace River, or Grand Rapids Dam on the Saskatchewan River, both constructed in the early 1960's, entire settlements and family units were forcibly relocated off of their traditional territories, often with no consultation or information, and were placed in makeshift communities erected by government (Loo, 2007; Rosenberg et al., 1995). In many circumstances, this relocation deprived community members the opportunity to harvest and sustain a livelihood within their traditional territory. Even when communities did move back into their traditional territories, they found a landscape that was vastly different compared to before the dams, with log choked reservoirs, wildlife movement patterns altered, and risks such as high mercury levels in fish caught in the reservoirs due to decaying organic matter (Baird et al., 2021; Loo, 2007; Rosenberg et al., 1995). Hydropower development also had profound social impacts on communities, families, and individuals given the loss of traditional ways of life, cultural ties to the land, and strain on the social fabric of communities (Loo, 2007; Rosenberg et al., 1995). It was compounded by other social components of colonization, such as the trauma imposed by residential schools, other resource development, and the legacy impacts of the fur trade era (Bombay et al., 2014; Elias et al., 2012). New roads that were built to support dam and reservoir construction, or other industrial activities in an area, also brought easier access to substances such as alcohol, which posed significant social challenges to a population collectively reeling from such drastic change and trauma (Rosenberg et al., 1995).

To better address the legacy issues, along with potential future issues posed by large-scale hydroelectric development, Indigenous Peoples need to be fully informed, involved, and empowered in all stages of hydroelectric development projects, including dam and reservoir operations once construction is complete. Facilities that were built back in the 1960’s were not subject to comprehensive impact assessment reviews and did not involve local Indigenous Peoples in project design. Minimal benefit sharing agreements and compensation programs were established, resulting in these having to occur retroactively through funding community compensation, environmental mitigation efforts, and providing livelihood opportunities through training and business development (Yunker, 2022).

Addressing the impacts of large-scale hydroelectric projects on Canada's Indigenous Peoples requires a comprehensive approach that respects Indigenous rights, knowledge, and aspirations. Meaningful involvement, equitable benefits-sharing and the integration of traditional ecological knowledge are key factors in mitigating the disproportionate impacts these projects often have on Indigenous communities. By fostering collaboration between Indigenous communities and hydropower operators, including on Indigenous led projects, it is possible to not only minimize negative effects but also harness Indigenous wisdom. This can support effective mitigation and restoration efforts that benefit all Canadians, give back to the natural environment, and enable hydropower to act as a reliable baseload energy source in Canada’s efforts to decarbonize the energy grid.

1.3 Reservoirs and Dust

An environmental challenge presented by some hydroelectric reservoirs developed in regions with fine underlying sediment deposits is wind erosion and resulting fugitive dust emissions that can present risks to human health, infrastructure, and the environment. Fugitive dust can pose human respiratory and cardiovascular health issues due to the fine particulates (Aghababaeian et al., 2021; Jones, 2020), as well as risks to daily activities caused by reduced visibility or contamination of drinking water. Environmental impacts and risks to infrastructure can result due to the abrasive action of windblown dust, along with sediment deposition, increased water turbidity, and reduced light penetration (Goudie, 2009; Middleton & Kang, 2017; Miri et al., 2009). Globally, the vast majority of dust emissions originate from desert regions, such as the Sahara or Gobi deserts, but other regions like drylands in the southern United States or even high latitude locations in Canada, Eurasia, and Antarctica contribute to global dust (Duniway et al., 2019; Meinander et al., 2022). Reservoirs in comparison emit a small proportion of global dust emissions, but their emissions can still pose serious issues for local communities and ecosystems, and therefore require attention regarding prevention and mitigation efforts.

Reservoirs constructed in regions where the underlying sediments are fine and highly erodible can experience intense fugitive dust events when wind scours exposed sediment from regions between the low and high water marks, commonly known as the drawdown zone (Arocena et al., 1996; Baker et al., 2000). For example, reservoirs in the province of British Columbia such as Williston, Arrow, Kinbasket, and Carpenter are prone to experience fugitive dust emissions during low water periods, typically in the months of April to June when water levels are at their lowest point. Elsewhere, like in Iceland, more recent reservoir construction such as that of the Kárahnjúkar Reservoir, which was completed in 2009 has also led to intense fugitive dust storms originating from the drawdown zone impacting local communities and ecosystems (Rekow, 2023).

The issue of dust from reservoir drawdown zones is not a new issue and has been a challenge since large dams like the previously mentioned ones in British Columbia were constructed dating back to the 1960's. Several dust mitigation techniques have been tried along reservoir drawdown zones or in similar environments such as drained lakes, but results have been mixed. Some of the mitigation techniques that have been trialed include controlled flooding, planting vegetation, soil binding agents, roughening the soil surface through excavations, natural or engineered objects placed on the soil surface, irrigation systems, wind fences, adding layers of gravel or cobble, and deployment of systems such as solar panels (Abiola, 2011; Carr et al., 1993; Moody, 2002; Owens Lake Scientific Advisory Panel et al., 2020; Vaartnou, 2010).

Overall, vegetation and controlled flooding appear to be the most effective dust mitigation technique that can scale at a reasonable cost (Moody, 2002; Owens Lake Scientific Advisory Panel et al., 2020; Wolfe & Nickling, 1993). Annual seeding of cover crop vegetation has been found to provide effective dust mitigation along parts of Arrow Reservoir in southern British Columbia and repeated seeding for a 20-year period resulted in natural encroachment of native species to a point where cover crop seeding was deemed not necessary anymore (Moody, 2002). Vegetation still presents challenges and implementation has been difficult along some reservoir drawdown zones, such as Williston Reservoir in northern British Columbia, due to factors such as remoteness, different climatic and sediment conditions, scale, and difficulty in building capacity (May, 2022). In terms of controlled flooding, given that many reservoirs in areas like British Columbia were constructed for electricity generation, retaining higher reservoir water levels can have large electricity production and financial impacts if outflows are significantly reduced and power production is cut to keep water levels high (Griffiths, 2023). Theoretically, keeping the drawdown zone flooded is the obvious solution to dust mitigation in reservoirs, but realistically it is very challenging given high electricity demands and the seasonal fluctuations in water inflows into the reservoirs.

In regards to Williston Reservoir, dust has been recognized as an issue dating back to the 1980's (Arocena et al., 1996; Baker et al., 2000; Jackson et al., 1995), and several attempts have been made to address the issue, using a combination of vegetation trials, irrigation systems, and mechanical tilling of the drawdown zone (Abiola, 2011; Burton, 2010; May, 2022; Nickling et al., 2014; Vaartnou, 2010). Tilling has been deemed not effective, particularly in areas with sandy soil, and irrigation is effective in close proximity to the sprinkler systems, but is short lasting, expensive, and incredibly difficult to scale (May, 2022). Seeding vegetation at scale, such as fall rye (*Secale cereale*), has indicated promising results along Williston Reservoir and has been used elsewhere, such as at Arrow Reservoir, but there has been a lack of scientific understanding about whether fall rye or another species can grow well along the Williston drawdown zone in the short dust season window, and how effective widespread vegetation cover could be at mitigating fugitive dust.

BC Hydro, the utility that operates Williston Reservoir has funded the various dust mitigation efforts and funds the current iteration through an agreement with Tsay Keh Dene Nation called the Williston Dust Mitigation Program (WDMP). I was fortunate enough to have gotten the chance to work on the WDMP as an undergraduate summer student starting in 2018 and saw the need for more scientific study regarding revegetation along the drawdown zone as part of the WDMP. Therefore, I decided to pursue my Master of Science thesis on the subject.

1.4 The Organization of this Thesis

For my thesis, I investigated the relationship between vegetation cover and fugitive dust emissions along Williston Reservoir, including looking at species selection, how to scale revegetation efforts, and how vegetation cover effects fugitive dust emissions. My research resulted in two separate thesis chapters, with the first focused on plant species selection, while the second looked at efforts to scale vegetation treatments and how these treatments affected fugitive dust emissions along the reservoir. The objective for the first chapter was to identify and test candidate plant species both in the greenhouse and in field conditions along Williston Reservoir. This would inform species selection for the WDMP as the program seeks to scale up the use of revegetation as a method for dust mitigation. The objective of the second chapter was to better understand how revegetation treatments could be scaled across the vast beaches and to what extent vegetation cover has on fugitive dust emissions. This information could then be used to determine how much seed is needed and what impact vegetation cover may have on overall fugitive dust emissions.

2 Selecting plant species for large-scale dust mitigation and restoration in transitional flood zones

2.1 Abstract

Selecting the right species for revegetation or restoration projects is important given the need to meet project objectives, while also contending with issues such as invasive species risk, cost, and species performance. Selecting species for revegetation as a form of dust control in areas such as hydropower reservoir drawdown zones is an example where plant selection is an important consideration given the various challenges posed by this kind of environment. Williston Reservoir, located in northern British Columbia, is an example of a dust emitting reservoir that impacts local First Nations communities and a program has been developed to try and mitigate fugitive dust in the region. To support these efforts, we tested 22 different grasses and forbs, both in the greenhouse and in field conditions, to inform future species selection for a rapid and scalable revegetation strategy to mitigate fugitive dust along Williston Reservoir. The greenhouse experiments tested germination and emergence of native and exotic grasses and forbs. In the field, a subset of 10 native and exotic grasses and forbs were seeded in plots along the reservoir drawdown zone and were monitored for two growing seasons. It was found that exotic cereale grain species such as fall rye (*Secale cereale*) and oats (*Avena sativa*) germinated more quickly and produced more plant biomass during the initial growing season. However, native perennials were the only species with second year growth at higher beach elevations and native species biomass also increased substantially. None of the tested species emerged after flooding occurred in lower elevation plots. The results suggest that annual exotic cover crop species should be used for fugitive dust control in areas where annual flooding occurs, while native perennials should be considered for use above the average high-water mark.

2.2 Introduction

Renewable energy continues to provide a greater percentage of our global energy supply each year as we shift away from fossil fuels and towards more sustainable sources (Gielen et al., 2019; Hosseini, 2020; Peake, 2018). Hydropower is often viewed as a great baseload renewable energy source due to its consistency and ability to act as a large potential energy storage system in the form of a water storing reservoir (Wasti et al., 2022). Mountainous regions with large river systems in particular have been viewed as excellent locations for hydropower, and several nations including China, Canada, Brazil, and the United States rely heavily on hydropower to support their energy grids (Moran et al., 2018). As the shift away from fossil fuel-based energy sources becomes more urgent in the face of climate change, new hydropower projects are being viewed in many countries, particularly in developing regions, as one of the solutions to reduce emissions while still meeting growing energy demands (Moran et al., 2018). However, consideration should be given to the known negative socio-ecological impacts hydropower projects can have on a region and what mitigation strategies will be most effective in minimizing the short- and long-term impacts (Gutierrez et al., 2019). When using vegetation as part of environmental mitigation or restoration, consideration should be given to using native and/or exotic species, where and when to use them, and the role they play in the long-term goals of a project.

The water storing reservoirs behind large hydropower facilities are human created ecosystems that can pose significant environmental, social, and health related challenges to nearby communities and ecosystems (Baker et al., 2000; Hill et al., 1998; Moran et al., 2018; Vilmundardóttir et al., 2010). The water levels in hydropower reservoirs, particularly in regions that experience large winter snowpacks, tend to fluctuate widely throughout a given year, sometimes experiencing 30 m in elevational change from low to high water marks (Baker et al., 2000; Gleick, 1992). A reservoir acts as a large storage battery of potential energy, so when inflows are high, such as in spring when snow is melting, the reservoir level rises to accommodate the increased water volume. During low inflow and high electricity demand periods, such as the winter months, stored water is sent through the dam facility to generate power and the reservoir level drops due to outflow being greater than the inflow. This fluctuation in water levels can expose vast amounts of periodically flooded land, typically referred to as the drawdown zone, and can result in widespread land degradation and erosion (Gleick, 1992). Some reservoir drawdown zones consist primarily of rock, therefore erosion is minimal, but others may lie in areas that consist of fluvioglacial material that is susceptible to both wind and hydrologic erosion processes (Vilmundardóttir et al., 2010). Reservoir shoreline erosion, both through wind and hydrologic processes, can cause major environmental degradation issues for reservoir storage facilities globally, and limits the effectiveness of standard erosion prevention techniques often deployed along coastal shorelines or lakeshore settings (Allen & Klimas, 1986; Newbury & McCullough, 1984; Yang et al., 2015). Reservoirs with large water fluctuations and that have highly erodible sedimentary material sometimes experience widespread wind erosion, which can create intense dust storms during periods when their drawdown zones are exposed because of low water levels (Arocena et al., 1996; Baker et al., 2000).

Addressing wind erosion and dust storms along reservoir drawdown zones has been ongoing in many cases since a boom in mega-hydropower projects began in the mid 20th century (Newbury & McCullough, 1984). A few experimental trials and some large-scale applications have largely concluded that using plants to revegetate drawdown zones is the most cost-effective and environmentally sound method to mitigate wind erosion (Allen & Klimas, 1986; Arocena et al., 1996; Baker et al., 2000). It is understood that vegetation can help reduce soil loss in three primary ways; (1) vegetation covers a proportion of the erodible soil surface, (2) vegetation transfers a portion of the winds momentum to the plant at a height above the soil surface, and (3) vegetation acts to trap and hold soil particles that are in movement along the soil surface (Wolfe & Nickling, 1993). It has been hypothesized by Arocena et al. (1996) that attaining a vegetative cover of 60% could theoretically reduce wind erosion by up to 95% in some regions. A critical step in using vegetation as a form of dust control along hydroelectric reservoirs is selecting the appropriate plants based on aspects such species origin, traits, and diversity.

Reservoir drawdown zone environments require hardy, fast growing species for initial vegetation establishment due to short periods of drawdown zone exposure, harsh growing conditions, and poor perennial establishment from seed or propagule due to prolonged flooding, in many cases by more than 10 meters of water (Abrahams, 2006). Therefore, it is crucial to identify species that can germinate quickly, mature rapidly, and are able to grow in conditions with poor soil quality, high winds, and may have unreliable access to surface water. Ideally, these species should also be able to withstand typical reservoir flooding regimes so that annual planting is not required, but this can be a tough threshold to meet (Jackson et al., 1995). Consideration should also be made to select species that do not pose a serious invasive threat to nearby ecosystems so that one potential solution does not result in an adjacent problem.

Secale cereale, commonly known as fall rye, has been one of the most widely used species to date for reservoir drawdown zone revegetation in North America, as it germinates quickly, rapidly produces large amounts of biomass, and is relatively inexpensive (Allen & Klimas, 1986; Jackson et al., 1995). Consideration must be made to monitor any application of fall rye for any potential establishment that could lead to invasive establishment, and seed must be properly sourced to avoid purchase of Ferale rye (*Secale cereale L.*), which is a known invasive spreading across parts of the US (Burger et al., 2007; Burger & Ellstrand, 2014; Roerig & Ransom, 2017). A worthy question to ask is – are there other fast-growing annual exotic species that can perform as well? Increasing the seed diversity used for reservoir revegetation could result in higher resilience to fluctuations in commercial seed availability, cost, and could provide a buffer against years when fall rye does not perform as well as alternative cover crops. Again, proper screening and monitoring should be done to assess any competitive invasion potential in adjacent environments.

Furthermore, if native plant options can achieve similar results as fall rye, then it may be possible to mitigate fugitive dust while also enhancing native plant communities and increasing their benefits within the reservoir drawdown zone environment. Inclusion of native species may allow for restoration in certain areas of reservoir drawdown zones, such as the higher elevation locations, and can potentially limit the chance of invasion from exotics (Arocena et al., 1996; Baker et al., 2000; Burton, 2010; Carr et al., 1993). Native species can also bolster local biodiversity in ways that agronomic species cannot (Middleton et al., 2010), and can lower the potential of negatively impacting cultural connections with the landscape (Pfeiffer & Voeks, 2008). However, native species can be more difficult to establish and can have slower growth rates, along with higher seed costs. Therefore, it is important to assess where fast growing exotic agronomics can be used for environmental mitigation along reservoir drawdown zones, and where native species can be used to achieve mitigation and restoration goals.

One hydroelectric reservoir where fugitive dust emissions originating from the drawdown zone is an issue for local communities, particularly local First Nation communities, is Williston Reservoir, located in north-central British Columbia (BC) in western Canada. Williston Reservoir is the water storage body for BC's largest hydroelectric facility, WAC Bennett Dam and the associated Gordon M. Shrum Generating Station, along with the smaller Peace Canyon Dam, and the new Site C project, which is scheduled to be completed in 2025 (Government of Canada, 2023). Together, these three hydroelectric facilities will provide over 30% of BC's electricity needs (City of Dawson Creek, 2023), thus making Williston Reservoir a key provincial energy asset. Recognizing the importance of Williston Reservoir and acknowledging the environmental and social impacts resulting from the dust storms, BC Hydro, and Tsay Keh Dene Nation (TKDN) created an agreement to try and address the ongoing dust issues, called the Williston Dust Mitigation Program (WDMP).

As part of the WDMP, this study aims to test the germination and growth capacity of several native and non-native graminoid and forb species both in the greenhouse and in field conditions along the Williston Reservoir drawdown zone to better understand their suitability as rapid vegetation options for reservoir drawdown zone dust control. The objective was to test if the species could germinate quickly, rapidly produce biomass, and survive a full year of reservoir drawdown zone conditions.

2.3 Methods

2.3.1 Site Information

The field study area lies along the north-eastern shore of Williston Reservoir, a portion often referred to as the Finlay Reach. Williston Reservoir is situated in northern British Columbia (Figure **2.1**), along the Rocky Mountain Trench, and was created by the WAC Bennett Dam which was completed in 1968. The WAC Bennett Dam and the resulting Williston Reservoir transformed this section of the northern Rocky Mountain Trench region by flooding the confluence area of the Finlay, Parsnip, and Peace Rivers, and resulted in BC's largest freshwater body (Baker et al., 2000). The creation of Williston Reservoir also resulted in the flooding of local Tsay Keh Dene Nation (TKDN) villages, including Fort Grahame, Finlay Forks, and Ingenika (Baker et al., 2000; Loo, 2007). The Finlay Reach lies within the traditional and unceded territory of Tsay Keh Dene Nation and the village of Tsay Keh Dene is now situated at the northern shore of the reservoir.

Several drawdown zone areas, referred to here after as beaches, along the Finlay Reach are the source of large, intense dust storms typically during the low water months between late April and late June (Arocena et al., 1996; Baker et al., 2000; Phaneuf, 2019). These dust storms are viewed as a concerning health risk, primarily for the inhabitants of Tsay Keh Dene village, but also others who live or spend time around the reservoir (Loo, 2007). The dust season typically lasts from early May until late June, but this depends on reservoir water levels. When the reservoir is at its lowest in late April or early May, high dust emitting beaches cover an area of roughly 3,000 hectares, predominately on the east side of the Finlay Reach. No peer-reviewed literature has been produced around the contents of the dust or the potential health related impacts of the dust on local inhabitants, but studies have quantified the dust emissions (Nickling et al., 2014; Phaneuf, 2019).

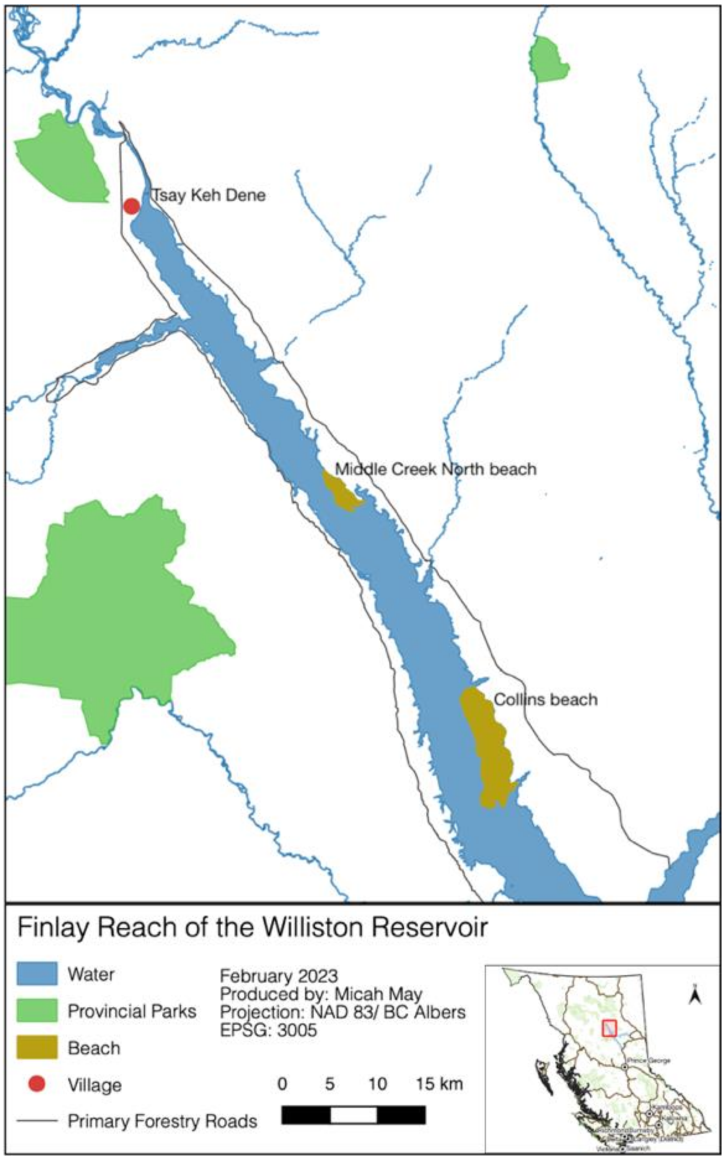

Figure 2.1: The two focal beaches, Middle Creek North, and Collins Beach, which when fully exposed in the spring, are 135 ha and 350 ha (respectively) of exposed sandy beach. The red dot at the north end of the reservoir represents the location of Tsay Keh Dene Village. Note, these two beaches represent a small portion of the dust emitting beach area at low water levels along the Finlay Reach, which can reach up to 8,000 ha in a low water year.

This study focused on two beaches along the east side of the Finlay Reach, known as Middle Creek North (latitude: 56.637502, longitude: 124.650220) and Collins (latitude: 56.431074, longitude: 124.401952) beaches, as they are two high dust emitting beaches that have easy road access. Dust monitoring using air quality and weather stations on these beaches and others has been ongoing for over a decade starting with data collected by (Nickling et al., 2014)) and more recently by Tsay Keh Dene Nation's wholly owned consulting company Chu Cho Environmental (Phaneuf, 2019). The beaches can be viewed as having three different elevational zones (Figure 2.2). The first zone is predominantly barren beach that floods on an annual basis and emits high levels of dust. The second zone floods typically every 3 – 5 years for short periods of time and supports native perennial vegetation along its upper edge. Finally, the third zone does not flood, but is still influenced hydrologically by reservoir fluctuations and supports mature vegetation. The difference in flooding regimes between the three zones influences plant survival, thus this study sought to investigate plant survival both above and below the projected high-water mark in the lower two zones for 2022.

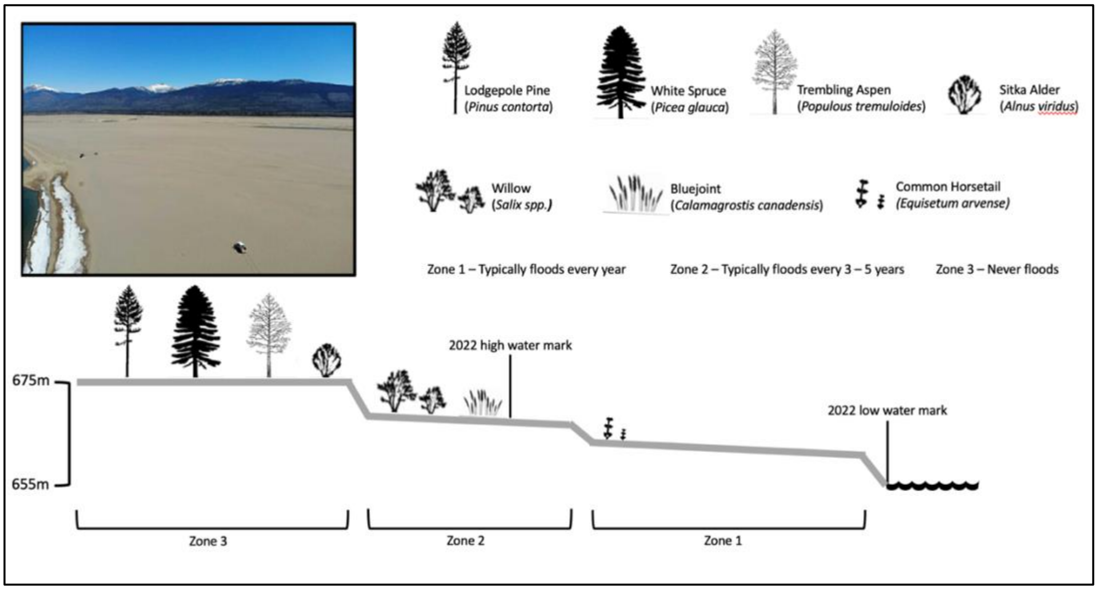

Figure 2.2: The Williston Reservoir drawdown zone typically has three different elevational zones. Zone 1 typically floods annually and does not support much vegetation, while Zone 2 tends to flood every 3 to 5 years depending on dam operations and supports an early colonizer plant community. Zone 3 does not flood but is influenced hydrologically by the reservoir and supports a largely unchanged forest community. Note, the majority of dust emissions originate from the Zone 1 region. (Clip Art: Natural Resources Canada, 2015).

2.3.2 Species Selection

The aim was to select plant species that would germinate and grow quickly, add species diversity to revegetation efforts, and not present a major invasive threat to the adjacent ecosystems of the Williston beaches. Species selection began by looking to prior species recommendations from previous work around Williston Reservoir beach revegetation efforts, particularly focused around native species (Abiola, 2011; Burton, 2010; Vaartnou, 2010). Grasses and forbs were selected because of the ability to spread their seed easily and since they tend to grow more quickly than woody species. Seed availability from suppliers within western Canada and seed cost were also factors that influenced species selection, as the ability to scale any revegetation method in a cost-effective manner was an important consideration. In total, 22 species were selected for the experiment, including 13 natives and 9 exotics (Table **2.1**). This number was reduced to ten species for the field experiments based on greenhouse results, seed availability, and known species traits.

Table 2.1: Complete list of the native and exotic plant species that were tested in the greenhouse and field experiments.

Origin	Latin Name	Common Name	Experiment Use
Native	*Poa secunda*	Sandberg Bluegrass	Greenhouse + Field
Native	*Poa palustris*	Fowl Bluegrass	Greenhouse + Field
Native	*Festuca saximontana*	Rocky Mountain Fescue	Greenhouse + Field
Native	*Achillea millefolium*	Common Yarrow	Greenhouse + Field
Native	*Elymus lanceolatus*	Northern Wheatgrass	Greenhouse + Field
Native	*Elymus trachycaulus*	Slender Wheatgrass	Greenhouse + Field
Native	*Elymus canadenis*	Canada Wildrye	Greenhouse
Native	*Poa alpina*	Alpine Bluegrass	Greenhouse
Native	*Bromus ciliatus*	Fringed Brome	Greenhouse
Native	*Astragalus canadensis*	Canada Milkvetch	Greenhouse
Native	*Calamagrostis canadensis*	Blue Joint	Greenhouse
Native	*Carex aquatilis*	Water Sedge	Greenhouse
Native	*Vicia americana*	American Vetch	Greenhouse
Exotic	*Fagopyrum esculentum*	Buckwheat	Greenhouse
Exotic	*Lolium multiflorum*	Annual ryegrass	Greenhouse
Exotic	*Triticum aestivum*	Winter Wheat	Greenhouse
Exotic	*Agrostis gigantea*	Red Top	Greenhouse
Exotic	*Trifolium repens*	White clover	Greenhouse
Exotic	*Avena sativa*	Oats	Greenhouse + Field
Exotic	*Hordeum vulgare*	Barley	Greenhouse + Field
Exotic	*Secale cereale*	Fall Rye	Greenhouse + Field
Exotic	*Trifolium pratense*	Red Clover	Greenhouse + Field

2.3.3 Greenhouse Experiments

Greenhouse experiments were used to investigate germination, emergence, and plant biomass traits to refine a list of species that could be tested in field conditions along the Williston Reservoir. The greenhouse experiments were designed to compare each species to a baseline species, *Secale cereale.* The reason for selecting *S. cereale* as a baseline was because it has been the most widely recommended species for drawdown zone revegetation in western Canada (Arocena et al., 1996; Jackson et al., 1995) and was being used as the primary species in recent revegetation trials on site. The greenhouse experiments consisted of two parts, with the first looking at seed germination to assess germination rate and overall germination performance. The second part investigated seedling emergence and post emergence growth rates, along with soil and fertilizer treatments to better understand field soil conditions and potential nutrient limitations.

2.3.3.1 Seed germination and plant growth experiments

Seed germination for each species was tested in growth chambers. Four replicates of 25 seeds per species were placed on top of two pieces of 8.4 cm diameter filter paper in 9 cm diameter plastic petri dish. Each set of filter papers were moistened with 5 mL of distilled water before the seeds were placed on top and the petri dishes were sealed using parafilm tape. Each set of four petri dishes were then sealed in a clear plastic bag and were randomly placed in a growth chamber. The petri dishes were incubated at a controlled temperature of 15^{o}C on a 12/12 h light/dark cycle for a duration of 21 days. Germination was said to have occurred once the radicle became visible. Germination was scored daily for the 21-day period, with all germinates being removed once scored. Each set of four petri dish bags were relocated randomly during each daily visit within the growth chamber.

Next, plant emergence and growth were investigated for each of the 22 selected species using 20 seeds per species. Each seed was individually planted in a planting tray cell with a diameter of 5 cm, depth of 7.5 cm and a surface area of 19.6 cm^{2}. Ten cells of each tray were filled with potting soil, while the other ten were filled with sand from one of the Williston Reservoir beaches. Half of the 10 potting soil cells and sand cells had 0.05 g of 21-7-14 NPK slow-release fertilizer applied to the upper 1 cm of soil, resulting in four treatments of five cells each. One seed was then planted at a depth of 1 cm in each of the cells, resulting in five seeds per treatment for each of the species. The trays were placed in the greenhouse where the temperature was roughly 20^{o}C and a 16/8 h light/dark cycle was set using overhead lighting for a duration of 7-weeks. Each cell received 10 mL of water every 3-days unless a cell was still visibly saturated. For the first 21-days, daily emergence data was collected, while for the latter 4-weeks, emergence was scored every three days.

After 7-weeks of growing, the plants were harvested to conduct an above and below ground biomass analysis. For each plant that had emerged, the above ground stems were cut at the soil surface and the below ground root structures were cleaned. Each sample was dried in an oven at 65 ^{o}C for 48 hours, after which each shoot and root sample was weighed.

2.3.4 Field Experiments

Field testing was important to investigate how each species responded to the harsh growing conditions that occur on the beaches of the Williston Reservoir. To that end, field experiments were implemented for two years along the Williston Reservoir to test candidate plant species in the beach environment. Species selection for the field experiments was based on greenhouse performance, but also observed water requirements in the greenhouse and seed availability at the time of the experiment. In year one, research plots on two beaches of the Williston Reservoir were seeded to compare emergence and productivity. In the second year, the same plots were revisited to again measure emergence and plant productivity.

For year one, ten species were selected for the field experiment out of the 22 that were tested in the greenhouse trials (Table **2.1**). For the experiment, a total of 300 plots, 2 m x 2 m in size, were established on the two Williston Reservoir beaches. Each beach had 150 plots broken into three elevation blocks, including below the expected high-water mark, around the expected high-water mark, and above the expected high-water mark. For each elevation block consisting of 50 plots, each of the 10 candidate species were hand seeded into five of the plots in a randomized design. The targeted seeding rate was 1,600 seeds/m^2 and this was achieved by measuring out exact amounts for each plot based on the number of seeds per gram for each species. After seeding, the upper 5 cm of soil was turned by a rake to mimic large-scale drill seeding methods currently available. Seeding was conducted in the last week of April and no additional irrigation or soil amendments were added.

The plots were monitored for a period of 7-weeks with stem density and plant biomass being assessed at the end of that period. A 1 m x 1 m monitoring frame with defined 20 cm^2 quadrats was used to collect the data. In the seventh week, ten healthy plant samples per plot were randomly harvested so that above and below biomass analysis could be completed. Both the shoot and root were collected and was dried at 65 ^{o}C for 48 hours in a drying oven and were weighed using a high-precision scale.

For the second year of the experiment, the field plots were revisited to again assess both stem density, and to collect 10 plant specimens from each plot. The two lower elevation blocks on each beach had been inundated for roughly 2-months during the summer of 2022 so it presented an opportunity to compare those plots with the upper elevational block, which had not been flooded. Stem density was recorded, along with ten shoot and root samples being collected from plots with evident growth. The plant tissue samples were dried at 65 ^{o}C in a drying oven for 48 hours and weighed using a high-precision scale.

2.3.5 Statistical Analysis

All analyses for both the greenhouse and field experiments were performed using R Statistical Software (v4.1.2; R Core Team, 2021). The data was analyzed and visualized using the tidyverse package (v1.3.2; Wickham et al., 2019).

2.3.5.1 Greenhouse

Analysis of growth chamber germination was conducted to investigate how each selected species performed in terms of proportional seed germination and germination rate. The germination data was analyzed by fitting a generalized linear model (GLM) with a Quasipoisson distribution (Zuur & Ieno, 2016) between the number of seeds that germinated (response) and the different species being investigated (fixed predictor). A normal Poisson distribution was tested, but we found the data was over dispersed. The model was validated by checking the distribution of the residuals in the model output and by plotting the residuals against the fitted values along with plotting a normal Q-Q plot to check for residual normality and homoskedasticity.

Analysis of stem emergence in the greenhouse was conducted to examine how emergence for each species would respond to different soil and fertilizer treatments. Each cell in a tray was viewed as a replicate, with a 1 or 0 being recorded based on whether the seed in that given cell emerged or not. An analysis of greenhouse stem emergence was performed by fitting a binomial GLM to test the fixed effect of species, soil type, and fertilizer (predictors) on stem emergence (the response). This design meant there were five replicates per set of predictor combinations. Model validation was completed by comparing the model's residual deviance by the residual degrees of freedom to check model dispersion, along with assessing residual patterns using a normal Q-Q plot and three residual plots separately comparing the species, the two soil treatments, and the fertilizer treatments.

Analysis of greenhouse plant biomass was conducted to investigate how the production of plant biomass would respond to different soil and fertilizer conditions. Any cell that did not have a plant growing in it at the end of the 7-week growth period was not included in this analysis so there were no values of zero in the data set. The data was visually inspected by plotting a histogram. A linear model was fit to investigate the relationship between the biomass response variable and the fixed effect of species, soil type, and fertilizer (predictors). The model was validated by looking at the normality of the residual distribution, along with comparing the residual standard error to the intercept estimate to determine prediction error.

2.3.5.2 Field Experiment

Analysis for the field experiment consisted of using the glmmTMB package (v1.1.4; Brooks et al., 2017) in R. Due to the number of plots having zero emergence it was concluded that a zero-inflated model would provide the best fitting model. Due to overdispersion of the response using a Poisson distribution, a negative binomial was used. The simpler parameterization of the negative binomial distribution called "nbinom 1" in the glmmTMB package was used where the variance is a multiple of the mean. We fit a zero-inflated GLM with Type I negative binomial distribution to test the relationship between stem count and the three fixed predictors: species, elevation, and beach location. The model was validated using the "simulateResiduals" command found in the DHARMa package (v0.4.6; (Hartig, 2022), where the residuals were plotted against the predicted values, along with the expected and observed residuals being plotted against each other to check residual normality and homoskedasticity. For the second-year field stem count data, the same model was used, except only with two predictors: species and beach location, due to the lower two elevation blocks having no plant growth.

For the field biomass analysis, like the greenhouse component, the data was visually inspected by plotting a histogram. A linear model was fit to investigate the relationship between the biomass response variable and the fixed effect of species, elevation, and beach location (predictors). The initial model fit was poor, so the biomass response variable was log transformed. Model fit was further assessed by looking at the residual distribution symmetry in the model output, which was strong. Residual standard error was much smaller than the intercept estimate, indicating an acceptable prediction error.

2.4 Results

2.4.1 Greenhouse: Germination

Germination of *S. cereale* was high (maximum = 25; T_{50} = 1.52 days). Overall, the other eight exotic species achieved similar results on average (maximum 23.5 ± 3.3; T_{50} = 2.2 ± 0.7 days), while the native species had lower and slower germination rates (maximum 17.6 ± 7.7; T_{50} = 7.8 ± 3.6 days).

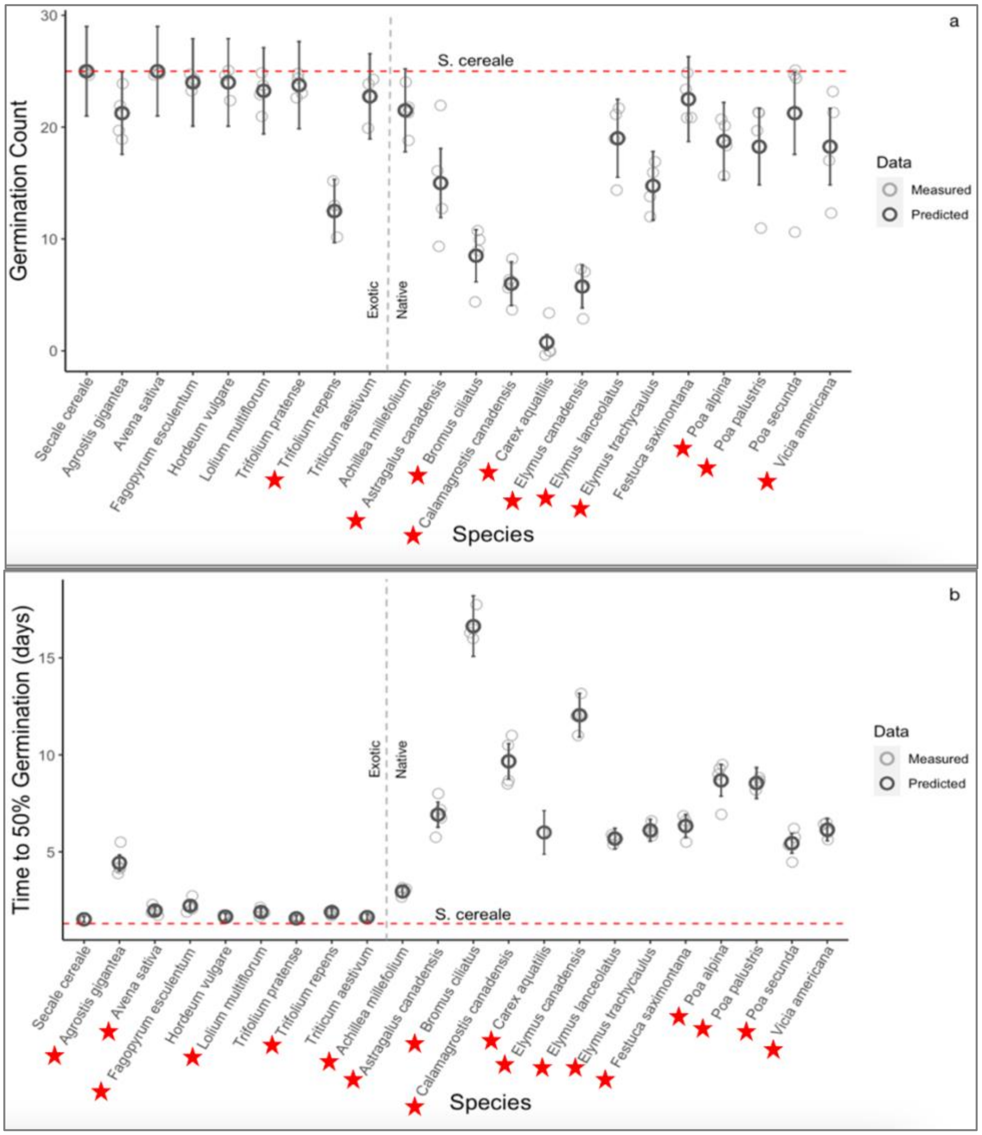

Figure 2.3: (a) S. cereale and A. sativa were the only species with complete germination of all 25 seeds, while 11 species, one exotic and 10 natives, had significantly lower germination than S. cereale. (b) S. cereale had the fastest time to 50% germination, while all the native species and five exotic species had significantly slower T50 rates compared to S. cereale. The red dashed line represents the mean S. cereale value, while the grey vertical dashed line splits the exotics on the left and the native species on the right. Species that differed significantly compared to S. cereale are marked with a red star.

Out of the 21 species that were compared to *S. cereale*, eleven were found to have a statistically significant difference in germination count, all of which were lower (**Figure 2.3:** (a) S. cereale and A. sativa were the only species with complete germination of all 25 seeds, while 11 species, one exotic and 10 natives, had significantly lower germination than S. cereale. (b) S. cereale had the fastest time to 50% germination, while all the native species and five exotic species had significantly slower T50 rates compared to S. cereale. The red dashed line represents the mean S. cereale value, while the grey vertical dashed line splits the exotics on the left and the native species on the right. Species that differed significantly compared to S. cereale are marked with a red star.Figure **2.3**a). Regrading germination rate, only three species, *H. vulgare, T. aestivum, and T. pratense* did not have significantly slower time to 50% max germination (Figure **2.3**b).

2.4.2 Greenhouse: Seedling Emergence

Of the 20 *S. cereale* seeds that were planted, nine emerged over the 7-week trial period and of these only two sprouted in sand, compared to seven in potting soil. Total emergence is presented in Figure **2.4**, along with the proportion that emerged in sand versus soil. Several species, both, exotic and native, surpassed *S. cereale* in terms of total emergence, while exotics as a group achieved 50% emergence much more quickly, on average only taking 2.3 days, while natives took 6.3 days.

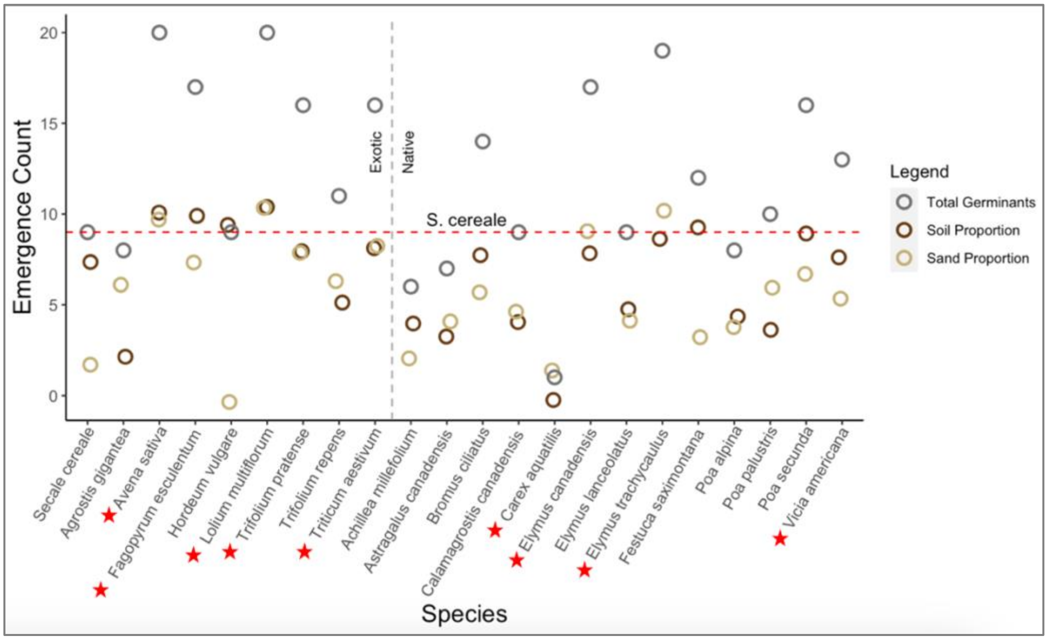

Figure 2.4: Eight species were found to have significantly higher emergence rates than S. cereale, five exotic and three natives, while one species had a significantly lower rate. The red dashed line in figure represents the mean S. cereale value, while the grey vertical dashed line splits the exotics on the left and the native species on the right. Species that differed significantly compared to S. cereale are marked with a red star.

When comparing the 21 other species to the emergence of *S. cereale*, the binomial GLM indicated a significant difference for nine species. All the significant species, other than *C. aquatilis,* achieved significantly higher stem emergence rates than *S. cereale*. The significantly lower germination of *C. aquatilis* was due to only one out of 20 seeds emerging throughout the 7-week growth experiment. In terms of the soil and fertilizer treatments, fertilizer was not found to have a significant effect on stem emergence in the study, but soil type did have a measured significant effect across all species, with seeds planted in sand resulting in significantly fewer stems emerging.

2.4.3 Greenhouse: Plant Biomass

The biomass results show that compared to *S. cereale,* only five species (*A. sativa, F. esculentum, H. vulgare, L. multiflorum,* and *T. aestivum*), all exotics, produced similar plant biomass over the 7-week growth trial (Figure **2.5**).

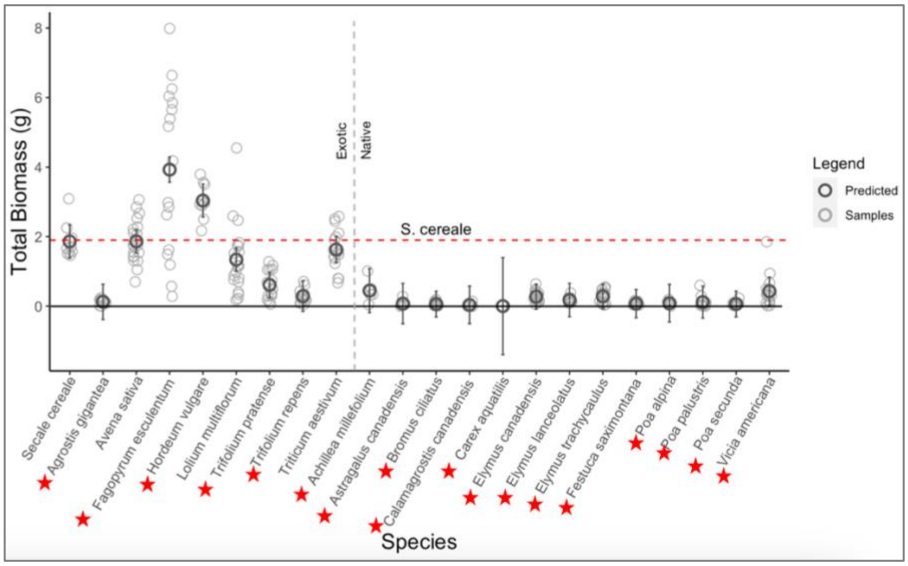

Figure 2.5: Only three exotic species, A. sativa, L. multiflorum, and T. aestivum did not differ significantly compared to S. cereale in terms of total plant biomass from the greenhouse experiment. The red dashed line represents the mean S. cereale value, while the grey vertical dashed line splits the exotics on the left with the native species on the right. Species that differed significantly compared to S. cereale are marked with a red star.

In terms of the soil and fertilizer treatments, the model indicated that both fertilizer and soil type had a significant effect on above ground biomass, but that only soil type had a significant effect on below ground biomass (Table **2.2**).

Table 2.2: Greenhouse biomass GLM results table for soil and fertilizer treatments. Red text signifies a significant negative effect, while green indicates a significant positive effect.

	Above Ground			Below Ground		
Treatment	ß$_{\text{coefficient}}$	Std. Error	P-value	ß$_{\text{coefficient}}$	Std. Error	P-value
Intercept	<0.01	0.481	0.998	0.6718	0.342	0.05
Fertilizer: Yes	**0.130**	**0.228**	**<0.01***	-0.445	0.125	0.190
Soil type: Sand	**-0.542**	**0.229**	**<0.01***	**-0.679**	**0.130**	**<0.01***

2.4.4 Field Experiment

In year one, *S. cereale* outperformed all other species on the beaches in terms of average stem emergence (mean = 54 ± 35 stems/m^2), with two species, *P. palustris* and *Achillea millefolium* not emerging at all, two species not being significantly different, *A. sativa* and *E. lanceolatus*, and the other five species having significantly fewer stems (Figure **2.6**a). No significant difference in stem emergence was observed between the two beach trial locations. However, elevation did appear to have a significant effect on stem emergence across both beaches, with stem count significantly increasing each time from low to mid to high elevation plots.

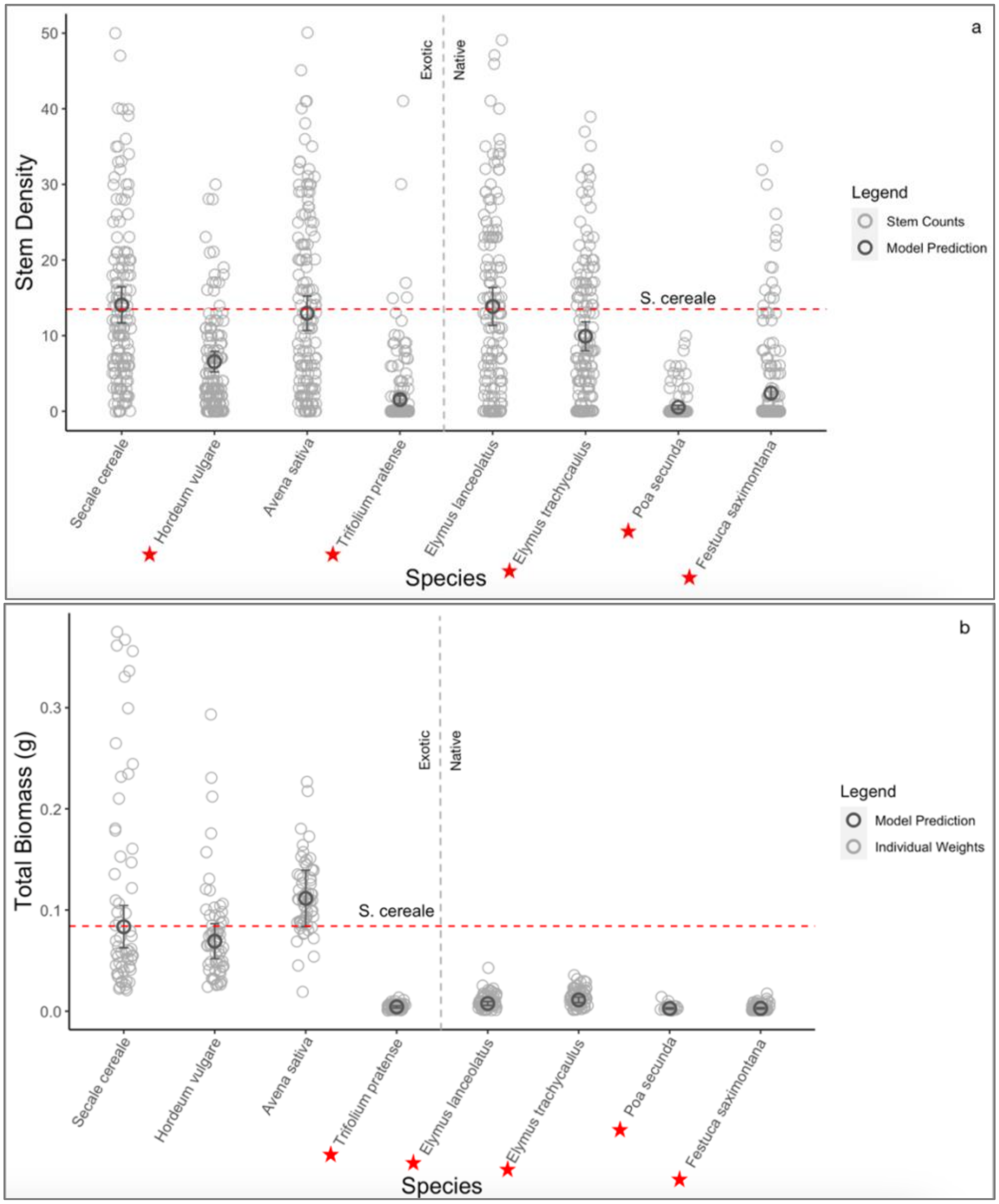

Figure 2.6: (a) Two species, A. sativa and E. lanceolatus, had similar stem densities in the field to S. cereale, while the other five species that emerged were significantly lower. (b) H. vulgare and A. sativa had similar field biomass weights to S. cereale, while all four natives and T. pratense were significantly lower. The red dashed line represents the mean S. cereale value, while the grey vertical dashed line splits the exotics on the left with the native species on the right. Species that differed significantly compared to S. cereale are marked with a red star.

For field plant biomass in year 1, *S. cereale* produced significantly more biomass than all the native species, as well as *T. pratense*, a non-native forb. *H. vulgare* produced similar biomass, while *A. sativa* produced significantly more biomass than *S. cereale* over the two-month growing season (Figure **2.6**b).

In year two, only four species, *E. trachycaulus*, *E. lanceolatus*, *P. secunda*, and *F. saximontana*, were found to be growing in the upper elevation block. All four species were present on Collins beach, while only *E. trachycaulus* and *E. lanceolatus* were present on Middle Creek North beach. Average stem-count decreased year over year for each species, except for *E. trachycaulus* on Collins beach, which increased 14%. However, total plant biomass significantly increased for all four species on both beaches with *P. secunda* having the greatest increase with 32 times more biomass per plant year-over-year (Table **2.3**).

Table 2.3: Year-over-year comparison of average stem density in field plots and total plant biomass for *E. trachycaulus*, *E. lanceolatus*, *P. secunda*, and *F. saximontana*. Red text signifies a decline, while green indicates an increase.

Species	**Average Change in Stem Density YOY**		**Average Change in Total Biomass YOY**	
	Collins Beach	Middle Creek North Beach	Collins Beach	Middle Creek North Beach
E. trachycaulus	**14.2%**	**68.5%**	**1,815%**	**1,547%**
E. lanceolatus	**33.1%**	**20.4%**	**2,800%**	**2,583%**
P. secunda	**10.3%**	N/A	**3,212%**	N/A
F. saximontana	**13.8%**	N/A	**1,956%**	N/A

2.5 Discussion

Growing conditions on the Williston Reservoir beaches are extremely poor; thus, any plant species selected for revegetation efforts to combat the dust issue should be able to germinate quickly and produce ample amounts of biomass in harsh conditions. Ideally, the species would also be able to survive periods of flooding. Overall, results from this study indicate that using agronomic cereal grains as annual cover crops on beach areas that flood annually is likely the most cost-effective revegetation strategy to mitigate dust emissions at scale. Native perennial grass species may be applicable to revegetate beach regions that do not typically flood every year, and thus would allow for perennials to establish. It is recommended that additional studies should be conducted to better understand what beach elevations and regions are best suited for annual cover crops versus native perennials, including grasses, forbs, and shrubs.

The reference species *S. cereale* performed best in the germination and first year field experiments. While it achieved <50% overall emergence in the greenhouse, along with *H. vulgare*, as with the other agronomic species the biomass results were high. As a group, the agronomic species performed similarly across the experiments, which was largely expected since these species have been bred to germinate and grow quickly (White et al., 1990). In year 1, the difference in plant biomass was clear, both in the greenhouse and the field, with the agronomic species producing on average ten times more biomass than the native species. However, second year growth of native perennials in the field showed significant increases in native plant biomass. Plant biomass is a key factor when considering vegetation as a form of wind erosion control, as the greater the biomass, particularly above ground, the more surface area there is to break the wind's shear force (Blackshaw, 2008; Kaul & Wilsey, 2022; Wolfe & Nickling, 1993).

However, biomass alone cannot be a deciding factor as visual observations throughout the greenhouse experiment noted that *F. esculentum* appeared to wilt much more quickly between watering periods than any of the other species, suggesting a greater need for frequent water supply (Aubert et al., 2021; Jacquemart et al., 2012). Therefore, even though *F. esculentum* produced the greatest amount of biomass of any species in the greenhouse, it was not included in the field portion of the study because of its heavy moisture dependency. This highlights the importance of testing plant species both in controlled conditions to look at potential constraints, but also to ensure a field component is included so that real environmental conditions are present as part of the experiment.

The agronomic species are also more cost-effective in flood prone regions, since species such as *S. cereale, H. vulgare,* and *A. sativa* were quoted on average for $0.50/kg, whereas species such as *E. trachycaulus* and *E. lanceolatus* were five to eight times as expensive, and species such as *A. millefolium* and *C. canadensis* were over 100 times. Cost becomes a greater concern when scale is considered – the Williston Reservoir has over 3,000 hectares of dust emitting beach that may be suitable for revegetation (May, 2022). As a result, any species selected to be included in widespread dust mitigation efforts cannot be prohibitively expensive. This coupled with the fact that seeding will likely be required on an annual basis for several years to come supports the necessity for cost-considerations. However, native species, such as *E. trachycaulus*, *E. lanceolatus*, *P. secunda*, and *F. saximontana* should still be considered for future investigations in the smaller, high elevation beach areas where long-term vegetation establishment may be feasible.

Our hypothesis for why *S. cereale* and *H. vulgare* performed poorly in terms of emergence in the greenhouse compared to the other agronomic species is that the warm greenhouse temperature of 20 ^{o}C may have negatively impacted their germination. *S. cereale* in particular is a species that has been bred to emerge in cool spring conditions (Huner, 1985), which are present along Williston Reservoir in

April and May. Despite some studies showing good germination potential of annual cereale grain species from below 5 °C to above 20 °C (Huner, 1985; White et al., 1990), the higher emergence in the field conditions also suggests that warm greenhouse temperatures may have impacted growth of these species.

Despite native species having a lower average performance in year 1, field results from year 2 indicate that species like *E. trachycaulus* and *E. lanceolatus* should be considered for inclusion in upper elevation beach revegetation, and *P. secunda*, *F. saximontana*, and *E. canadensis*, while not as successful, may also be suitable. It is recommended that native forb and shrub species be considered as well, either through seeding or local transplanting, which could bolster vegetation biodiversity and potentially increase the pace of natural plant recruitment and restoration. It is well understood that native species as a group emerge more slowly than exotics (Abraham et al., 2009; Balshor et al., 2017; Beckmann et al., 2011; Gioria et al., 2018), particularly when compared with cereal grain species such as in this study. However, this study has shown that some native perennial grasses can establish on the beaches above the high-water mark and given the right conditions, could help build an annually recurring vegetation cover along the upper regions of certain Williston Reservoir beaches. Past revegetation efforts along reservoir beaches have shown that grass cover can create conditions for nearby native perennials to encroach and establish (Carr et al., 1993). Consideration should be given to developing a native seed mix that includes both native perennial forbs, ideally ones growing near the beaches, along with grass species like *E. trachycaulus* and *E. lanceolatus* because co-seeding grasses and forbs has been found to boost species richness and overall forb performance (Kiss et al., 2022). Seed cost will need to be examined, since *E. trachycaulus* and *E. lanceolatus* seed is on the lower end of perennial native grass seed. However, Pedrini et al., (2022) found that native perennial grass and forb seed did not differ drastically in terms of cost per live seed, suggesting that some native forb seed may be sourced at a similar cost.

Since the beaches of Williston Reservoir are known to be nutrient deficient (Arocena et al., 1996), a fertilizer experiment was deemed necessary as part of this study but was not implemented in the field because of the number of plots that would have been necessary, limited monitoring capacity, and a separate fertilizer trial was planned for the following year. Given that fertilizer boosted plant biomass in the greenhouse, particularly in cells with sand, and that total biomass for species like *S. cereale* and *A. sativa* were nearly 20 times higher in fertilized sand cells compared to the field biomass results, it suggests that fertilizer should be tested in field conditions to assess the potential benefits of increasing plant biomass and vegetation cover for dust control. Obviously, greenhouse growing conditions were more favourable, so field results would likely not exhibit as large of a difference between fertilized and unfertilized sites, but these results suggest it is worth investigating. Increases in above ground biomass tend to increase vegetation cover, which is key to addressing the fugitive dust issue (Wolfe & Nickling, 1993). Greater vegetation cover, even increases as low as 20%, can significantly decrease sediment transport by up to 95% (Owens Lake Scientific Advisory Panel et al., 2020). Reservoirs, such as Williston, are known to be oligotrophic (Stockner et al., 2005), and other studies along BC reservoirs have found the application of fertilizer in revegetation efforts have minimal effects on overall reservoir nutrient levels (Moody, 2002). Even so, fertilizer use should be limited to only what is necessary for early plant growth to limit any potential nutrient leaching and fertilizer placement should also be tested to determine the best application method available in such a remote environment.

Beach location also had a significant effect on plant biomass, with Collins beach producing more biomass per species on average than Middle Creek North beach. However, there was not a difference in stem count, which possibly indicates discrepancies in growing conditions, such as wind or sun exposure, soil type, and depth to the water table. Conversely, plot elevation did have a significant effect on stem count, with overall stem count increasing as elevation increased. Biomass did not match this trend, but the increase in stem count as elevation increased could be due to harsher growing conditions as the distance from the existing riparian edge becomes further and environmental factors such as wind and sediment transport may increase.

Overall, agronomic species were found to germinate and emerge more quickly, achieve higher stem densities in field site conditions, and produced more above and below ground biomass compared to that of the native species. However, certain native species managed to establish, and second year growth was much greater than that of the first year, suggesting they are good candidates for areas that do not flood every year. It is recommended that a mix of annual cereale grains be used for revegetation in areas that annually flood, while a mix of cereale grains and native grasses be considered for upper elevation regions.

2.6 Conclusion

Hydropower reservoir drawdown zones can prove to be extremely challenging environments to re-establish vegetation due to periodic flooding, poor soil conditions, and harsh growing conditions. In some cases, drawdown zones can be the source of intense dust storms during low-water periods that can pose risks to human health, but through this study, our results indicate that fast-growing cereale crops such as *S. cereale*, *A. sativa,* and *H. vulgare* may present a suitable and scalable option for using revegetation as a method to address fugitive dust. These three species germinated quickly and were found to produce sufficient biomass during the short two month growing season to be a suitable option for the high dust emitting beaches of the Williston Reservoir. This study also found that native perennial grass species like *E. trachycaulus*, *E. lanceolatus*, *P. secunda*, and *F. saximontana* can establish in the sandy soil conditions found along Williston Reservoir, but it can take a full year for the plants to establish and produce higher amounts of biomass. This study suggests that native species should be included in revegetation areas where flooding does not occur every year, thus allowing the plants to establish and enabling an increase in local biodiversity. Annual cover crop species can play a role in providing rapid vegetation cover in areas that annually flood to address immediate environmental issues, such as fugitive dust, while also providing micro-habitats to support natural native vegetation recruitment.

3 Scaling the use of annual revegetation as a method of dust control along the Williston Reservoir drawdown zone in British Columbia, Canada.

3.1 Abstract

Revegetation along Williston Reservoir in northern British Columbia has demonstrated that ground cover as low as 5 – 10 % provided by cover crops can significantly reduce fugitive dust emissions that arise from the reservoir drawdown zone, and this can provide a scalable dust mitigation technique in suitable locations. Worldwide, desertification, drought, and human development is resulting in widespread fugitive dust that can pose human health risks, along with damage to infrastructure. Large hydropower reservoirs, such as Williston Reservoir, can be a source of fugitive dust and scalable dust mitigation strategies are needed to address the issue. By testing different seeding rates (100, 200, and 300 kg ha^{-1}) along with the application of fertilizer, this study found that sparse vegetation cover can significantly reduce dust emissions, and increases in vegetation cover resulting from additive treatments such as fertilizer, and to a lesser extent increases in seed rate, can improve mitigation results even during high wind events.

3.2 Introduction

Renewable energy projects, both large and small, play a crucial role in the global transition from fossil fuels to clean, low-carbon energy sources (Bilgen et al., 2004; Gielen et al., 2019; Piterou & Coles, 2021; Steffen, 2018). Hydropower can provide reliable baseload electricity to support a transition away from fossil fuels (Chang et al., 2013; Egre & Milewski, 2002; Wasti et al., 2022), but consideration must be made about the environmental impacts of large-scale hydropower facilities (Botelho et al., 2017; Egre & Milewski, 2002; Gemechu & Kumar, 2022). An example of an environmental impact caused by large hydroelectric reservoirs is erosion within the drawdown zone, the area of a reservoir that is periodically inundated between the high and low water marks (Yuan et al., 2013). Erosion within the drawdown zone can pose serious challenges for mitigation efforts and is typically caused by a combination of hydrologic processes (i.e., waves, currents, and changes in water level) (Yuan et al., 2013), and aeolian processes that transport exposed sediment and can result in large dust storms (Arocena et al., 1996; Baker et al., 2000; Polzin et al., 2023).

Wind-driven erosion and fugitive dust pose serious environmental and human health issues around the globe (Duniway et al., 2019). Fugitive dust can pose a myriad of different challenges with the primary being reduced air quality that can negatively impact human respiratory health, along with contaminating drinking water, and reducing visibility (Duniway et al., 2019; Kavazanjian et al., 2009; Skidmore, 2000). Fugitive dust can also impact local environments through increased water turbidity, hindering light penetration, and increasing wind erosion due to the abrasive nature of airborne sediment particles (Duniway et al., 2019). This can erode vegetation and strip nearby topsoil, which can further exacerbate the issue. Sediment transport by wind, which can lead to dust, occurs in three ways; suspension, saltation or surface creep (Nordstrom & Hotta, 2004). Fugitive dust consists of the suspended soil particles, while saltation and surface creep relate to larger soil particles that do not typically travel long distances in the air column, although their movement can increase the amount of suspended soil particulates (Gillette & Passi, 1988; Nordstrom & Hotta, 2004). Drylands in the US and elsewhere are areas where dust is becoming a greater issue, in part from activities such as industry development, livestock grazing, and offroad vehicle use, while also experiencing the impacts of climate change and the associated effects like more intense and prolonged drought (Duniway et al., 2019). Globally, deserts such as the Sahara in Africa and the Gobi in eastern Asia are the largest dust emitters, and with increases in desertification due to human activities and climate change these dust sources have the potential to produce even greater dust emissions (Goudie, 2009; Middleton, 2017).

In locations where hydropower reservoirs are created on top of fine sediments, such as glacial till deposits, water level fluctuations can present an environment within the drawdown zone where fugitive dust emissions can occur (Baker et al., 2000; Jackson et al., 1995; Vilmundardóttir et al., 2010). Reservoirs that act as dust sources are small in comparison to deserts, but they still present sizeable human created environments that can pose dust associated risks to nearby communities and ecosystems. Several hydroelectric reservoirs in British Columbia experience dust events during low water levels in the spring and early summer months (Arocena et al., 1996; Baker et al., 2000; Jackson et al., 1995), while elsewhere like in Iceland, dust emissions from the Blöndulón hydro-electric reservoir has been an ongoing issue since the reservoir’s construction in 1992 (Vilmundardóttir et al., 2010). Similar dust issues also occur in reservoir like environments, such as Owens Lake in California, where water diversion projects in the 20th century have resulted in the lake drying and becoming a salty brine pool that periodically floods after large rain events (Owens Lake Scientific Advisory Panel et al., 2020). Since 2000 the Los Angeles Department of Water and Power has spent over $2 billion dollars on dust control measures for Owens Lake, which highlights the financial impact dust can have on a region. Dust mitigation along reservoir drawdown zones poses various challenges, but project scale, fluctuating water levels, site access, and harsh growing environments are often the most difficult components of mitigating dust in these environments (Allen & Klimas, 1986).

Various dust control strategies have been tested along reservoir drawdown zones, including irrigation, tilling, laying down gravel, wind fencing, and chemical soil tackifiers, but vegetation-based approaches are often viewed as the most cost effective and scalable, so long as the drawdown zone substrate and environment are suitable for revegetation (Abrahams, 2006; Allen & Klimas, 1986). Revegetation typically works best in regions of a drawdown zone that have predominately fine sediments and enough soil moisture during low water periods to support vegetation (Allen & Klimas, 1986). Vegetation helps mitigate dust emissions by covering a portion of the soil surface, breaking the winds sheer force along the ground, and preventing suspension, saltation and surface creep (Wolfe & Nickling, 1993).

Cover crops are one type of vegetation used widely in the agricultural sector to prevent wind erosion (Bartkowski et al., 2023; Haramoto, 2019; Haruna et al., 2020) and have been applied as an erosion control option for dust control along hydroelectric reservoirs (Abrahams, 2006; Allen & Klimas, 1986; Carr et al., 1993; Moody, 2002). By quickly establishing a vegetation cover and root structure, cover crops help prevent surface soil loss through their roots stabilizing the soil and their above ground biomass breaking the winds sheer force, thus preventing wind driven sediment transport (Bartkowski et al., 2023; Wolfe & Nickling, 1993). Cover crops can also help improve soil moisture retention, add to a soil's organic matter when they die, and provide forage and habitat for various fauna (Haruna et al., 2020; Schipanski et al., 2014). For dust control along reservoir shorelines, species such as fall rye (*Secale cereale*) have been successful in establishing an annual vegetation cover to limit widespread dust emissions on certain reservoirs in the US and southern Canada (Arocena et al., 1996; Baker et al., 2000; Burton, 2010; Carr et al., 1993). In the reservoir drawdown zone environment, species such as *S. cereale* typically must be seeded annually since annual flooding tends to kill the plants before they reach maturity, or if maturity is reached, their seeds are washed away by reservoir currents.

Since vegetation cover is the primary goal for vegetation-based dust mitigation strategies, a better understanding of the relationship between vegetation cover and dust emissions at scale can benefit the design and implementation of large dust mitigation projects. For cover crops, optimizing seeding rates can allow for the necessary vegetation cover to be achieved, while also minimizing the cost per hectare required to implement revegetation at a large-scale. The application of fertilizer is also used to boost cover crop growth, thus resulting in greater plant biomass and more cover, but does bring a suite of potential issues such as nutrient loading, additional costs, and the associated greenhouse gas emissions (Balkcom et al., 2012). However, there is not a clear understanding in the published literature about what seeding rates and fertilizer applications are needed in reservoir drawdown environments for cover crops to be optimally used for dust mitigation. In poorer soils, such as those along most reservoirs, higher seeding rates may benefit cover crop growth by; 1) providing a dense canopy cover that can reduce surface moisture evaporation and provide a microclimate that retains moisture for a longer period; and 2) compensating for a poor germination (Adetunji et al., 2020; Dos Santos Cordeiro et al., 2021).

Given the harsh conditions of many reservoir substrates, the addition of fertilizer to seeded drawdown zone areas could provide cover crops with necessary nutrients, namely nitrogen and phosphorus. Drawdown zones tend to be nutrient deficient, and fertilizer could both minimize plant competitive stress and speed individual growth with enhanced resource availability. However, there are risks associated with both potential management practices. Using higher seed rates and fertilizer may result in higher costs per hectare, add excessive nutrients to the reservoir ecosystem, and come with additional logistical resources and time required to bring the material to site. Therefore, gaining a better understanding of the impact of seeding rate and fertilizer on overall vegetation cover, and ultimately reductions in fugitive dust emissions can better inform the implementation of reservoir drawdown zone dust mitigation projects.

This study aimed to better understand this relationship between cover crop seed rate and fertilizer application with vegetation cover and subsequent dust mitigation along a highly erodible reservoir drawdown zone. This project tested the amount of vegetation cover needed to significantly reduce dust, while also trying to determine the minimum required inputs. This allows for better estimates of the amount of seed and additional treatment needed for effective dust control, while minimizing annual expenses on consumables (seed and fertilizer). Thus, we asked 1) how different seeding rates affect overall vegetation ground cover; 2) if the addition of slow-release fertilizer post-seeding influences vegetation ground cover; and 3) how these potential different levels of ground cover affect fugitive dust emissions.

3.3 Methods

3.3.1 Site Information

The study is situated along the north-eastern shore of Williston Reservoir in northern British Columbia (Figure **3.1**). The reservoir was created through the construction of the WAC Bennett Dam, which was finished in 1968 as part of British Columbia's Two River Policy (Poirier, 2019; Sims, 2017). Williston Reservoir transformed the region by flooding a total of 1,773 km^2 of land, including the confluence of the Finlay, Parsnip, and Peace Rivers, and resulted in BC's largest freshwater reservoir (Baker et al., 2000; Poirier, 2019; Sims, 2017). The reservoir level fluctuates on average >10 m in elevation each year between low pool in early spring and high pool in early fall after reservoir recharge (Stockner et al., 2005). As a result of the construction, several Tsay Keh Dene Nation (TKDN) villages were flooded, including Fort Grahame, Finlay Forks, and Ingenika, along with a substantial portion of their traditional territory (Baker et al., 2000; Loo, 2007). Members of TKDN were forced to flee their homes ahead of the flooding and have fought for the right to return to their territory. The primary reserve of TKDN now lies at the northern edge of Williston Reservoir where the village of Tsay Keh Dene is located (Figure **3.1**). The fluctuating water levels expose vast, erodible areas of drawdown zone along the reservoir and are the source of large dust events that impact local communities, particularly that of TKD, along with the surrounding ecosystems.

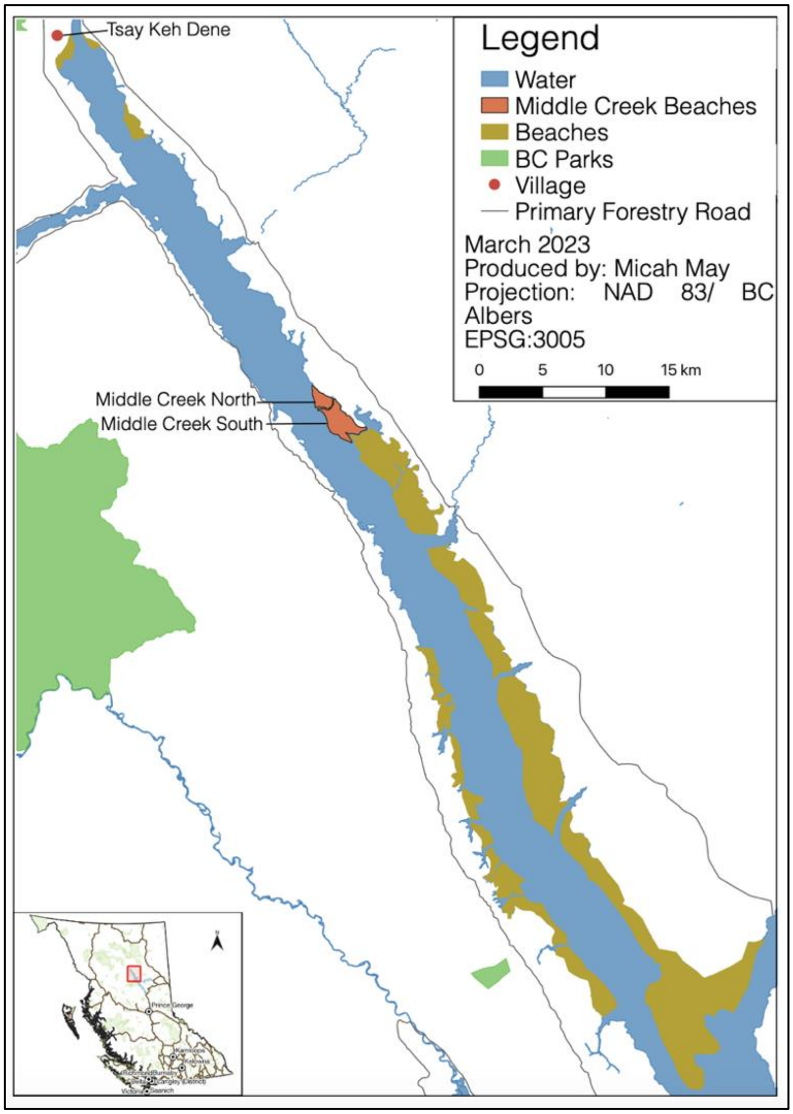

Figure 3.1: Overview map of the Finlay Reach of Williston Reservoir, highlighting Middle Creek North and Middle Creek South beaches, which were the study locations for this research, along with the other drawdown zone beaches and the village of Tsay Keh Dene at the north end of the reservoir.

This study focused on two draw down zone areas, referred to hereafter as beaches. Each of the beaches (Figure **3.1**), named Middle Creek North (MCN) and Middle Creek South (MCS), are known to be some of the largest contributors to the intense dust storms that typically occur during the low water months between April and July (Arocena et al., 1996; Baker et al., 2000; Phaneuf, 2019). This study sought to investigate different vegetation-based dust mitigation treatments at scale; thus, each beach had a different study focus. Middle Creek North, which is roughly 135 hectares (ha), was the test location for different seeding rates and fugitive dust emission sampling. Middle Creek South, which is nearly 420 ha, was the location of a fertilizer application experiment.

The soils found on these two beaches have a very high sand content, along with some fine silt and clay components. Previous soil textural analysis (Nickling et al., 2011) showed that MCN was classified as having a soil type of (sand = 92.4%, silt = 2.1%, clay = 5.5%), while MCS was (sand = 94.8%, silt = 1.2%, clay = 4.0%). The beaches of Williston Reservoir are known to have poor macro-nutrients, such as available nitrogen, phosphorus, and potassium (Abiola, 2011; Vaartnou, 2010). The dust storms that originate due to strong southerly winds are a concerning health risk to local inhabitants of Tsay Keh Dene village and surrounding area (Loo, 2007). No peer-reviewed literature has been produced that attempts to systematically identify and quantify the contents of the dust or the potential health related impacts of the dust on local inhabitants, but studies have estimated the amount of dust being emitted from the beaches (Nickling et al., 2014; Phaneuf, 2019).

Average daily weather data collected from the Mackenzie weather station, 175 km to the south of the beaches, is shown in Table **3.1**. Temperatures for the 2023 season were above average in both May and June, while cumulative precipitation was well below average.

Table 3.1: Average weather data from May 1 to June 23, 2023, from the Mackenzie, BC Environment Canada weather station and historic weather data from 1981 – 2010 (Environment and Natural Resources Canada, 2023).

Month	**Average Daily Max Temperature (C°)**	**Average Daily Minimum Temperature (C°)**	**Average Daily Mean Temperature (C°)**	**Historic Daily Mean Temperature (C°)**	**Total Cumulative Precipitation (mm)**	**Historic Cumulative Precipitation (mm)**
May	21.8	4.4	13.1	8.9	22.5	48.0
June	22.1	6.0	14.1	13.3	13.3	56.9

3.3.2 Plant Species Selection

This study focused on cereal grain cover crop species based on prior research conducted on Williston Reservoir beaches (Abiola, 2011; Burton, 2010; May, 2022; Vaartnou, 2010), and other reservoir revegetation work (Abrahams, 2006; Allen & Klimas, 1986; Carr et al., 1993). The established program had a specific seed mix developed for the 2023 seeding program that consisted by weight of 50% fall rye, 15% oats (*Avena sativa*), 15% barley (*Hordeum vulgare*), and 15% winter wheat (*Triticum aestivum*).

3.3.3 Seed Rate Treatment Implementation

Three different seed rate treatments were tested on MCN, including 100, 200, and 300 kg ha^{-1} by weight, hereafter referred to as “low”, “medium”, and “high”; a control treatment without any vegetation was also established. Each of the three vegetated treatment areas was 40 ha, while the control treatment was 15 ha. Each treatment area ran south-east to north-west, which runs parallel to the orientation of the reservoir and the prevailing winds that blow dust towards the village of Tsay Keh Dene. This design was implemented to limit the effect between treatments and to enable the control treatment to be smaller so a majority of the beach could still be vegetated for dust control. This study was run in conjunction with the ongoing dust mitigation program so minimizing dust emission was a priority, and complex treatment replication was not feasible, both due to scale so each treatment had a measurable effect on dust emissions and due to limitations in capacity. Treatments were seeded using a Great Plains 1006NT no-till drill seeder with 19 cm row spacing at each of the specified seeding rates. On MCN seeding commenced on May 1, and finished May 4, while for MCS seeding started on May 4, and finished May 9. Seeded rows were established perpendicular to the prevailing south-easterly winds, as this has been found to provide a more effective approach for linear dust control treatments (Fryrear et al., 2011). No pre-treatments were applied to the beach surface prior to seeding and no soil amendments or irrigation was applied post-seeding.

3.3.4 Fertilizer Treatment Application

To test the effect of fertilizer amendment on vegetation cover in beach conditions a block treatment design was set up on MCS beach that consisted of two 50 ha fertilized treatment blocks and two 100 ha non-fertilized blocks (Figure **3.2**). The entire 300 ha treatment area was seeded between May 6 and May 9 using a Great Plains 1006NT no-till drill seeder with 19 cm row spacing with the seed mix at a seeding rate of 200 kg ha^{-1}. On May 22, two weeks after seeding was completed, the two 50 ha blocks had fertilizer applied to them using a pellet 18-18-18 nitrogen, phosphorus, and potassium (NPK) balanced blend fertilizer from Terralink Horticulture. Fertilizer was spread using a Willmar S-500 spreader at a rate of 150 kg ha^{-1}. The treatment blocks were set up so that the two fertilizer blocks were diagonally across from each other and vice-versa for the control blocks.

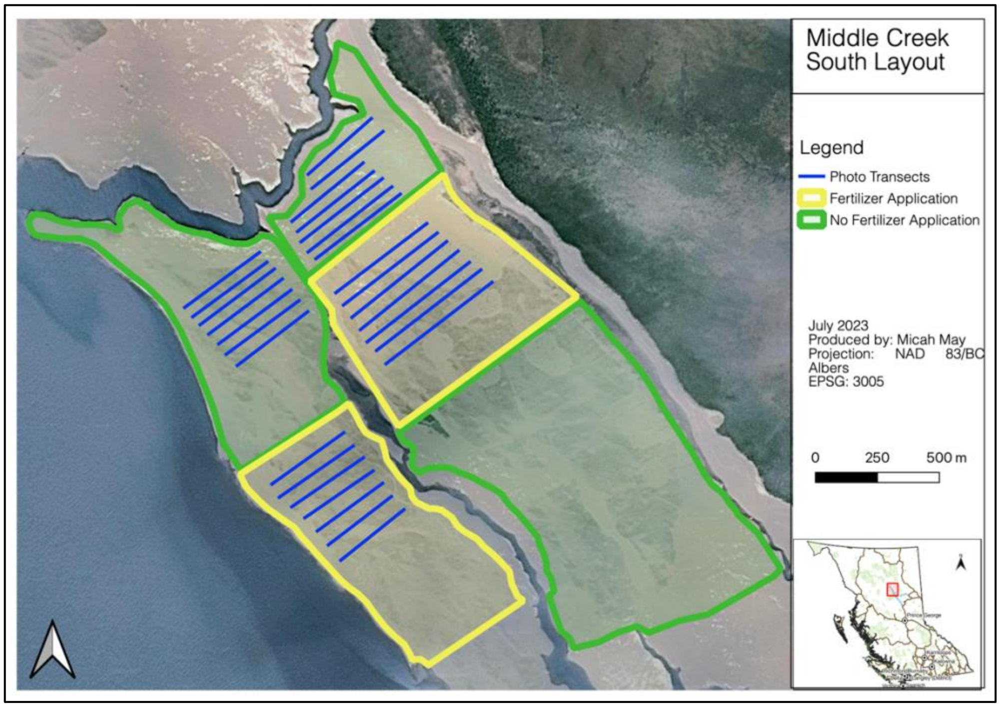

Figure 3.2: A total of 300 ha was seeded on Middle Creek South beach at a seeding rate of 200 kg ha^{-1}. Fertilizer was then applied to two treatment areas totalling 100 ha at an application rate of 150 kg ha^{-}1. Photo transects were done within each of the treatments to estimate vegetation cover.

3.3.5 Quantifying Dust Emissions

A critical component of any dust mitigation approach is monitoring the effectiveness of the application to understand what impact is being made, and what modifications might be required (Owens Lake Scientific Advisory Panel et al., 2020). One tested sampling device that has been used widely to inform wind-driven erosion models is by (Fryrear, 1986) called the Big Spring Number Eight (BSNE) sampler. The BSNE was calibrated using wind tunnel conditions for collecting sand and dust particles (Fryrear, 1986) but has been used in the field across the globe for measuring erodible sediment transport (Mendez et al., 2011). The BSNE sampler is a passive, wedge-shaped dust sampling device with a 60 mesh screen on the top of the wedge to allow airflow out of the sampler, while a removable tray at the bottom collects airborne sediment particles (Fryrear, 1986).The efficiency of the BSNE sampler has been found to decrease with height due to higher wind speeds at elevated heights coupled with smaller particle sizes (Mendez et al., 2011), but the BSNE sampler is viewed as a reliable and simple measuring tool for erodible sediment and fugitive dust emissions in field conditions.

The purpose of gathering dust emission data on MCN was to try and quantify any potential effects the revegetation treatments had on fugitive dust emissions. BSNE samplers were used to collect dust samples across the four treatment areas on MCN beach. For this study, two BSNE samplers were attached to a metal pole, one at 20 cm to measure localized dust emissions and the other 100 cm above the ground to measure fugitive dust emissions, to form a single vertical array (Figure **3.3**). No dust sampling was conducted on MCS as the primary objective on this beach was to assess the effect of fertilizer application on vegetation cover.

Figure 3.3: BSNE dust sampler array on MCN beach in the medium (200 kg ha^{-1}) treatment area on June 3, 2023.

Within each treatment area 11 BSNE sampler arrays were set up, with six set up along the treatment edges, and the remaining five set up randomly inside (Figure **3.4**). The BSNE samplers were first deployed on MCN May 21, 2023.

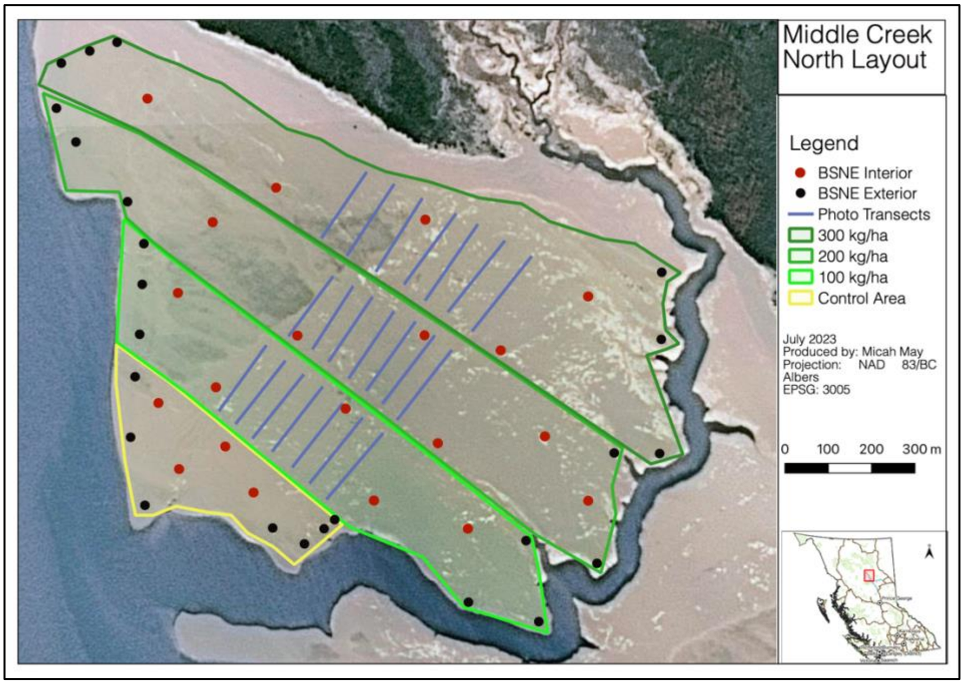

Figure 3.4: Three different seed rate treatments were applied on Middle Creek North beach along with one control. The seeding rates were 100, 200, and 300 kg ha^{-1} while the control was not seeded. Eleven BSNE dust sampler arrays were placed in each of the treatment areas with six being placed on the exterior edge and five on the interior region. Photo transects were done within each of the three seeded treatments to estimate vegetation cover.

3.3.6 Data Collection

3.3.6.1 Ground Cover

Overhead photos were taken to estimate vegetated ground cover in the different vegetation treatments on June 19, 2023. Photos were taken every 25 m along a set transect line. On both MCN and MCS, seven 200 m transects were established within each of the four treatment areas for a total of 56 photos per treatment. Each photo was taken at a height of 1.5 m above using a OnePlus 6 (OnePlus, Shenzhen, China) smartphone camera (resolution 12 megapixels) between 9 AM to 4 PM on a sunny day to minimize shadow effect. The phone was set on top of a 1.5 m plastic pipe to ensure all photos were taken from the same height. Photos were analyzed using the digital image-based software SamplePoint (https://www.samplepoint.org/). SamplePoint is a free computer software designed for the Windows operating system for manual image analysis. SamplePoint enables users to manually analyze nadir imagery by superimposing an array of crosshair targets onto an image, allowing the user to classify each pixel a crosshair lands on in a systematic fashion (Terrance Booth et al., 2005). For this study, each crosshair pixel was either classified as having grass or soil present, and the data was saved and exported in an excel spreadsheet from the software.

3.3.6.2 BSNE Samplers

The aim was to collect BSNE samplers every two-weeks, but a high-wind event resulted in an extra collection taking place, resulting in three data collection periods, a planned collection on June 3, 2023, a collection post-dust storm on June 5, 2023, and a second planned collection on June 18, 2023. Once each sampler set was collected, they were placed in a drying oven (Yamato DKN812) at 105 ^{o}C for 24 hours, after which the sediment samples were weighed using a precision scale (0.0001 g).

3.3.7 Statistical Analysis

All analyses were performed using R Statistical Software (v4.1.2; R Core Team, 2021). The data was analyzed and visualized using the tidyverse package (v1.3.2; Wickham et al., 2019).

Analysis of seed rate and fertilizer test data was done using the glmmTMB package (v1.1.4; Brooks et al., 2017) in R. Analysis was conducted to investigate how differing seed rates and the application of fertilizer effect the amount of resulting vegetation cover on Williston Reservoir beaches. Seed rate data was analyzed by fitting a beta family linear model to assess total vegetation cover (response) based on the three different seeding rates (predictor). Fertilizer experiment data was also fit using a beta family linear model where vegetation was the response and fertilizer application was the predictor. The beta family was chosen because the vegetation cover values were transformed into decimals between 0 and 1, but not inclusive, and beta is often used for modelling vegetation cover (Damgaard, 2014). The model was validated using the “simulateResiduals” command found in the DHARMa package (v0.4.6; (Hartig, 2022), where the residuals were plotted against the predicted values, along with the expected and observed residuals being plotted against each other to check residual normality and homoskedasticity.

For the BSNE data, analysis looked at how vegetation cover, including differing levels of vegetation cover, effected fugitive dust emissions on MCN. The data was split into two sets, with the June 3rd and June 19th being combined to represent typical background dust levels, and June 5th data being analyzed separately representing an intense 24-hour dust event. Vegetation cover was used as a proxy, as it is acknowledged that vegetation cover was only assessed once on June 20th after all dust collection periods; therefore, we are assuming that the relative difference in cover between treatments remained the same over the course of the growing season after plant emergence.

The absolute difference in dust between control areas and vegetated areas was so great that it masked any signal from two key variables of interest – relative plant cover and distance from the edge of vegetation. Thus, dust models were each split into two, with the first comparing the amount of dust collected as the response to simplified treatment categories (vegetation or control) as the predictor. The second model excluded the control area and only focused on the vegetated area with dust mass as the response and vegetation cover and distance to vegetation edge as the predictors. Separate models were run for dust samples collected at the height of 20 cm and 100 cm. For the June 3/19 models, date was also added as a fixed effect to investigate if there was a difference between the two collection periods.

Linear models were fitted for all the BSNE data. Residuals were found to be non-normal, and the data was subsequently log transformed to improve model fit. The models were validated by checking the distribution of the residuals through plotting the residuals against the fitted values along with a normal Q-Q plot to check for residual normality and homoskedasticity.

3.4 Results

Vegetation cover in the seeded treatment areas on MCN ranged from 1% to 26% with the median being 7%, while the control area had no vegetation cover. For the seeding treatments, the low (100 kg ha^{-1}) seed rate had significantly less average vegetation cover (4.9 % ± 2.7%) when compared to the medium (200 kg ha^{-1}) seed rate (9.9% ± 4.5%) and the high (300 kg ha^{-1}) seed rate (9.1% ± 5.9%) (Figure **3.5**). Based on seeding rate, the model predicted a cover value of 5.3% ± 0.5% for the low seed rate block, 10.2% ± 0.6% for the medium seed rate block, and 8.6% ± 0.6% for the high seed rate block.

On MCS, vegetation cover ranged from 2% to 48% with the median being 14%. When comparing treatments, fertilizer was found to have a significant effect on vegetation cover with non-fertilized areas having an average cover of 9.2% ± 4.3%, while fertilized blocks had an average cover of 23.3% ± 8.5%

(Figure **3.5**). In terms of modelling, the model predicted a cover value of 9.6% ± 0.5% for non-fertilized blocks, while it predicted a cover of 23.1% ± 0.7% for the fertilized blocks.

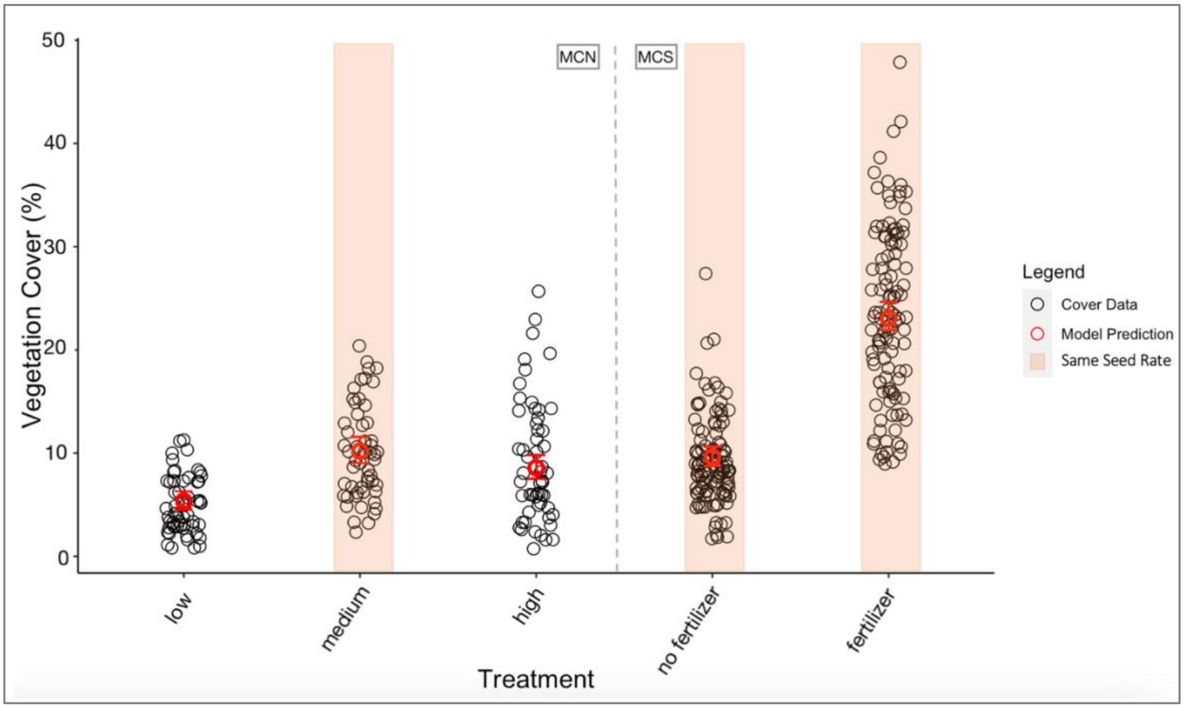

Figure 3.5: On MCN mean vegetation cover was 9.1% and 9.9% for high and medium seed rates, while the low block had a mean of 4.9%. The control treatment had no vegetation cover. On MCS, which had the same seed rate as the MCN medium block, the unfertilized blocks had a mean vegetation cover of 9.2%, while fertilized blocks had an average of 23.3% vegetation cover.

Results from the BSNE samplers on MCN at a height of 20 cm above the ground indicate that vegetation had a significant effect on decreasing local dust emissions, with a 94% decrease found in the June 3rd collection (Figure **3.6**) and a 91% decrease from the June 19th collection (Figure **3.6**). During the storm event captured by the June 5th collection, a 76% decrease was found (Figure **3.6**). For the June 3rd and June 19th collection periods, degree of vegetation cover did not show any significant difference in the amount of dust collected (Figure **3.6**; Table **3.3**). However, distance to the vegetated edge did have a significant effect for June 3rd and 19th, with BSNE samplers further from the vegetated edge having lower amounts of fugitive dust and sand particles (Table **3.3**). For the June 5th collection, immediately after an intense dust event, vegetation cover did have a significant effect, with higher levels of vegetation cover in the medium and high treatment areas having significantly less dust and sand in the BSNE dust traps (Table **3.3**). Distance from the vegetated edge did not have a significant effect on June 5th regarding dust levels.

Table 3.2: A significant decrease in dust emissions because of vegetation cover was found for all four data groups, both at the 20 cm and 100 cm height, and for all collection dates. There was also a significant difference in dust levels at 100 cm between the June 3rd and June 19th collection periods with the later collection having more dust.

Model	Intercept	Vegetation (yes or no)	Date
20 cm June 3/19	3.20	-3.34 ± 0.69 ***	0.55 ± 0.60
20 cm June 5	6.18	-2.49 ± 1.23 ***	N/A
100 cm June 3/19	-1.01	-0.41 ± 0.36 **	0.55 ± 0.31 ***
100 cm June 5	0.91	-1.49 ± 0.51 ***	N/A

Table 3.3: Variation in the amount of vegetation cover only had a significant effect for the June 5th collection with the medium and high areas having significantly less dust emissions both at 20 cm and 100 cm. When excluding the control area, there was a significant difference for the June 3/19 collections with BSNE samplers closer to the vegetation edge having significantly more dust. There was also a significant difference in dust levels at both the 20 cm and 100 cm heights between the June 3rd and June 19th collection periods with the later collection having more dust.

Model	Intercept	Level of vegetation cover	Distance to veg edge	Date
20 cm June 3/19	1.08	-0.06 ± 0.13	-0.007 ± 0.002***	0.63 ± 0.56*
20 cm June 5	7.01	-0.43 ± 0.31 **	0.001 ± 0.005	N/A
100 cm June 3/19	-1.13	-0.01 ± 0.07	-0.004 ± 0.001 ***	0.58 ± 0.31 ***
100 cm June 5	0.61	-0.13 ± 0.12 *	-0.001 ± 0.002	N/A

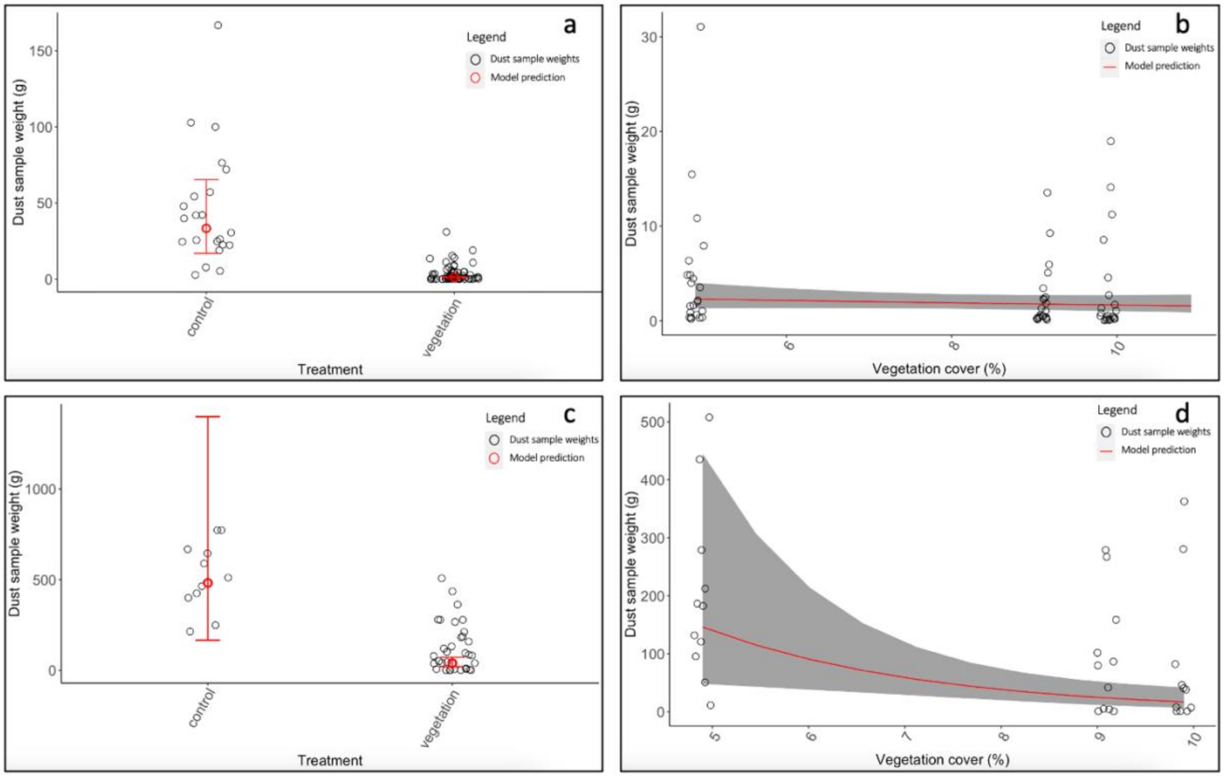

Figure 3.6: (a) Vegetation cover resulted in a significant decrease in dust collected at a height of 20 cm above the ground for the June 3/19 collections. (b) Amount of vegetation cover did not have a significant effect on dust emissions at a height of 20 cm for June 3/19. (c) Vegetation cover resulted in a significant decrease in dust collected at a height of 20 cm on June 5th. (d) Level of vegetation cover had a significant effect on dust emissions at a height of 20 cm on June 5th with the less vegetation cover (left side) emitting significantly more sediment than higher levels of vegetation cover (right side).

Results from the BSNE samplers set at 100 cm above the ground showed a significant decrease in dust emissions between the vegetated treatments and the control both for the June 3rd and June 19th collection periods, and for the major dust event on June 5th (Figure **3.7**). Results were a decrease of 11.5% for June 3rd and 19.5% for June 19th, while for the June 5th collection a decrease of 72.6% occurred. For June 5th, amount of vegetation cover did have a significant effect, with medium and high seed rate areas having significantly lower amounts of collected dust compared to the low seed rate area (Figure **3.7**; Table **3.3**). Level of vegetation cover did not have a significant effect for the June 3/19 collections. Distance from the vegetated edge did have a significant effect on the June 3/19 collections, but not for June 5th during the major dust event at the 100 cm height.

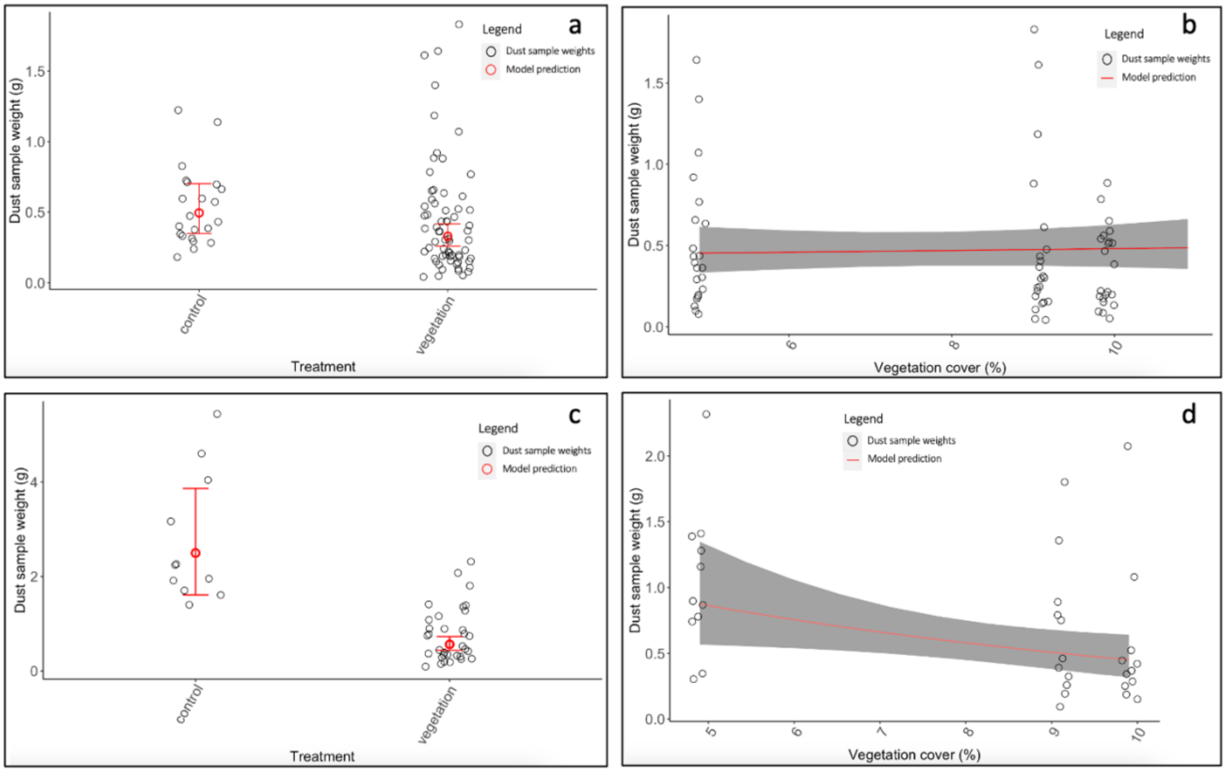

Figure 3.7: (a) Vegetation cover resulted in a significant decrease in dust collected at a height of 100 cm above the ground for the June 3/19 collections. (b) Amount of vegetation cover did not have a significant effect on dust emissions at a height of 100 cm for June 3/19. (c) Vegetation cover resulted in a significant decrease in dust collected at a height of 100 cm on June 5th. (d) The level of vegetation cover had a significant effect on dust emissions at a height of 100 cm on June 5th with the low seed rate emitting significantly more dust and sediment than the medium and high seed rate areas.

3.5 Discussion

The presence of vegetation cover provided by cover crops on the beaches of Williston Reservoir acts to significantly reduce fugitive dust emissions and this suggests a strong use case for revegetation as a method for dust mitigation. Vegetation cover was beneficial both during ambient accumulated dust periods and high intensity dust events, like the one that occurred on June 4th, and was the case for both locally emitted dust at the 20 cm height and fugitive dust at the 100 cm height. For the June 4th dust storm, increased levels of vegetation cover significantly reduce sediment transport compared to areas with more sparse vegetation, suggesting that treatments that promote increased cover, such as fertilizer, should be considered to boost vegetation cover to reduce the impacts of high-intensity wind events.

Results from this study suggest that lower levels of vegetation cover than previously estimated may be adequate to achieve effective dust emission reductions along Williston Reservoir. Previous theoretical studies estimated that having a vegetation cover of 30% could reduce dust emissions by 80%, while a cover of 60% could reduce dust by up to 95% (Baker et al., 2000). Our results suggest that even achieving 10% cover can result in significant reductions of over 90% at a height of 20cm above the ground during typical wind periods and over 70% at both 20 cm and 100 cm heights during high intensity storms. Studies at Owens Lake in California found reductions of 95% in sand movement from plots with saltgrass (*Distichlis spicata*) cover lower than 20% (Lancaster & Baas, 1998; Owens Lake Scientific Advisory Panel et al., 2020), which further suggests that sparse vegetation can have a significant effect on reducing dust. Greater cover is likely needed to decrease the fine dust levels at the 100 cm height due to the winds ability to suspend fine particles even amongst sparse vegetation, but this provides a possible motive to include fertilizer to raise the vegetation cover levels above 20%. The Owens Lake project has set 20% vegetation cover as their minimum to ensure consistent dust mitigation is achieved across the areas of the delta that are suitable for vegetation (Owens Lake Scientific Advisory Panel et al., 2020), and this target appears similarly achievable in the context of Williston Reservoir with the inclusion of fertilizer. Reaching higher cover levels, for example above 50%, may not be feasible along Williston Reservoir during the spring dust season, but these results suggest lower amounts of cover can provide ample dust mitigation potential and further supports establishing vegetation as a good method of dust control in fine sediments environments, such as reservoir drawdown zones.

The effect of seed rate on vegetation cover from this study suggests that an optimal seeding rate lies between 100 and 200 kg ha^{-1} given the slight negative trend in ground cover between the medium and high treatments. The increase in cover between low (100 kg ha^{-1}) and medium (200 kg ha^{-1}) seed rates is supported by other studies that found increases in cover when increasing seeding rate (Boyd et al., 2009; Brennan & Leap, 2014; Haramoto, 2019). However, this study found vegetation cover to plateau above the medium seed rate. Increasing seed rates can compensate for lower seed germination in conditions where soil moisture is low or in soils that lack essential nutrients (Dhillon et al., 2022).

However, inter plant competition and a lack of soil nutrients is likely the cause for the plateauing of cover between the medium and high seed rates, indicating a threshold where a higher rate does not result in more plant cover. By adding the fertilizer treatment on MCS, cover increased dramatically when using the medium seeding rate, suggesting that inter-plant competition for limited resources is a large driver and supports the hypothesis of a seed rate threshold based on a lack of available nutrients. This is supported by other studies that found soil nutrients to be a large driver of vegetation biomass and cover when compared to seeding rates alone, particularly for cover crop mixes that comprise several species which may exhibit different traits (Baraibar et al., 2020; Bybee-Finley et al., 2022).

Due to the broadcast fertilizer treatment on MCS resulting in significantly more vegetation cover, it suggests that inclusion of fertilizer when seeding cover crops for dust mitigation can be beneficial. It is important to determine the appropriate fertilization rate so that the necessary nutrients are provided to the nutrient deficient environment, but that fertilizer cost and the potential impacts of excessive nutrient loading on the aquatic environment are minimized. Williston Reservoir is known to have very low aquatic productivity and has a classification of ultra-oligotrophic (Stockner et al., 2005), but it is still important to minimize any potential cumulative impacts fertilizer application potentially could have on the reservoir ecosystem. Reservoirs in BC tend to become oligotrophic over time due to sedimentation and outflows (Stockner et al., 2001) and some, such as Arrow Reservoir, have had ongoing nutrient restoration programs for over 20 years to try and address nutrient imbalances within the reservoir system (Bassett et al., 2020). Despite Williston being ultra-oligotrophic, minimizing nutrient loading from dust mitigation activities is advised. Further investigation around fertilizer application is recommended due to the unique growing conditions present on the reservoir beaches.

Seed-placed fertilization may be one potential alternative that reduces overall amount of applied fertilizer. The method involves placing the fertilizer in the same seed row as the seed and at the same time, typically using a seed drill (Malhi et al., 2001; Randall & Hoeft, 1988). Other forms of fertilizer application such as knifing, side banding, and incorporated broadcast spreading are used in the agricultural industry, but they either require additional passes, or require additional equipment that is not suitable for the reservoir beach environment. Seed-placed application is typically more efficient than broadcasting due to the available nutrients being placed below the soil surface, making them more available to the developing roots and not requiring precipitation and soil moisture to move nutrients subsurface (Malhi et al., 2001). However, applying excessive nitrogen (N) too close to a seed can result in seed damage due to ammonia toxicity, known more commonly as the salt effect, where the osmotic pressure from the ammonia pulls nearby soil moisture away from the seed, thus hampering its germination (Alberta Agriculture and Food, 2008). Broadcast spreading limits the risk of seed damage, but does increase the potential of nutrient leaching, particularly of N, and can make some nutrients, such as potassium (K) and phosphorus (P) less accessible to plant roots due to their presence on the soil surface, requiring precipitation to move them subsurface (Alberta Agriculture and Food, 2008). If less fertilizer can be seed-placed using the existing drill seeders without significant decreases in vegetation cover compared to broadcasting, then overall costs would be lower and there would be a reduced chance of nutrient loading into the reservoir environment.

Cost is an important consideration for dust mitigation along Williston Reservoir, but also any large-scale project seeking to mitigate or restore environmental degradation. Conducting a cost benefit analysis can provide insight into what options are available and their respective prices. Table **3.4** provides an example for Williston Reservoir that outlines four potential treatment options that could be considered for dust mitigation. Without conducting a basic comparison like this, it is not necessarily clear which treatment combination will provide maximal efficacy for minimal cost. A lower seeding rate coupled with fertilizer is likely to produce satisfactory vegetation cover, while not being exceedingly expense per hectare. Given there are several thousand hectares of dust emitting beach along Williston Reservoir, the cost per hectare is vital to understand, along with the effectiveness of each treatment option.

Table 3.4: Four different treatment options that include and exclude fertilizer application, along with varying seed rates. The cost per hectare estimate is in Canadian dollars and is based on cover crop seed and fertilizer costs from the 2023 season. This is not an exhaustive list of treatment options, rather four potential options for Williston Reservoir based on the study results and findings from similar studies on other reservoirs.

Treatment Options	Seeding rate (kg ha^{-1})	Estimated Seed Cost ($ ha^{-1})	Fertilizer rate (kg ha^{-1})	Estimated Fertilizer Cost ($ ha^{-1})	Total Cost per hectare ($)
Seed only	200	240.00	N/A	N/A	240.00
Seed and fertilizer (#1)	50	60.00	50	70.00	130.00
Seed and fertilizer (#2)	125	150.00	50	70.00	220.00
Seed and fertilizer (#3)	200	240.00	50	70.00	310.00

Hydropower reservoirs present challenging environments in which to implement dust mitigation activities, but this study suggests that vegetation can be an effective and scalable dust mitigation treatment along Williston Reservoir and builds on prior findings from reservoirs in more southerly latitudes (Allen & Klimas, 1986; Carr et al., 1993; Moody, 2002; Newbury & McCullough, 1984; Owens Lake Scientific Advisory Panel et al., 2020). This study also highlights the role sparse vegetation can play in helping control aeolian sediment transport and fugitive dust emissions in other environments, which can be beneficial in areas around the globe, such as arid drylands or regions facing desertification, that are seeing the growing impacts of climate change.

3.6 Conclusion

Fugitive dust resulting from aeolian erosion is an ongoing challenge worldwide due to factors such as desertification, increased drought due to climate change, and widespread human development (Duniway et al., 2019; Goudie, 2009; Schweitzer et al., 2018; Wang et al., 2015). Hydroelectric reservoirs are a potential dust emission source, particularly older reservoirs that may not be located and designed with dust control as a goal. In a time where large-scale renewable energy, such as hydropower, is in high demand, special consideration must be made to mitigate potential environmental impacts. For existing hydropower facilities, such as Williston Reservoir, that deal with fugitive dust issues, this study showcases how cover crops can be used in combination with properly applied soil amendments to mitigate fugitive dust emissions within drawdown zone environments. Planting cover crops with effectively placed fertilizer can help promote rapid vegetation cover that will reduce dust emissions, while helping ensure as much of the fertilizer nutrients are used by the plants and do not leach into the reservoir environments. Using cover crops to address fugitive dust issues can then allow for other resources to be spent looking at restoration opportunities where native plant communities may be established long term.

4 General Conclusion

4.1 Summary of Research Findings

This research was driven by my prior work experience on the WDMP and the apparent need for a study looking at how revegetation methods could be improved to benefit the WDMP and the nearby community of Tsay Keh Dene. The primary aim of this project was to identify which species should be used for revegetation efforts, if soil amendments are needed to achieve necessary vegetation cover, and how vegetation cover effects fugitive dust emissions on Williston Reservoir beaches. However, this project also sought to improve the capacity of Chu Cho Industries, and through the company, the community and members of Tsay Keh Dene Nation, whose lives and traditional territory have been irreversibly damaged because of Williston Reservoir and the dust it emits. By improving our understanding of how vegetation can be used as a dust mitigation tool, Chu Cho Industries can be more effective in implementing the WDMP, thus helping reduce fugitive dust that impacts the village of Tsay Keh Dene, but can also provide employment and training opportunities for community members, revenue for the Nation to put towards community development, and to build the company's capacity to help implement other large-scale mitigation and restoration projects that benefit the environment.

Chapter 2 has two main findings. The first is that cover crop species, such as *S. cereale, A. sativa,* and *H. vulgare* are the best species out of the ones tested for large-scale revegetation for the purpose of dust control in areas that flood on an annual basis. These species germinate quickly and produce large amounts of biomass at a low cost per hectare, which is desirable for a project such as the WDMP. Second, native species, such as *E. lanceolatus, E. trachycaulus, P. secunda,* and *F. saximontana*, can establish in the upper elevation beach environment and should be considered for restoration efforts in these areas where flooding occurs on an infrequent basis.

Chapter 3 has three primary findings. First, vegetation cover provided by cover crops significantly reduced local dust emissions at the study beach and strongly suggests cover crops are a good treatment for dust control. Second, the level of vegetation cover needed to significantly reduce dust is likely lower than previously estimated by past studies (Arocena et al., 1996; Baker et al., 2000), but higher levels of cover do significantly reduce dust, especially during intense wind events. Finally, the application of fertilizer appears to provide beneficial increases in vegetation cover and could enhance the effectiveness of lower seed rates, thus reducing overall costs while increasing the overall effectiveness of the dust mitigation program.

4.2 Overview

Mitigation efforts, such as dust along Williston Reservoir, are likely to be multi-year efforts that may never fully be resolved given the nature of the reservoir environment. This research provides insight into how cover crops and native species can be used in combination to mitigate dust issues, and work to restore portions of the reservoir environment to more of a functioning and diverse ecosystem, even if it differs from the original ecosystem prior to creation of the reservoir. The results from this study suggests that using cover crop species can enable revegetation efforts to scale, which should allow the WDMP to effectively target the large, sandy beaches that are the highest dust emitters. In 2023, a total of 660 hectares (ha) was seeded as part of the WDMP, but there is a need to further scale revegetation efforts to address the widespread fugitive dust issue. When water levels are low, around 658 m above sea level (asl) or lower, there is an estimated 15,000 ha of drawdown zone along Williston Reservoir, with a large portion of that being dust emitting (Nickling et al., 2013).

A large portion of that area, which has not been calculated to date, is not suitable for revegetation for three reasons, 1) it floods too quickly for plants to grow; 2) the sediment type is not conducive for vegetation; and 3) the sites are inaccessible for mitigation activities. However, based on preliminary desktop spatial analysis and site visits conducted throughout my MSc, it is estimated that nearly 1,100 ha of sandy drawdown zone is suitable for cover crop seeding, along with targeted restoration treatments using native species in higher elevation locations. This 1,100 ha area is comprised of four large beaches, Davis North, Shovel, Middle Creek South, and Middle Creek North, along with two smaller ones, Van Somer and Tsay Keh beaches. Additional areas may be suitable, particularly when it comes to restoration opportunities in the higher regions of the drawdown zone, and it is recommended that efforts be made to survey for additional sites.

Through this research and the continued work as part of the WDMP, there is a strong likelihood that fugitive dust emissions can be reduced along Williston Reservoir by expanding the use of cover crops, restoring higher elevation regions of drawdown with vegetation, and building the programs capacity to implement such a large-scale mitigation project on an annual basis. This work adds to previous work done along Williston Reservoir and clearly lays out a strategy that could allow for widespread dust mitigation to be achieved, likely not by 100%, but a significant reduction, which has not been done to date. It also adds to the growing research around reservoir drawdown zone management and revegetation, which is spreads across the globe and is an important topic for many communities living close to reservoir facilities.

4.3 Limitations of this Research

Chapter 2 does not investigate all the possible plant species native to the Williston Reservoir region that may be suitable for inclusion in revegetation efforts. Species selection was based on recommendations from prior studies and inventories, as well as seed availability, hence there may be additional native plants species that would be good candidates to include in a revegetation program but were not mentioned in previous works, were not available at the time seed was ordered, or were not suitable for this short study, such as woody species. Hopefully any future research looking at native species planting along Williston Reservoir will consider looking at any additional species that might be suitable and testing them in a similar manner to this study.

The sample size for the greenhouse growth trials could have been larger by placing 5 -10 seeds in each cell instead of only one. This would have increased the sample size and strengthened the statistical analysis for this portion of the research, which was small and thus limited the analysis that could be done.

For Chapter 3, one limitation of the research design was that vegetation cover was only assessed on June 20th and resulted in me assuming the ratio between low, medium, and high areas was the same two weeks earlier during the June 3rd and June 5th BSNE collection periods. Vegetation cover could have varied between the three treatments earlier in the study period, which would result in errors in the statistical analysis for the June 3rd and June 5th collection periods. Another limitation was that vegetation cover was only collected along the transect lines, not at each of the BSNE sample arrays, which could have had different vegetation cover adjacent to the array. My study design assumed that vegetation cover for each of the treatment area was uniform and that the transect line results were representative of each treatment area, which may not have been the case. If vegetation cover differed in the immediate vicinity of the BSNE sampler arrays, the collected dust results could be misrepresentative when compared to the vegetation cover from the photo transects. From visual observation it does not seem that this was the case, but it is important to highlight the possibility.

Finally, another limitation for Chapter 3 is that BSNE samplers were not set out in the treatments on MCS where fertilizer was applied, thus any assumptions that the increase in vegetation cover provided by fertilizer application is inferred from the MCN results where increased seed rate, resulted in increased cover, and reduced dust emissions. BSNE samplers were not added to MCS due to a lack of additional BSNE equipment and a lack of capacity to collect and process the additional samplers. Fertilizer treatments could have been added to MCN, but this was not implemented due to logistical challenges and how the wind blows across MCN beach. It would have been extremely difficult to include fertilizer treatments on MCN without making it much more difficult to parse out the different effects of each treatment on overall dust emissions. Even with the layout that was used, it is possible that each treatment may have influenced BSNE samplers in adjacent treatments, particularly when the wind was not blowing from the southeast.

4.4 Suggestions for Future Research

While this research adds to the growing body of literature on the revegetation of reservoir drawdown zones, it provides new insights into options for Williston Reservoir, and there still are many questions that are not fully answered, both regarding Williston Reservoir, but also reservoirs more broadly. First, many previous works (Abiola, 2011; Allen & Klimas, 1986; Arocena et al., 1996; Baker et al., 2000; Burton, 2010; Carr et al., 1993; May, 2022; Vaartnou, 2010) have highlighted the importance of identifying ways to implement revegetation efforts that result in perennial, native plant establishment and there are still questions about the best way to implement such restoration efforts. Each reservoir has a unique set of variables, but further study about what general practices work best to implement restoration at scale in remote and hard to access locations is needed, along with options specific to Williston Reservoir.

Investigating how the use of cover crops as a form of dust control impacts the broader reservoir ecosystem would also be worthy of further study. There is evidence that vegetation cover in shallow aquatic regions can provide cover and increase food availability for fish (Massicotte et al., 2015). The flooding of cover crop plants has been found to provide similar aquatic ecosystem benefits in reservoir environments, such as Arrow Reservoir in southern BC, where the aquatic environment was heavily impacted and is largely novel (AIM Ecologic Consultants Ltd. et al., 2000; CARR Environmental Consultants & AIM Ecologic Consultants Ltd., 2002). This type of study has not been conducted along Williston Reservoir to date, but it would be beneficial to inform fisheries management. This is a worthy topic to explore given that the dust issue is not going away any time soon and revegetation efforts are likely to occur on an annual basis for several years, if not decades, to come.

In a similar vein, long-term monitoring should be implemented on the beaches of Williston Reservoir where revegetation efforts take place to investigate what the impact of annually seeding cover crops is having on natural native species recruitment. Moody (2002) found that annual seeding of *S. cereale* along the drawdown zone of Arrow Reservoir in southern British Columbia between 1987 and 2001 resulted in extensive native species recruitment and a drastic reduction in the total area requiring dust mitigation treatment via seeding. While Williston Reservoir is much further north in latitude and the sediment differs in some areas, there is a likelihood that a similar result could occur if annual seeding is implemented.

Working on this thesis has given me a great appreciation for the difficulty in designing field-based research experiments, particularly at scale, and have left me excited to continue working as part of this project after I finish my MSc. This research has given me insight into the need and challenges of large-scale restoration, and I look forward to using the skills and experience I have gained through my thesis as I move into a career in ecological restoration in the private sector. I also deeply grateful for the relationships I have established or have continued to build with Tsay Keh Dene members, my lab mates, my supervisor, and my mentors.

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