IOSI PROJECT FINAL REPORT

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EXECUTIVE SUMMARY

The production of synthetic crude oil in Northern Alberta results in large volumes of waste material known as oil sands tailings. In 2017, the Government of Alberta implemented Directive 085 for progressive reclamation of oil sands waste to ensure that all fluid fine tailings (FFT) associated with a project are ready to reclaim (RTR) within ten years after the end of mine life of that project. Large time and cost savings would be achieved if the treated tailings could both meet the designated reclaimed strength and be integrated into the surrounding environment directly with reduced or potentially without capping. The integration of plants has the potential to enhance dewatering of treated tailings, improve both stability and strength, and enable progressive reclamation. Both untreated and treated FFT are often devoid of critical nutrients required to support and sustain the physical and chemical functions and process of plants. FFT also exhibits low geotechnical stability, and the deposits are non-trafficable. Furthermore, the low hydraulic conductivity of clay dominated FFT makes it difficult for adequate moisture flow to occur around roots, resulting in water logging or drought conditions. Adding sand to FFT improves the hydraulic conductivity of the tailings and allows for better transfer of moisture to occur. In this study, polymer A3338-treated FFT was blended with sand to form tailings with three sand-to-fines ratios (SFR) – namely SFR 0.0, SFR 1.5, and SFR 3.0, to mimic the SFR in a Luvisolic soil. This soil order commonly occurs in the Athabasca oil sands region and throughout northern Alberta. In addition, three potential sources of supplemental nutrients were incorporated into the treated FFT; two were from organic materials (compost and alfalfa) and the third was an inorganic nitrogen source (urea). These amendments were evaluated against the no amendment condition as a control group.

The protocols of flocculations were investigated and determined based on the Net Water Release (NWR), release water quality, and the repeatability of the tests. The tailings of SFR 0.0 exhibited little geotechnical stability and low particle size distribution. The tailings of SFR 3.0 resembled wet sand rather than sand-filled-flocs. Consequently, neither SFR 0.0 or SFR 3.0 emulated the targeted Luvisolic soil. Furthermore, complications in flocculation arising from the excessively sandy nature of FFT at SFR 3.0 made it undesirable for further scale up. Tailings with SFR 1.5 behaved as an optimal middle-ground of sand and FFT and more closely emulated a Luvisolic soil type. The NWR was consistent across all nutritional amendment conditions. The protocols of flocculation for SFR 1.5 were repeatable. Therefore, the upscaling of the protocol should also be feasible.

Once the FFT at various SFR and nutritional amendments were prepared, they were used as a growth medium for one species of native grass (*Elymus trachycaulus,* slender wheatgrass), one species of shrub (*Salix interior,* sandbar willow) and one wetland forb species (*Rumex occidentalis,* western dock). Seedlings were measured before and after a six-week growth period to evaluate plant response to each SFR/nutrient amendments combination. In the case of the slender wheatgrass, seedling emergence was significantly inhibited with the addition of alfalfa pellets at the SFR of 3.0. The presence of compost strongly enhanced the growth of slender wheatgrass at all SFR levels. Sandbar willow showed the best growth at an SFR of 1.5, with a nutrient amendment of either compost or urea. The more stable soil structure provided at this SFR likely allowed for improved root growth. Similarly, western dock also showed the best growth at SFR 1.5, with compost as the nutritional amendment. Based on the results from the FFT mixing study, it is recommended that the SFR of future artificial soils studies to not exceed 1.5. It should be noted that sand contains no nutrients, and adding sand serves to dilute the existing nutrient level in the artificial soils. In addition, depending on the source, tailings sand may contain high levels of salt which can negatively impact growth of plants. Therefore, future studies should accommodate this effect by amending artificial soils with higher nutritional content when sand is added.

Of the nutritional amendments investigated, compost consistently improved the growth and establishment of all three species. The compost used dissolved easily into the tailings and likely provided very accessible forms of the nutrients. Compost was also the only amendment to provide a broad spectrum of nutrients. Other studies conducted by the Centre for Boreal Research have all used a broad-spectrum fertilizer to good effect and have shown that alfalfa shows an initial inhibitory response but is an effective additive in longer growth trials. Further work is recommended to investigate the impact of nutrients over a longer growing season.

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1 INTRODUCTION

The production of synthetic crude oil results in large volumes of waste material made up of connate and process water, sand, silt, clay, residual bitumen and diluent, and inorganic and organic by-products of the extraction process (Allen, 2008; Bedair, 2013). These materials are stored in manufactured tailings management and storage facilities, on-site, until they are reintegrated into the natural environment and reclaimed. As of 2018, reports indicate that over 1250 Mm^3 (Alberta Energy Regulator, 2019) of fluid fine tailings (FFT), a tailings slurry comprised of fine clay particles with solids content ranging from 30 to 45% (BGC Engineering Inc., 2010; Long, Li, Xu, & Masliyah, 2006; Powter et.al., 2011), has accumulated in Alberta's tailings ponds. The major issue with fluid fine tailings is the activity of the clay content, prohibiting the consolidation of the material into trafficable deposits. The new tailings management framework outlines the goal for fluid tailings - treatment and on-site direct placement (Government of Alberta, 2015). Under this scenario, placed treated tailings require monitoring, and the physical and chemical characteristics of the materials must be managed to achieve the desired performance criteria.

The Government of Alberta (2015) has implemented Directive 085 to ensure that all fluid tailings associated with a project are ready to reclaim (RTR) ten years after the end of mine life of that project. Oil sands companies have explored a variety of tailings treatment technologies to achieve the regulated goals. Technologies used differ across operators owing to the variation in the mined ore grade and quality of the extraction processes. Technologies have included physical and/or mechanical methods, natural processes, chemical and/or biological amendments, and co-disposal mechanisms (BGC Engineering Inc., 2010). Such technologies are expected to speed up the transformation of tailings slurries into trafficable deposits, making them ready-to-reclaim (RTR), and allowing operators to overcome tailings deposition challenges like lack of strength, stability and structure. Most tailings research, to date, has been focused on achieving end products that are geotechnically stable. This has resulted in four main types of tailings – coarse sand tailings, composite/consolidated/non-segregating tailings (CT/NST), flocculated and dried fluid fine tailings, and flocculated fluid fine tailings (FFT). Mature fine tailings (MFT) is a subset of FFT with sand to fines ratio (SFR) < 1 and a solids content > 30%. Coarse tailings are considered to be reasonably geotechnically stable and easy to reclaim. Coarse tailings must be capped or covered with salvaged reclamation material (e.g., peat mineral mix) of sufficient depth to reduce interaction with the underlying material. Without this cover, coarse tailings have little moisture holding capacity. Dried MFT can be integrated into a soil profile when capped with overburden sand and peat mineral mix (Luna Wolter & Naeth, 2014).

Flocculated MFTs are created through the mixture of fine tailings enhanced with a flocculant or coagulant/flocculant combination to reduce the water content of the tailings. The addition of the flocculant changes the typical solids content from 30% to 45-50%. This increases the strength of the material moving it from very fluid to semi solid which is more able to support a seed or seedling. The treated FFT also introduces poly acrylamide at approximately 1300 grams per tonne (clay basis) to the mixture, which is representative for tailings of present fines content. Although significant release water is expected after proper flocculation, the structure of the flocculated tailings has been found to be comprised of very small, isolated pores (Boxil, 2016) which makes additional dewatering difficult. Furthermore, FFT is dominated by the presence of fine clays, which also naturally hold water but can become very hard and difficult to re-wet when dried completely.

Consequently, these materials are initially extremely wet; however, when the surface dries out, it creates a water infiltration barrier that is similar to the 'Bnt' horizon of Solonetzic soils in southern Alberta (i.e., poor seedbed properties and inhospitable to vegetation growth and establishment). Also, fluid fine tailings, even when flocculated, create extremely soft landscapes that are not geotechnically stable enough to conduct reclamation activities unless capped or dewatered further. Capping these very soft deposits is challenging (COSIA, 2017).

There are still uncertainties in the selection of optimal tailings treatment technologies, in addition to the quantity of treated tailings that can be integrated into a landscape, and the optimal location of treated tailings within a reconstructed soil profile. Time and cost savings would be achieved if treated tailings could both meet the desired strength and be integrated into the environment directly without capping.

Even if the treated tailings can be modified to exhibit Luvisol-like soil structure, the FFT materials are often devoid of critical nutrients required to support and sustain plant physical and chemical functions and processes. Without a vegetative cover, these landforms are also prone to erosion. Therefore, placed tailings still currently require the addition of soil covers with various mixtures and thicknesses of either: (1) oil sands materials (sand, peat, topsoil), (2) organic soils, and/or (3) salvaged mineral soils over-stripped from low-lying areas prior to mining. Major factors that control the fate and availability of plant essential nutrients include the geology of the surrounding natural soil and bedrock (Whitfield, Aherne, & Watmough, 2009), the composition of transient surface water and groundwater; quality of organic matter; above-ground biomass (Raab & Bayley, 2013), climatic conditions (Tucker, 1999), and, atmospheric deposition (Whitfield, Aherne, & Watmough, 2009).

The integration of plants can serve multiple purposes, including the following:

- Enhanced dewatering of treated tailings through direct evapotranspiration (M J Silva et.al., 1998, Marvin Jose Silva, 2000) following the placement of lifts during soil profile reconstruction;
- Plants' root mass can act as a binder for the tailings material, similar to that of natural geosynthetic materials, improving both stability and strength;
- Meeting reclamation criteria to achieve equivalent land capability, as specified in oil sands approvals.

In previous studies, flocculated fluid fine tailings, and CT/NST were found to support the establishment of agronomic and native species when sufficient nutrients were provided (Wu, Sego, Naeth, & Wang, 2011a, 2011b, 2010).

Returning oil sand tailings deposits to an ecosystem of equivalent land capability is a major challenge faced by all operators in the Athabasca oil sands region. There is impetus to find innovative, sustainable, cost effective and efficient solutions to dewater and stabilize soft tailings to facilitate progressive reclamation with the ultimate goal of certification. However, there are still questions regarding how to integrate tailings deposits into reclaimed closure landscapes to ensure that the dried tailings materials (1) are geotechnically stable, (2) have acceptable shallow soil water and run-off quality, (3) permit soil process development consistent with boreal forest soils, and (4) have functional and structural ecological aspects consistent with the regional boreal forest (Government of Alberta, 2015). Focused trials are required to determine how to passively treat and revegetate tailings for progressive reclamation, in terms of achieving both landform stability and ecosystem sustainability.

In the first phase of this project a detailed literature review was conducted (Y. Li, Chigbo, Kaminsky, Schoonmaker, & Degenhardt, 2019) to evaluate how FFT could be best modified to support plant growth while the plants dewater the tailings. The literature review provided guidance for the next step of this project: creating artificial soil by mixing tailings with other materials to mimic regional soil. The conclusions from the literature review were as follows:

- Adding sand to polymer-treated FFT may allow the FFT to behave more like natural soil of the area. The soil type most closely resembling FFT was found to be a Luvisol.
- Adding sand may also increase the density of the treated product which will benefit reclamation. The sand-to-fines ratios chosen to mimic Luvisolic soils were 1.5 and 3.0. A condition with no sand amendment (SFR 0.0) was included for comparison as a control.
- Nitrogen was identified as the most likely limiting nutrient, therefore additives which provide substantial nitrogen such as fertilizer, compost or alfalfa, may best support plant growth and development in tailings.

The objectives of this current phase of the study are to:

- To develop artificial soil prototypes using FFT by adding sand and various nutrients
- To test the flocculation performance of FFT when different forms of nutrients (inorganic and organic sources) and quantities of sand (to achieve targeted SFR levels) were added.
- To assess the survivability, short-term growth, and development of selected plant species planted in the artificial soil prototypes.

Over the course of the project, key training of Highly Qualified Personnel (HQP) included:

- Student research assistants Patric McGlashan and Catalina Romero Calducho, who each performed over 300 flocculations to support the creation of the artificial soils. They also gained experience handling oil sands tailings materials and other chemicals, method development, and working safely in an industrial lab setting.
- Recent M.Sc. graduate Simon Sun joined the project after the experimental work had been completed, and gained valuable experience compiling results and preparing the reporting for this research project.

2 PART 1: MIXING STUDY – 300g METHOD DEVELOPMENT

2.1 Background and Context of Study

The mixing study focused on the literature review, testing and results of various combinations of SFR and nutritional amendments within fluid fine tailings (FFT) that had potential to mimic native soils, specifically Luvisols, after the dewatering process of flocculation. A key component of this study was first validating that the process of modifying the SFR in combination with incorporation of amendments did not have a detrimental effect on the dewatering process.

2.1.1 Characterization of FFT

The FFT samples were tested using Dean and Stark (D&S) analysis (Dean & Stark, 1920), methylene blue index (MBI) (Kaminsky, 2014), and particle size distribution (PSD) analysis at COSS (Table 1 and Figure 1). The pH of the tailings was 8.2 and overall the chemistry was consistent with expectation for this type of FFT (Table 2.)

Table 1. The average results of FFT characterization from D&S, MBI, and PSD.

wt% Bitumen	wt% Mineral	wt% Water	MBI	vol% Fines
1.23	24.68	73.64	13.2	92.8

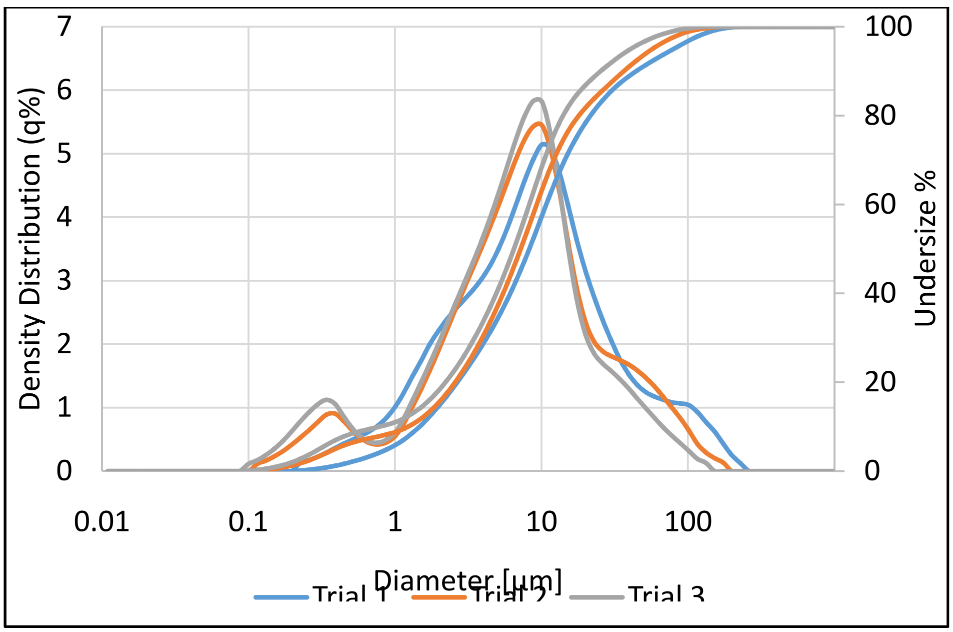

Figure 1. PSD results of raw FFT in triplicate.

Table 2: Water chemistry results for FFT used to create artificial soil.

Component	Concentration (mgL^{-1})
Lithium	1.8
Sodium	381.0
Calcium	52.2
Magnesium	34.9
Potassium	20.5
Chloride	205.7
Nitrate	2.79
Nitrite	not detected
Sulfate	303.9
Bromide	not detected
Phosphate	not detected
Fluoride	2.48
Carbonate	9.0
Bicarbonate	300.6

2.1.2 Introduction to artificial soils according to Sand-to-Fines Ratio (SFR)

Sand-to-Fines-Ratio (SFR) is described as the mass ratio of mineral solids with a particle size >44 µm to the mineral solids with a particle size ≤44 µm (COSIA, 2014). Different SFR values in the raw FFT may have various impacts on the flocculating processes, properties of flocs, and the quantity of release water. The purpose of increasing SFR within FFT is to replicate the geotechnical stability and the PSD of natural soils, which in turn will facilitate the germination and growth of various native plant species with the further aid of fertilizing amendments. The solids content of the FFT was measured to be 7% above 44 µm and the sand was 4% below 44 µm. However, the solids in the FFT was assumed to be 100% fines, and the sand was assumed to be 100% coarse for the purposes of calculating the mass of FFT and sand required to achieve the target SFR. This is because the exact SFR wasn't critical, rather it was important to have a range of SFR that would capture the range of Luvisolic properties. The SFR of the mixed materials was calculated as the mass ratio of added sand to the mass of the solids in the homogenized FFT. For example, if 400 g of FFT at 25% solids was mixed with 100 g of sand, the assumed SFR was 1.0. Table 3 presents the calculated SFR values of the samples prepared in this study. The mineral content for the FFT, as determined by Dean & Stark Analysis, was 25 wt% for all samples. For simplicity, SFR was rounded to the nearest 0.5 for the report.

Table 3: Comparison of calculated SFR and presented SFR

Mass of FFT (g)	Mass of Sand (g)	Calculated SFR	Reported SFR
300g mixing study			
300	0	0.00	0.0
214	86	1.61	1.5
167	133	3.19	3.0
1L test production			
1013	0	0.00	0.0
724	289	1.60	1.5
563	450	3.20	3.0

Raw FFT was determined to contain 25.57 wt% solids with a yield stress of 3.25 Pa on average. The solids content of polymer A3338-flocculated tailings increased to an average of 36.80 wt% after 24-hour water release with a considerably higher yield stress, averaging at 318.23 Pa. The PSD was assumed to remain unchanged after flocculation.

Luvisols are expected to be made up of 12-48% clay and 15-65% sand which would be expected to be an SFR range between 0.4 and 3.0. To cover the range of SFR within the budgeted time and cost, 0.0, 1.5 and 3.0 were the three chosen SFRs to be flocculated and analyzed, as more in-depth coverage of SFR range would have possibly doubled the amount of testing that needed to be done across both the mixing study and the production stage and would exceed the constraints of the current project budget.

2.1.3 Introduction of nutrient amendments to artificial soils

Nitrogen, phosphorus, water, and carbon are the most important soil-related factors for the germination and growth of plants, with nitrogen being the most critical nutrient. Flocculated FFT contains low amounts of nitrogen and phosphorous, and little readily available carbon. Thus, these nutrients must be supplied through amendments. Water is in abundance within FFT, and the plant species are expected to remove a large portion of that water content so long as they are able to withstand the high salinity. Amendments that were initially identified for the mixing study include alfalfa pellets, urea, compost, bone meal, Organix/fusion fertilizers mix, hydrochar, phosphogypsum, biodegradable polymers, peat, and nitrogen fixing bacteria. While promising, bone meal, biodegradable polymers, microbes and hydrochar were not considered to be commercially viable at the scale required. Phosphogypsum was good for phosphorus content but was eliminated from consideration as it is not a good source of nitrogen.Compost was included as a potentially local secondary waste stream that could be of great interest, though commercial scale-up could be a challenge. Peat was eliminated for this stage of work due to the variability of the nutrients contained as well as the expected scarcity of this resource on some sites.

The first phase of testing considered Organix (a commercial product with a combination of micronutrients and straw), and LOFe (a commercial blend of plant growth promoting bacteria), alfalfa, urea, and compost. In the initial design it was assumed that the addition of the nutrients would have an immediate, negative impact on mixing but that there might be an acceptable dose where the impact was manageable. For this reason, there were two rates identified. The lower rate consisted of 0.83 g of alfalfa, Organix and compost, and 0.10 g of urea, and LOFe while the higher rate made up 5.63 g of alfalfa and compost, and 0.34 g of urea. It was assumed that the variation in these rates may also be helpful to plant growth.

2.1.4 Mixing study objectives

In-line flocculation is sensitive to subtle changes in mixing conditions. At the bench scale, these conditions include the rate and position of polymer injection, the speed of mixing during polymer injection, and the speed and duration of mixing after polymer injection. Each of these parameters translates to different conditions that should be controlled during field testing, often through the sizing of pipes and by controlling the individual flow rate of polymer and FFT. The objective of these tests was to identify a mixing protocol at each SFR which provided the most easily repeatable flocculations, with the intent to scale up to the larger 1L projection phase. Once the appropriate mixing protocol at each SFR was identified, the procedure was used with each amendment to determine what effects, if any, the amendments had on the flocculation Key Performance Indicators (KPIs). The KPIs of flocculation are the Net Water Release, clay-based dosage of polymer required to achieve optimal flocs, solid content remaining in flocs, and released water colour and clarity.

2.2 Methodology

2.2.1 Protocol development and determination at SFR 0.0

At the bench scale, every flocculation procedure can be divided into several distinct stages. Initially, the subsampled FFT is mixed to ensure homogeneity. Then, the flocculant is injected and allowed to blend into the FFT to form flocs. Finally, the mixing speed is reduced, and gentle churning is used to encourage more water release. This final stage is referred to as conditioning. The testing began at a small scale, flocculating 300 g FFT each trial. Flocculation time, mixer speed, and spatula movements were the most important factors affecting each flocculation. The spatula movements were fixed for a set amount of time to minimize experiment variability. Mixing time and speed were factors that increased deviation from the optimal flocs. Therefore, 3 separate initial protocols (protocol #5, #6, #7) were created, all giving high amounts of release water but with separate mixer speeds and mixing times. The details of these protocols are found in Appendix A.

While protocol 7 had the advantage of being the fastest procedure by approximately 1 minute along with the second highest water release across the three protocols, replication was difficult due to the increased shear during conditioning. Due to this lack of consistency, protocol 7 was eliminated as an option for flocculation. The other two options favored for gentler conditioning and reducing shearing at high speeds. Protocols 5 and 6 were repeated, with special attention given to net water release (NWR, see Equation 1) and clarity of the released water. Based on operator judgement, flocculations performed with protocol 6 showed more NWR compared to protocol 5, indicating an increase in solids content within the flocs. The high amount of water released and consistent repeatability of protocol 6 was worth carrying on at the ideal flocculation protocol for an SFR of 0.0. Lower release water clarity suggested the flocs were slightly more sheared in protocol 6 than protocol 5. As the suspensions are sheared, a higher portion of fine solids are carried into the release water and reduces clarity. However, water clarity was not a deciding factor in the decision-making process of what method to follow.

Equation 1. Calculation of net water release (NWR).

$$Net\ water\ release\ (NWR) = \frac{Volume\ of\ Release\ water - Volume\ of\ polymer\ added}{Volume\ of\ original\ water\ in\ FFT} \times 100\%$$

2.2.2 Protocol development and determination at SFR 1.5

The testing for SFR 1.5 began at 300 g trials, using 214 g of FFT with 86 g of tailings beach sand, added together in a small metal beaker prior to mixing. The most prominent issue with adding sand to FFT for flocculation was that it caused the polymer-amended flocs to break down significantly more quickly due to the increased friction of the coarse sand particles. The protocols incorporated less mixing time at high speeds. This means that the addition of sand will require a change in the operation of an in-line system to be implemented at larger scale. However, it was possible to come up with two protocols at bench scale that had acceptable results. This indicates that some in-line systems may be able to accommodate the scale up of the sand flocculation without too much difficulty. The protocols developed are shown in **Error! Reference source not found.**.

The three key differences between protocols 3 and 4 are:

1. Movement of the spatula in protocol 4 versus only holding spatula in place in protocol 3,
2. quickly transferring the flocs from the beaker onto the sieve in protocol 3,
3. conditioning at 30 rpm in protocol 3 versus 10 rpm in protocol 4

Key differences were observed in the results between the two protocols: the manual movement of the spatula in protocol 4 caused the polymer to easily mix in with the FFT, resulting in more efficient flocculation and a higher clarity in the release water. The quick transfer caused the water to not be re-absorbed into the sandy mixture, explaining the higher NWR from protocol 3. The higher conditioning speed used in protocol 3 introduced more shear to the flocs, causing both more water release and lower clarity due to fines seeping into the release water (Table 4). Since Protocol 4 was more consistent and required a lower polymer dose than protocol 3 it was selected as the mixing protocol for use with SFR 1.5 material.

Table 4:Mean NWR and water clarity fromprotocols tested in 1.5 SFR 300g trials. Values inbrackets are one standard deviation of the mean (n=3).

Protocol ID	Mean NWR (%)	Mean water clarity
3	11.2 (4.2)	10 (16)
4	7.1 (0.4)	22 (1)

2.2.3 Protocol development and determination at SFR 3.0

The 133 g of sand that was added to 167 g FFT to make up SFR 3.0 was so high that the friction caused by the coarse grains nearly over-sheared the flocs by the time the necessary amount of polymer was injected into the mixture. As a result, sand addition both before and after flocculation needed to be considered. Due to this issue, 300 g trials were used for sand added before flocculation, and 600 g trials were used for sand addition after flocculation (Appendix A). This was done to compensate for the 133 g loss of mixture from 300 g to 167 g of FFT, as it would cause design issues in the flocculation process that would result in splashing, improper mixing and improper shearing of the flocs. This meant that protocol 8 used 300 g of raw FFT while protocol9 used 600 g.

Protocols 8 and 9 were repeated and compared in quadruplicate trials, noticing the differences between adding and mixing sand both before and after the flocculation, and attempting to find the protocol with the highest amount of repeatable water release. Operators found protocol 9 to be more easily replicated, with significantly higher NWR (Table 5). Therefore, protocol 9 was the preferred choice to carry forward into amendment testing.

Table 5:Mean NWR and water clarity fromprotocols tested in 1.5 SFR 300g trials. Values in brackets are one standard deviation of the mean (n=4).

Protocol ID	Mean NWR (%)	Mean water clarity
8	0.8 (1.7)	24 (26)
9	12.9 (1.0)	1 (1)

2.3 Results and Discussion

2.3.1 Effect of Amendments on Flocculation Efficacy

It is accepted that both unflocculated and flocculated FFT have little-to-no nitrogen and phosphorus content, with no readily available carbon and little porosity (Grant, Woynillowicz, & Dyer, 2008). Therefore, nutrients must be amended to the FFT to facilitate the growth of plant life, and several KPIs were measured to ensure the amendments did not negatively impact the flocculation. Using the most optimal protocols determined in the mixing study, amendments such as alfalfa pellets, compost, urea, and other commercially available fertilizers were compared to determine the impact each had on the KPIs of NWR%, solids content in the flocs, required polymer dosage, release water clarity, and release water colour.

Overall, it was concluded that none of the amendments had statistically significant impact on the key flocculation characteristics at SFR 0.0. In the following sections, the effect of amendments are explained in detail at an SFR of 0.0. To avoid repetition, the discussion is not reiterated for SFR 1.5 and 3.0. However, the data is available in Appendix B. Furthermore, amendments LOFe, Organix, and the Urea+Alfalfa combination were not examined at higher SRFs, since the other amendments performed equally well and were more commercially viable.

2.3.2 Effect of amendments on net water release (NWR)

In Figure 2, all amendments have similar NWR%, and did not deviate with statistical significance from the control condition (no amendments) flocculation at 300 g of raw FFT.

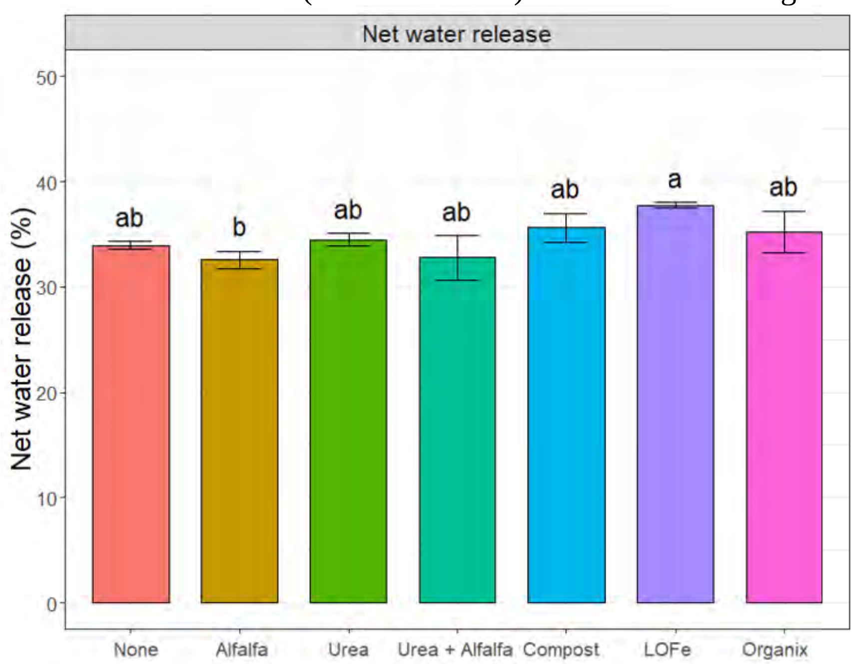

Figure 2: Comparison of average NWR% between chosen additives, added to SFR 0.0 before flocculation. Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type.

2.3.3 Effect of amendments on solids content in flocs

Figure 3 shows the solids content of the flocs was not significantly different regardless of the chosen amendment, suggesting that the chosen amendments had no effect on flocculation performance.

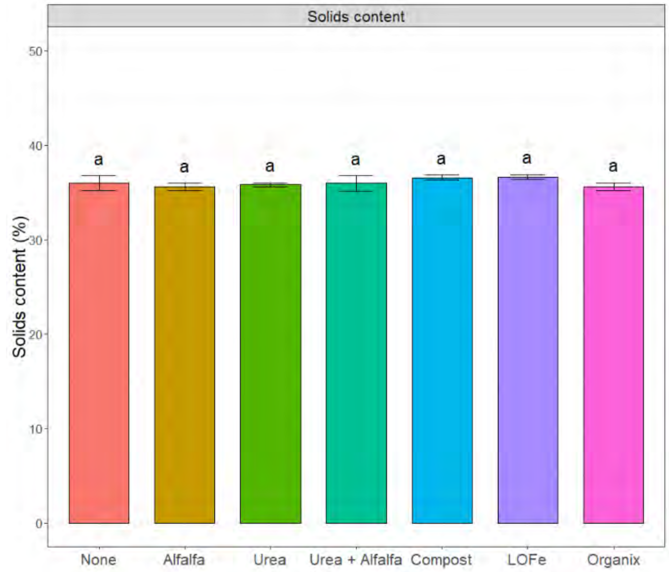

Figure 3: Comparison of average solids content present in flocs between chosen additives at SFR 0.0.Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type.*Effect of amendments on polymer dosage required to achieve optimal flocculation*

As shown in Figure 4, no statistically significant differences were observed in the required clay-based polymer dosage for optimal flocculation between the various amendments. These results confirm that the amendments have very little to no effect on the amount and cost of the polymer at the industrial scale after scale-up.

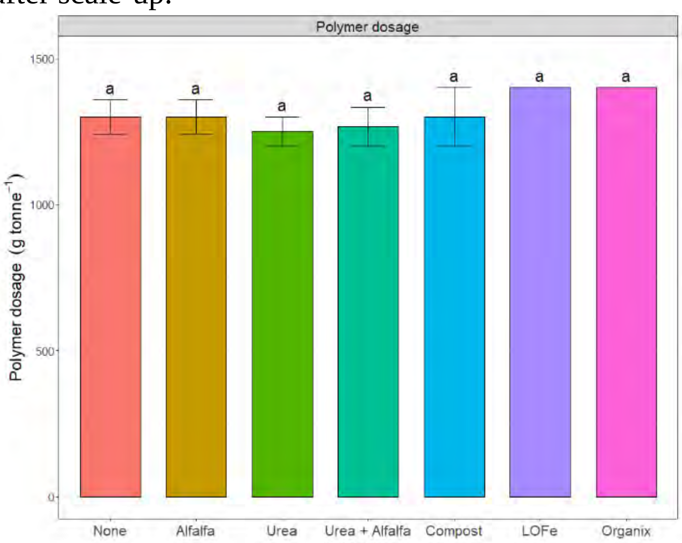

Figure 4: Comparison of average clay-based polymer dosage required to achieve optimal flocculation for various additives at SFR 0.0. Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type.

2.3.5 *Effect of amendments on release water clarity*

As shown in Figure 5 the release water clarity was not affected by amendments.

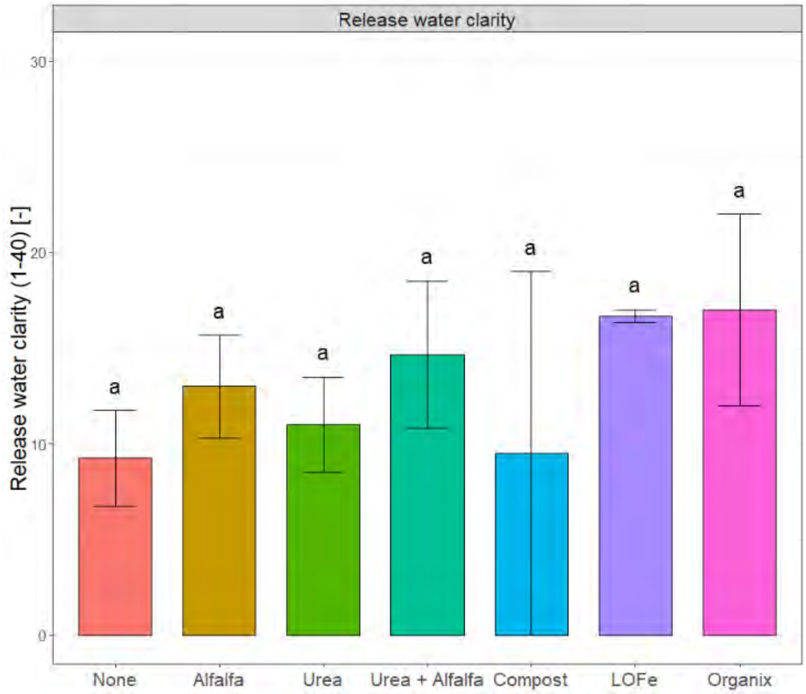

Figure 5: Comparison of average release water clarity between chosen additives at SFR 0.0. Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type.

2.3.6 *Effect of amendments on release water colour*

The colour of the released water after flocculation was determined by a five-level scale (Figure 6), and results show that amendments had no significant effect on the released water colour (Figure 7, and Table 9). Alfalfa-amended samples released water with a green tint.

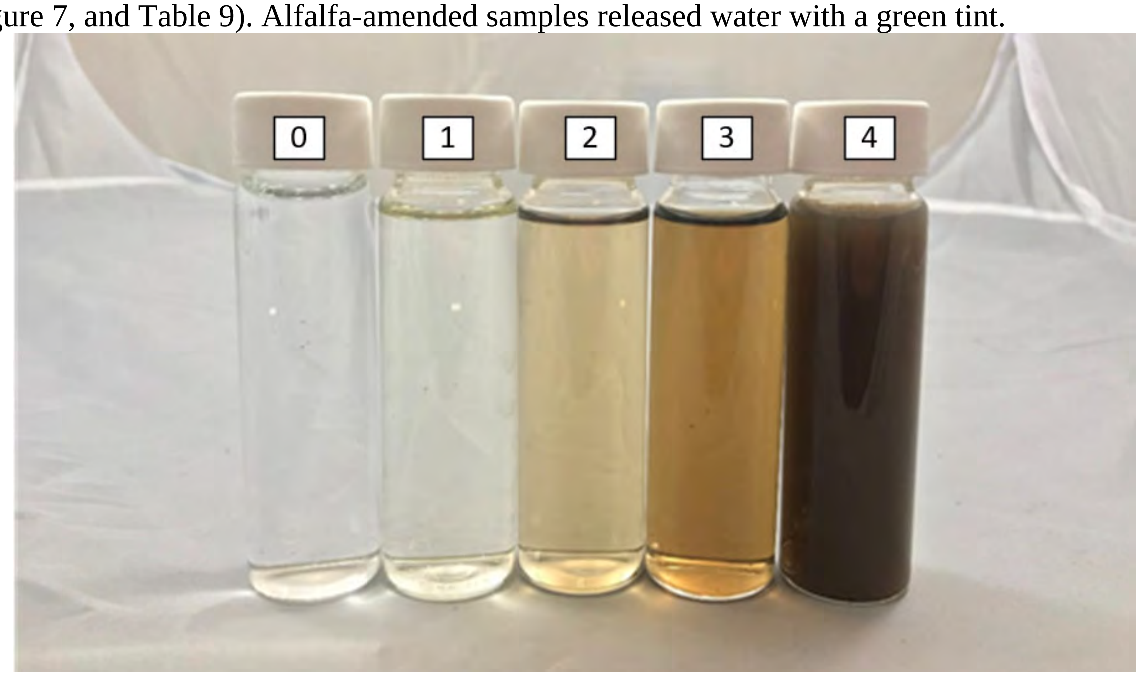

Figure 6: Standard colour scale used to assess release water. 0=colourless; 1=light yellow; 2=yellow; 3=brown' 4=dark brown / black

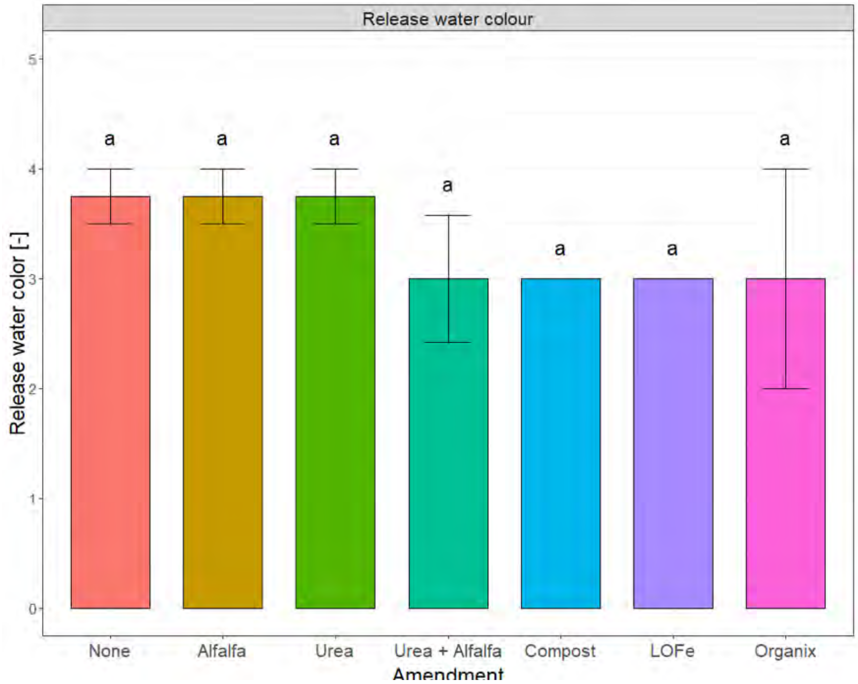

Figure 7: Comparison of average water colour between chosen additives, added to SFR 0.0 FFT before flocculation. Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type.

2.3.7 Effect of SFR on Flocculation Characteristics

Luvisols, which are native to the Athabasca oil sands region, typically exhibit an SFR range of 0.4-3.0. In this study, non-zero SFR conditions were chosen to be SFR 1.5 and 3.0, to cover the expected values of Luvisols at equal intervals. It was intended that the sand would contribute geotechnical stability to the FFT and provide a more conducive growth medium.

The results for amendment impact on all three SFR are summarized in **Error! Reference source not found.**. There were two significant differences with flocculation performance between the SFRs. Firstly, the net water release was lower from the non-zero SFR samples than from the SFR 0 samples. This indicates that sand does impact the flocculation efficiency. The rough, non-uniform edges of the sand grains tended to destroy the polymer flocculant immediately after initial dosing. In addition, the water released from the SFR 3.0 flocculations tended to have significantly reduced clarity compared to the lower SFR's for some amendments (Figure 8). The reduced clarity was most likely due to the tendency for the sand to reduce the flocs into fine particles which were able pass through the sieve.

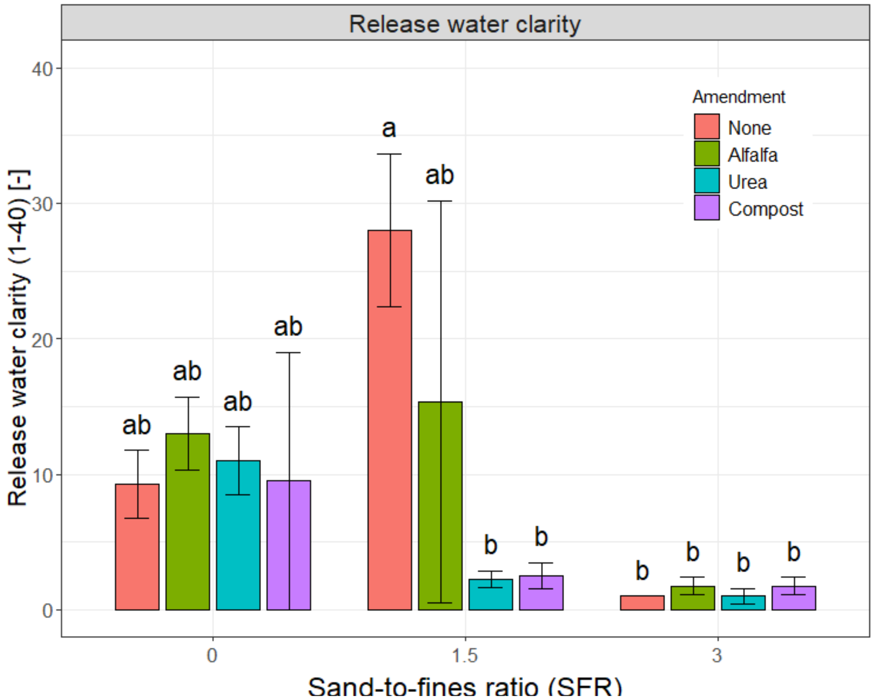

Figure 8: Average released water clarity for four amendments and three SFRs. Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type or SFR.

2.4 Conclusions from 300g Tests

FFT is naturally lacking in the nutrients and structural stability essential for plant growth. A successful artificial soil capable of sustaining heavier plant life must be amended to accommodate for these deficiencies. In this mixing study phase of the project, seven amendment conditions were examined at three SFR values to determine the impact of nutrients and sand addition on the flocculation characteristics of FFT. It was concluded that, of the amendment conditions studied (alfalfa, compost, urea, LOFe, organix, urea+alfalfa, blank), none had significant impact on the net water release potential of the flocculated FFT at any of the three SFRs (0.0. 1.5, 3.0). Similarly, the amendments also had negligible impact on the clay-based polymer dosage required to achieve optimal flocculation, release water colour, though urea and compost were observed to decrease water clarity compared to the other amendments at SFR 1.5.

Due to the similarity of the results it was concluded that the type and quantity of nutrient amendment had no impact on the flocculation. This presented a small challenge in that the budget was only sufficient to allow for the production of 110 1L containers for the greenhouse trials. As each successful combination selected requires a minimum of 4L for each plant species tested, the test matrix needed to be reduced. As such, the plan was modified so that only the most easily sourced and cheapest nutrients at the highest amendment level were moved to the germination/growth phase. Therefore, only Alfalfa, Urea and Compost were tested in the growth study and SFR 3 was tested only for the impact on grasses.

When comparing the three sand addition rates on flocculation characteristics, it was noted that SFR 0.0 produced the most release water. However, without the hydraulic conductivity and structural stability provided by sand, an artificial soil with an SFR of 0.0 is not ideal for supporting plants such as shrubs. When SFR was increased to 3.0, the high sand content rendered flocculation difficult to perform and inconsistent due to the rapid degradation of polymer upon grinding between sand particles. Despite the poorer performance in flocculation the SFR 3.0 condition was tested forone species (slender wheatgrass) in the larger scale growth trial. The grass was selected as being the species most likely to prefer a sandier soil type and therefore the one that would most likely show a benefit of the added sand. The effects of SFR on flocculation KPIs are further discussed for the 1L production phase in Section **Error! Reference source not found.**.

SFR 1.5 was the artificial soil which most closely emulated the characteristics of naturally occurring Luvisol soils. At this SFR, structural stability is present, but the sand content does not significantly reduce the flocculation efficacy. Therefore, SFR 1.5 was deemed to have to highest potential for producing an artificial soil receptive to sustaining plant growth.

In the next phase of the project, learnings from the mixing study were applied as the 300 g trials were scaled up to 1 L tests in the plant germination and early growth study.

3 MIXING STUDY – 1L TEST PRODUCTION

3.1 Background and context of study

The intent of the smaller-scale mixing study was to confirm that chosen nutrient amendments did not have adverse effects on the flocculation performance at different levels of SFR, along with gaining insight as to how protocols must be developed with varying amounts of sand to optimize high water release and high solids content in the flocs. In the production stage, protocols were developed to accommodate 1.013 kg trials based on the knowledge gained from the mixing study, using all three chosen amendments (alfalfa pellets, compost, and urea) at three chosen SFRs (0.0, 1.5 and 3.0). Flocculated FFT was produced and transferred into clear 1 L (32 oz) containers, where they could be seeded or planted with vegetation.

Typically, 1.75 flocculation batches were required to fill 1 container. Three different species (slender wheatgrass, sandbar willow, and western dock) were to be tested in SFR 0.0 and 1.5 with nutrient amendment, while only slender wheatgrass was tested at 3.0 SFR. All trials were replicated four times leading to a total of 112 containers. In total, approximately 215 flocculations were performed.

Data on each condition was analyzed, and the production stage compared all four amendment conditions at all three SFRs. Like the mixing study, the key performance indicators of flocculation success were the NWR%, required polymer dosage, water clarity, and water colour. Solids content of the flocs was not assessed because it was deemed to be too heavily time-consuming to analyze across over 200 flocculations.

Finally, soil chemistry and nutrient analysis was performed on the artificial soils prepared at the production stage.

3.2 Methodology

3.2.1 Protocol for production of SFR 0.0

The main learning at the 1 kg trials which was heavily influenced from the 300 g trials was a longer conditioning period, less shearing, even if there was much more material to shear. Another difference that needed to be compensated for was the change in beaker size from a 4" beaker to a 6" beaker, which influenced a heavier spatula movement to cover the larger gap between the edges of the blade and the inside walls of the beaker. Otherwise, a similar protocol to the 300 g SFR 0.0 trials was developed for the 1 kg SFR 0.0 trials, releasing high amounts of water on a consistent basis. The most successful protocol for the 1 kg SFR 0.0 trials are detailed in step-by-step format in Appendix A.

3.2.2 Protocol for production of SFR 1.5

Based on the learnings from the mixing study, improvements were made between the 300 g trials and the 1 kg trials. Increased volume of water release, clarity, and colour were all observed, along with tighter, more compressed flocs.

At equivalent SFR, the most important factor was the relative increase of polymer volume. This caused a substantially higher fraction of fines to be collected by the flocculant. This positively impacted the other KPIs, increasing quantity of water released and resulted in tighter flocs. Because the majority of the fines in suspension were captured by the polymer, and then filtered by the sand, the water that was released was of high clarity.

The flocculation protocol for SFR 1.5 was developed such that at the optimal polymer dose, release water volumes would be consistent and of high quality. Although the initial release water clarity was high immediately after flocculation, sand and fines would pass through the sieve openings at unpredictable rates, causing a high standard deviation of clarity of the release water after 24 hours. The most promising protocol developed for SFR 1.5 is described in a step-by-step format in Appendix A.

3.2.3 Protocol for production at SFR 3.0

Due to the negative impact of high sand content on flocculation observed in the mixing study, production of samples at SFR 3.0 added a step in the protocol for the 1 kg trials where water was decanted off the flocs right after flocculation, and sand added as final step. This allowed more water to be released from the flocs. However, the sand grains tended to clog the pores of the sieve and minimized the passing of fines and water.

Since SFR 3.0 trials being of lower priority for scale-up, perfect optimization was not attempted. Protocol A.3 found in Appendix A prioritized repeatable results as much as possible, but not optimized for perfection due to time constraints.

3.3 Results

The data in the production stage was analyzed, comparing each SFR directly with respect to NWR%, polymer dosage and release water clarity & colour. NWR% was deemed the most important metric measured at the production stage, as it was the best indication of which flocculation protocol would be most ideal for scale-up and adoption within the industry.

3.3.1 NWR%

An ideal artificial soil must have high water release without significant variation when scaled-up. High repeatability and consistent results through the various nutritional amendments are critical so that industry can adopt different amendments without drastically changing procedures. SFR 0.0 clearly had the highest NWR values at the production stage for all nutrient amendments, as shown in Figure 9.

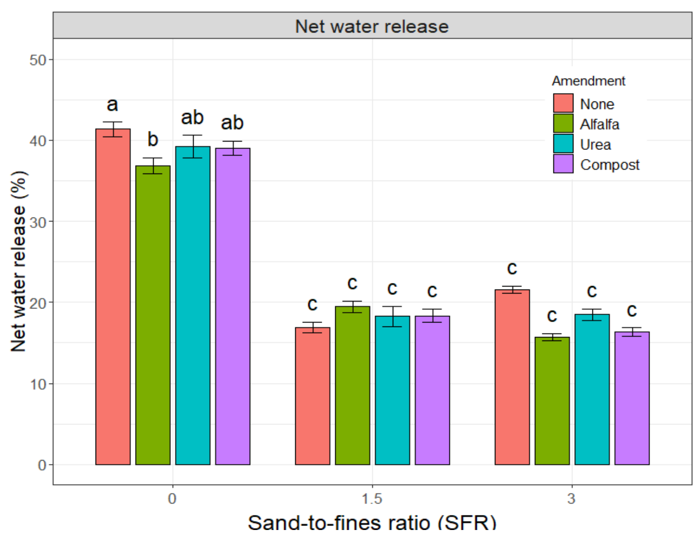

Figure 9: Average net water release % of all conditions performed in the production stage. Error bars represent one standard error of the mean (± SE, n = 24). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type or SFR.

While SFR 0.0 had the highest NWR, it also produced a flocculated structure with the lowest final solids content (as determined by a mass balance calculation from NWR data). The low solids content corresponds with a lower average density making capping more challenging. Furthermore, without the addition of sand, the characteristics of the SFR 0.0 artificial soil did not match the expected particle size range of naturally occurring Luvisols.

Conversely, due to the challenges with producing SFR 3.0, these samples were characterized by extremely low released water clarity and lack of consistency between results. For these reasons, SFR 3.0 is not recommended for further investigation nor scale-up.

SFR 1.5 was observed to be a well-behaving middle-ground of sand and FFT to mimic Luvisols, as its NWR% was consistent across all four amendment conditions with statistically insignificant variance between amendments. Furthermore, the protocol was reasonable for time, difficulty, and repeatability. The flocs were observed to be strong and consistent. The scale-up of the protocol would also be feasible, as the sand and nutrient amendments could be blended with FFT before the addition of the polymer. Based on the NWR metric, an artificial soil at an SFR of 1.5 has the most potential to reach the goal of high water release on a repeatable basis across different conditions/amendments.

3.3.2 Polymer dosage

Figure 10 shows the clay-based polymer dosage required to give optimal flocculant performance at each SFR. Optimal polymer dosage naturally differs slightly as the solids content of untreated FFT has variation. Although these minimal differences were noticed, nutritional amendments had negligible impact on the optimal polymer dosage. These observations were consistent with the results of the mixing study.

The most interesting observation was the difference in polymer dosage required as the SFR increased. There was a ~6-7 mL (~108-126 g $tonne^{-1}$ solids) increase of polymer required for optimal flocculation when the SFR was increased from 0.0 to 1.5. This was likely to compensate for the sand particles that the polymer must accommodate on top of the FFT. With the increase of polymer dosage at SFR 1.5, high-quality release water was observed (Figure 11 and Figure 12). SFR 3.0 had lower polymer flocculant dosages required, but due to the protocol, it was only to flocculate an initial 563 g of FFT before the sand was added. Using ~40.5 mL (~740 g $tonne^{-1}$ clay solids) for 563 g of FFT was equivalent to 1350 g $tonne^{-1}$ clay solids for 1.013 kg of FFT, making no improvement on polymer dosage at an industrial scale. The complex mixing protocol required would also be challenging to perform in the field.

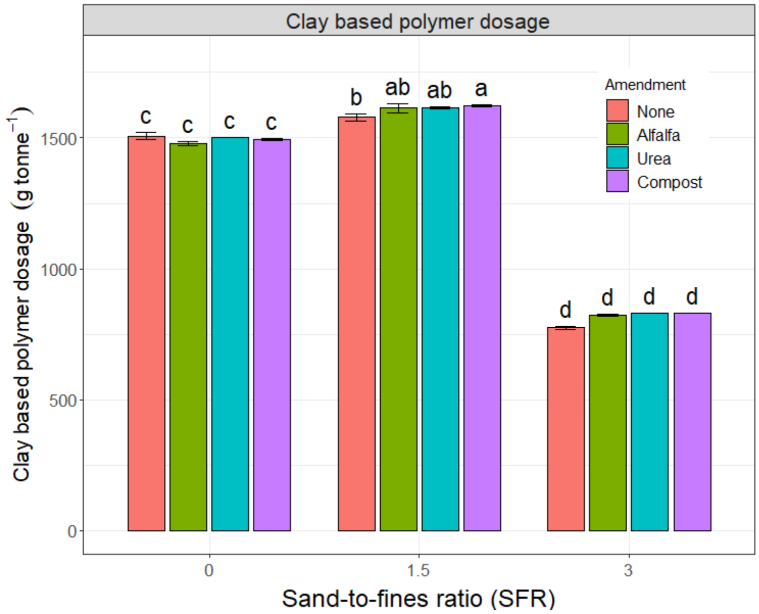

Figure 10: Clay-based polymer dosage required to optimally flocculate all SFR conditions performed in the production stage. Error bars represent one standard error of the mean (± SE, n = 24). Different letters indicate a significant difference (p <0.05) amongst amendment type or SFR.

3.3.3 Water Quality

The quality of the release water was included for a reference towards future studies. Unlike the original mixing study results, in the production study the 1.5 SRF produced the highest quality release water (Figure 11 and Figure 12). The low clarity and dark colour of the released water at SFR 3.0 indicated that the sand caused high amounts of physical degradation to the flocculated clays, and subsequently allowed much of the fines to be carried into the released water.

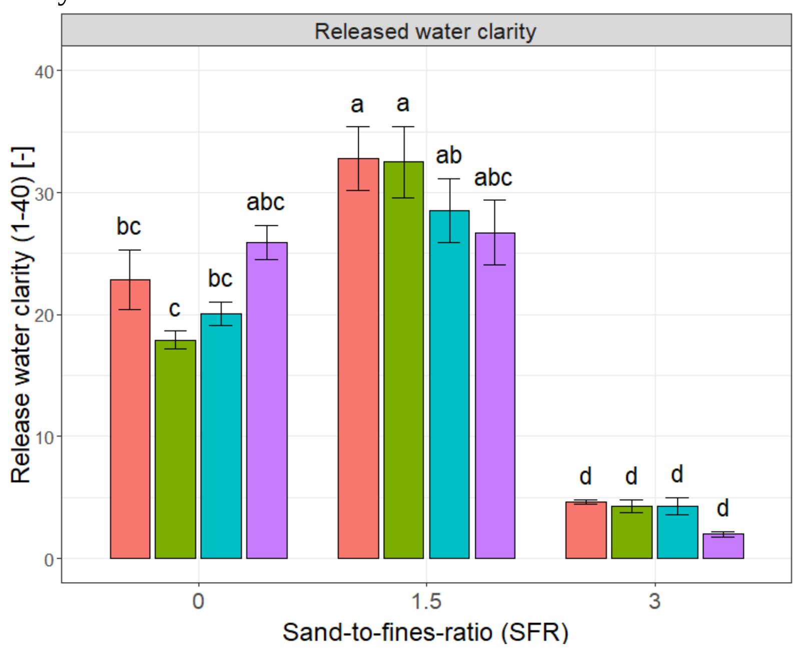

Figure 11: Average water clarity of all tested conditions during the production phase. Error bars represent one standard error of the mean (± SE, n = 24). Different letters indicate a significant difference (p <0.05) amongst amendment type or SFR.

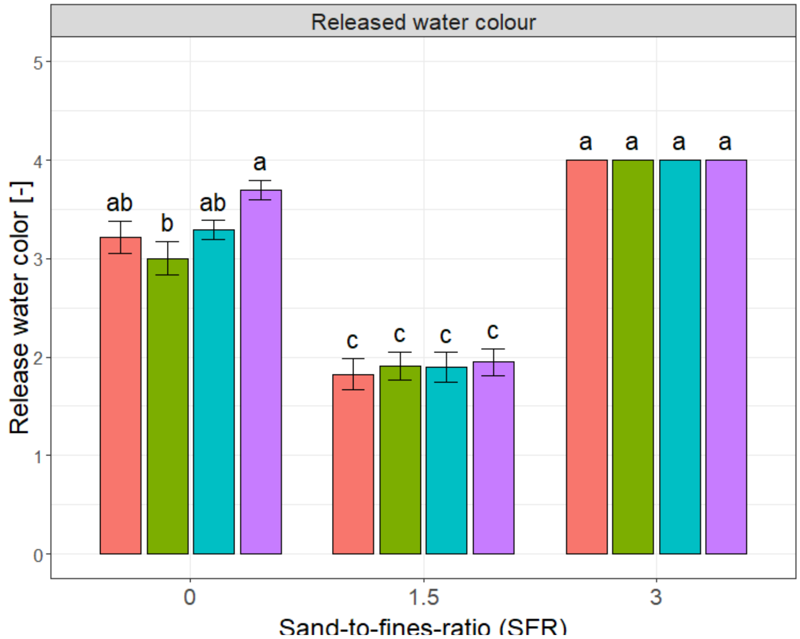

Figure 12: Average water colour of all tested conditions during the production phase. Error bars represent one standard error of the mean (± SE, n = 24). Different letters indicate a significant difference ($p < 0.05$) amongst amendment type or SFR.

3.3.4 Sediment Chemistry Analysis

Once the containers had been prepared, a subsample of each condition was sent for nutrient analysis to the University of Alberta. Table 7 presents the pH and electrical conductivity data for various amendments at three SFR. The pH and EC are similar with each amendment within the same SFR but decreased/increased respectively as SFR increased. The pH and EC differences observed with increasing SFR are likely a result of high salinity pore water in the sand. Higher electrical conductivity is known to decrease growth in plants and may have been a confounding variable in this study.

Table 6: pH and Electrical Conductivity (EC) measured for the artificial soil samples.

Amendment	**SFR**	**pH**	**EC [dSm^{-1}]**
Alfalfa	0.0	8.14	3.65
Blank	0.0	8.06	3.88
Compost	0.0	8.01	3.99
Urea	0.0	8.03	4.19
Alfalfa	1.5	7.51	6.94
Blank	1.5	7.35	5.06
Compost	1.5	7.27	6.46
Urea	1.5	7.35	7.42
Alfalfa	3.0	6.85	7.55
Blank	3.0	6.88	6.88
Compost	3.0	6.72	6.76
Urea	3.0	6.91	6.79

Nutrient analysis was performed on the artificial soils, assessing for plant-enriching elements including sodium, potassium, manganese, iron, zinc, calcium, magnesium, phosphorus, and sulfur (Table 8). As SFR increased, the proportion of all nutrients were observed to decrease. This is because sand adds only volume and presents a dilution effect on the existing nutrient content of the artificial soil. This means the sand dominated materials are more nutrient deficient than the clay rich materials.

Compost was the only nutrient source tested that added carbon, nitrogen and phosphorus to the tailings. Urea primarily added nitrogen and alfalfa added both carbon and nitrogen in significant quantities.

Total nitrogen and total carbon were also analyzed for each amendment/SFR combination using dry combustion in triplicate (Table 8). In some cases, the expected value for carbon to nitrogen (Exp. C:N) content was lower than present. This was most likely due to carbon being unaccounted for from two sources:

1. The FFT contained some residual bitumen, which was not controlled and varied on a per sample basis.
2. The acrylamide-based polymer flocculant contained approximately 50 wt% carbon, translating to 600 ppm.

Table 7: Elemental nutrient analysis on artificial soils by ICP analysis of dried solids. Copper levels were below detection levels in all samples.

Amendment	SFR	Na [mg kg^{-1}]	K [%]	Mn [mg kg^{-1}]	Fe [%]	Zn [mg kg^{-1}]	Ca [%]	Mg [%]	P [%]	S [%]
Alfalfa	0.0	861.3	0.224	201.0	0.766	37.2	0.400	0.246	0.042	0.352
Blank	0.0	887.3	0.195	202.7	0.772	37.5	0.391	0.244	0.039	0.347
Compost	0.0	881.2	0.192	204.8	0.801	43.4	0.422	0.255	0.058	0.365
Urea	0.0	941.5	0.186	202.3	0.779	38.5	0.391	0.248	0.041	0.365
Alfalfa	1.5	451.0	0.105	86.8	0.479	16.5	0.174	0.106	0.018	0.293
Blank	1.5	409.4	0.082	87.8	0.462	17.2	0.162	0.102	0.017	0.284
Compost	1.5	464.3	0.123	90.7	0.483	20.2	0.186	0.120	0.026	0.301
Urea	1.5	393.2	0.099	80.7	0.410	15.2	0.140	0.101	0.015	0.235
Alfalfa	3.0	356.2	0.123	69.6	0.458	15.1	0.157	0.094	0.015	0.283
Blank	3.0	343.7	0.088	62.8	0.426	13.2	0.124	0.081	0.012	0.280
Compost	3.0	246.6	0.066	51.5	0.341	12.7	0.109	0.066	0.017	0.236
Urea	3.0	338.8	0.092	61.1	0.429	13.1	0.120	0.080	0.011	0.268

Table 8: Total Nitrogen (TN) and Total Carbon (TC) analysis

Amendment	SFR	Avg. TN [wt%]	St.Dev TN [wt%]	Avg. TC [wt%]	St.Dev. TC [wt%]	N Added [wt%]	C Added [wt%]	C:N Ratio	Exp. C:N
Alfalfa	0.0	0.12	0.00	7.33	0.02	0.03	0.51	18.79	14
Blank	0.0	0.10	0.00	6.82	0.05	0.00	0.00	-	-
Compost	0.0	0.11	0.00	7.04	0.04	0.02	0.22	14.36	10
Urea	0.0	0.14	0.00	6.84	0.01	0.05	0.02	0.49	0.2
Alfalfa	1.5	0.07	0.00	3.48	0.02	0.02	0.45	21.80	14
Blank	1.5	0.05	0.00	3.02	0.03	0.00	0.00	-	-
Compost	1.5	0.06	0.00	3.34	0.16	0.01	0.32	32.73	10
Urea	1.5	0.08	0.00	3.30	0.10	0.03	0.28	10.14	0.2
Alfalfa	3.0	0.07	0.00	1.93	0.05	0.04	-0.04	-1.03	14
Blank	3.0	0.03	0.00	1.97	0.02	0.00	0.00	-	-
Compost	3.0	0.03	0.00	2.05	0.05	0.00	0.09	20.23	10
Urea	3.0	0.07	0.00	2.44	0.06	0.05	0.47	10.31	0.2

4 PART 2: PLANT GERMINATION AND EARLY GROWTH STUDY

4.1 Background and context of study

4.1.1 Greenhouse experimental design and set up

Utilizing the amended tailings (artificial soil prototype), a greenhouse study was initiated in March 2019 to evaluate the survival and development of plant species within the amended tailings. Three native species were selected for this study: a native grass (*Elymus trachycaulus*, hereafter, slender wheatgrass), shrub (*Salix interior*, hereafter, sandbar willow) and a wetland forb (*Rumex occidentalis*, hereafter, western dock).The amended tailings were divided into replicate non-draining 1 L containers and the effect of two or three SFR rates (0.0, 1.5, and 3.0) and amendments (compost, urea or alfalfa pellets) were evaluated.

Four replicates of each treatment combination were evaluated resulting in a total of 112 pots experiment wide. Following pot filling, one rooted seedling of sandbar willow and western dock were planted, while 25 seeds of slender wheatgrass was hand sown from seed and thinned to 5 plants per pot after 14 days. All pots were watered as required, throughout the trial.

4.1.2 Nursery production of seedlings

Sandbar willow and western dock seedlings were propagated at the NAIT Center for Boreal Research in Peace River, AB from March 11, 2019 to March 28, 2019. All seedlings of western dockand cuttings of sandbar willow were grown in mini peat plugs and hydroponic plugs respectively. All plants were watered as needed and fertigated 2-3 times per week.

At the time of seedling lifting, a subset of seedlings was destructively harvested, and the following plant parameters were measured (Table 9):

- Total plant height (measured using a measuring tape to 0.5 mm accuracy) and root collar diameter (measured using a Vernier caliper to 0.05 mm accuracy).
- Aboveground biomass was clipped and leaves were separated from stems.
- Aboveground biomass was dried in an oven at 70°C until weight constancy and dry mass was determined to the nearest 0.1 grams.
- Total root mass was determined by hand separation of roots from the soil through immersion in water and the use of sieves to capture roots. Roots were dried in an oven at 70°C until weight constancy and dry mass determined to the nearest 0.1 grams.

Table 9:Mean height, root collar diameter, leaf biomass and root biomass of nursery production of *S. interior* (sandbar willow) and*R. occidentalis* (western dock), propagated from March 11, 2019 to March 28, 2019.

Species	Height (cm)	Root collar diameter (mm)	Leaf biomass (g)	Root biomass (g)
Sandbar willow	17.2 ± 0.6	5.9 ± 1.5	0.113 ± 0.03	0.015 ± 0.01
Western dock	2.0 ± 0.0	-	0.006 ± 0.01	0.002 ± 0.00

4.1.3 Plant measurements

The greenhouse trial was evaluated for 6 weeks and throughout the growing period, plant survival or seed emergence was tracked weekly. At the conclusion of the growing period, the aboveground biomass of all species was removed with hand clippers and the following measurements were made:

- Maximum plant height (measured using a measuring tape to 0.5 mm accuracy).
- Aboveground biomass was clipped, and leaves were separated from stems (for sandbar willow).
- Aboveground biomass was dried in an oven at 70°C until weight constancy and dry mass determined to the nearest 0.1 grams.

4.1.4 Statistical analysis

Effects of SFR (0.0,1.5 or 3.0), and amendment application (none, compost, urea or alfalfa pellets) on the seed emergence, leaf biomass, stem biomass, and total aboveground biomass of tested species were analyzed using the statistical program R 3.4.1 (R Core Team, 2019). Analysis of variance was performed using the linear models via the lme*()* function of the *nlme* package. The posthoc analysisand the calculation of least squares means was completed usingthe *lsmeans* package (Lenth, 2018).

4.1.5 Slender wheatgrass response to artificial soil prototype

The emergence of slender wheatgrass was not affected by amendment type regardless of the SFR, except at 3.0 SFR, where the addition of alfalfa pellets significantly limited seed emergence by over 94% (Figure 13). The limiting effect of alfalfa pellets on seed emergence has been observed in other projects, and there is a possibility that the allelopathic chemicals contained in alfalfa pellets that are initially released as the pellet breaks down could inhibit seed germination and short-term growth though in longer trials (not this study), these effects tend to dissipate and improved growth is often observed. However, compost increased shoot biomass significantly when compared to other amendments for all SFR (**P<0.05**, Figure 14). Without amendments, each of the three tested SFR's did not show any significant differences, but with the addition of compost, the increase in shoot biomass was only limited in 3.0 SFR artificial soil prototype, and this could be due to high sand content. Similar results were observed for the shoot height of slender wheatgrass, where compost application significantly increased shoot height by over 100% relative to other tested amendments, but with no interaction between the amendment and SFR (**P=0.0557,** Figure 14).

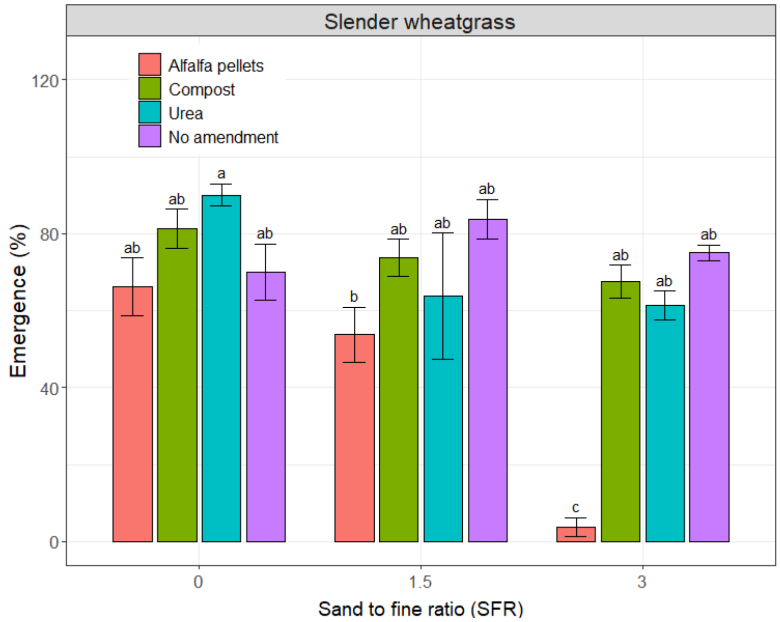

Figure 13:Mean emergence rate (%) of *E. trachycaulus* (slender wheatgrass), planted in artificial soil prototype of 0, 1.5 and 3 SFR, amended with 3 amendments (alfalfa pellets, compost, and urea). Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference (p <0.05) amongst different amendments.

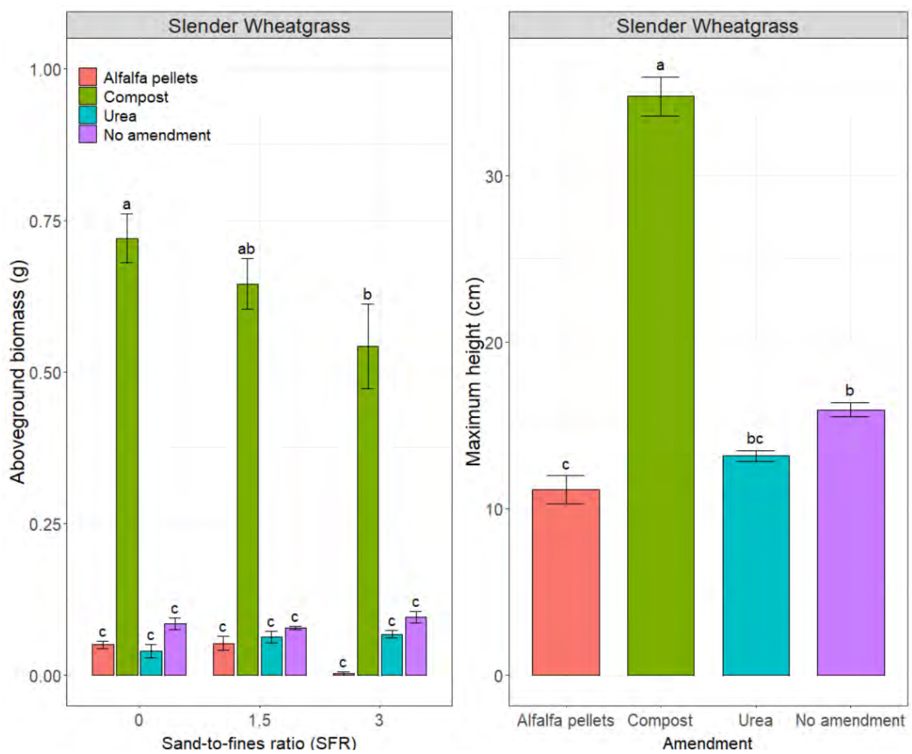

Figure 14: Mean aboveground biomass and maximum height of *E. trachycaulus* (slender wheatgrass), planted in artificial soil prototype of 0, 1.5 and 3 SFR, amended with 3 amendments (alfalfa pellets, compost, and urea).Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference (p <0.05) amongst different amendments.

Figure 15 shows the long, large grass roots that formed in the compost amended samples for SFR 0 and SFR 1.5.

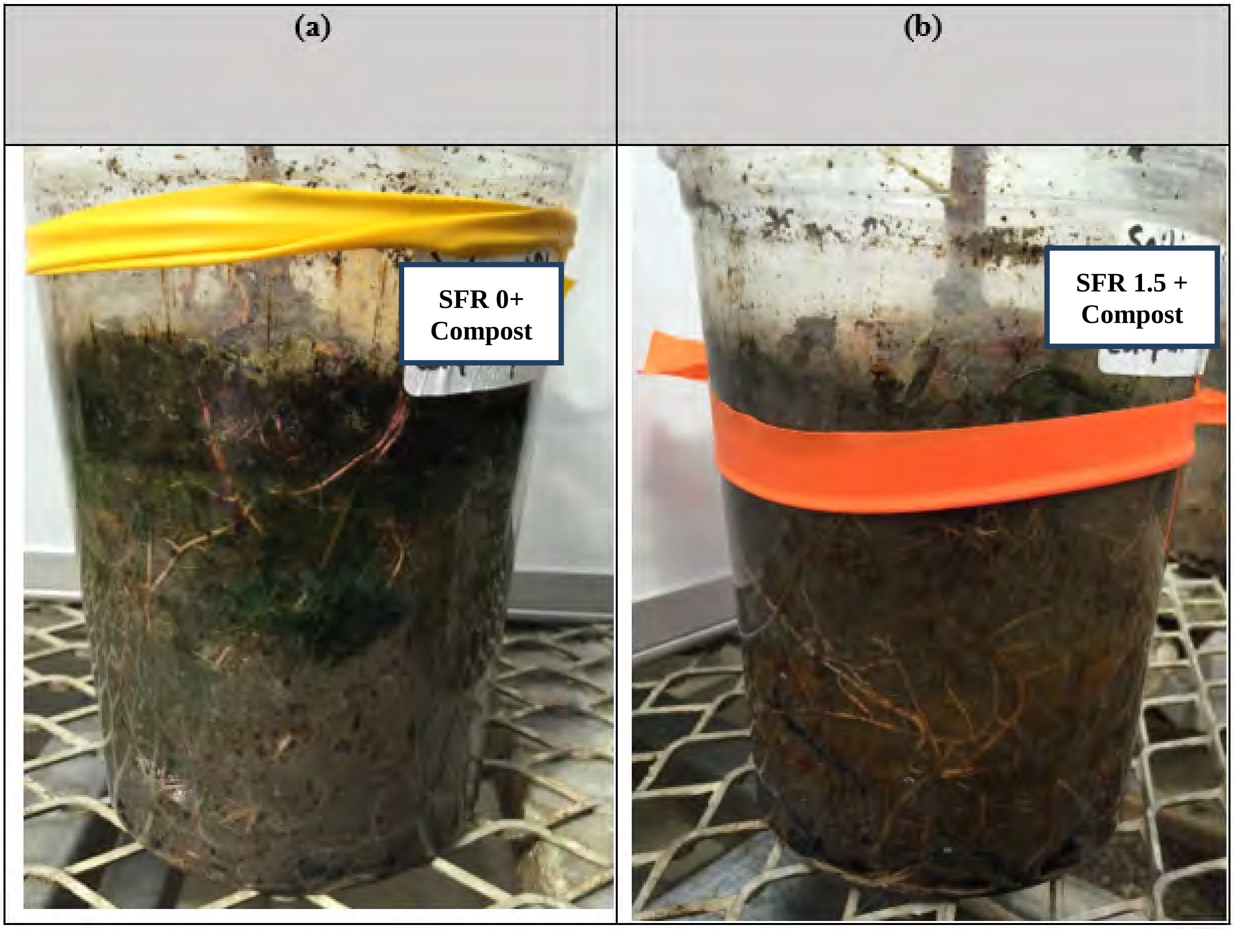

Figure 15: Photos of root of *S. interior* (sandbar willow) grown in artificial soil prototypes: (a) 0 SFR+ compost (b) 1.5 SFR+ compost after harvest from May 9, 2019

4.1.6 Sandbar willowresponse to artificial soil prototype

The incorporation of amendments and sand had interacting effects on the development of new leaf biomass in sandbar willow as there was no significant difference amongst amendment types with SFR 0 but at SFR 1.5, both urea and compost resulted in significantly greater quantities of new leaf biomass in sandbar willow compared with the control and alfalfa treatments ($P<0.05$,Figure 16). Similarly, urea or compost significantly increased the maximum height of sandbar willow though there was no significant difference between SFR or interaction between SFR and amendment ($P<0.05$,Figure 16). Adequate soil structure for plant growth depends on the presence of stable aggregates, and a soil with desirable aggregate size distribution consists of small intra-aggregate pores and large inter-aggregate pores that hold water and plant nutrients, providing shelter for micro-organisms, sites for many chemical and biological reactions in soil, and improved infiltration. Plant establishment without suitable structure (such as in oil sands tailings) could be challenging, however, once aggregates are initially created by increasing SFR, more aggregates will be established through natural processes, and also in this case through amendments such as compost or urea leading to improved stability of the artificial soil prototype (X. Li & Fung, 1996).

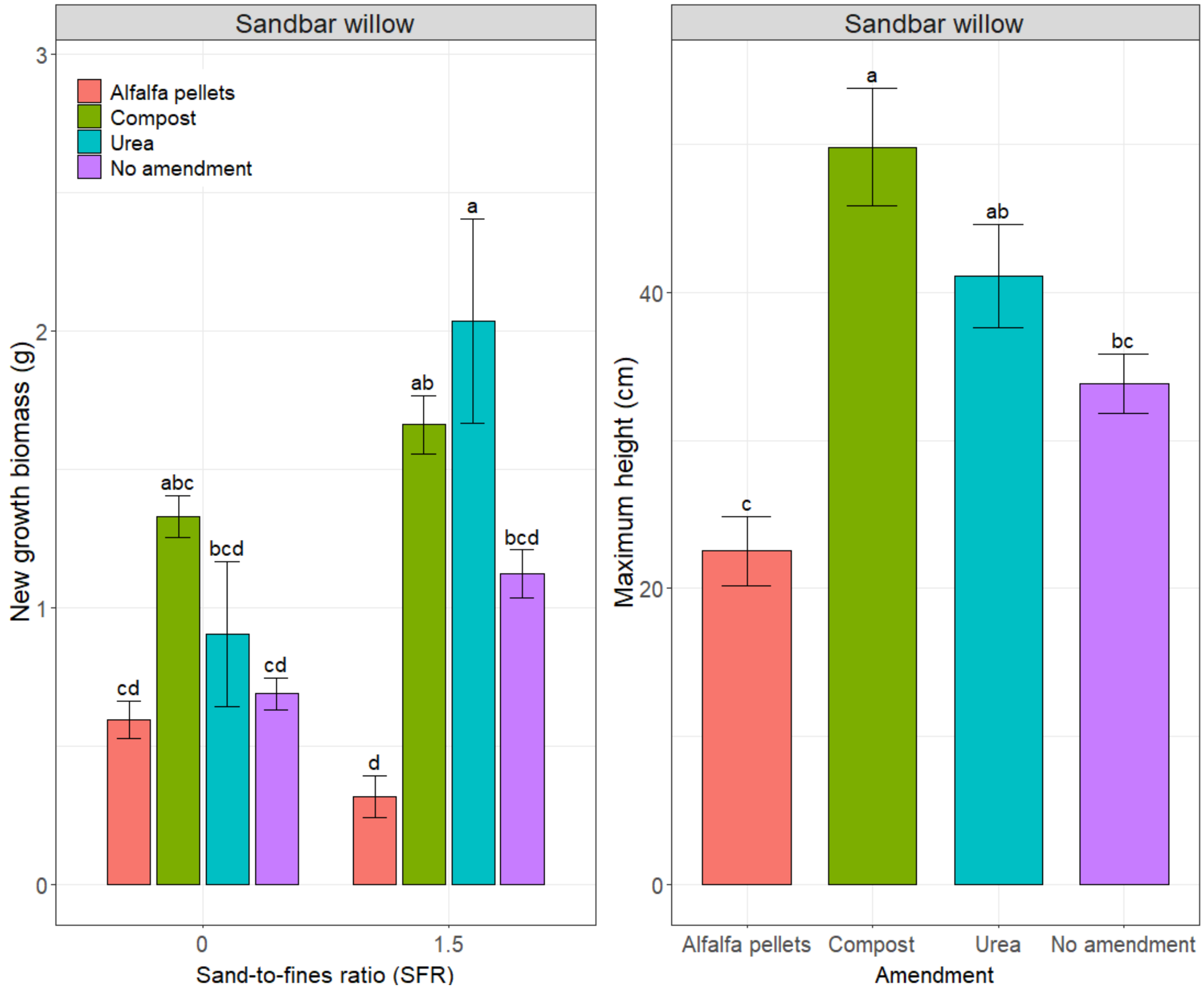

Figure 16: Mean aboveground biomass and maximum height of S. interior (sandbar willow), planted in artificial soil prototype of 0 and 1.5 SFR, amended with 3 amendments (alfalfa pellets, compost, and urea). Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst different amendments.

4.1.7 *Western dock response to artificial soil prototype*

There was no interaction between SFR and the amendments ($P = 0.338$) in total height of western dock and compost and alfalfa pellets showed significant differences ($P < 0.05$) in shoot height of western dock, increasing by 5.5 cm and 1.1 cm respectively relative to unamended soil prototype (Figure 17). However only compost displayed a significant improvement in biomass, regardless of the SFR (Figure 16) whereas urea displayed a significant reduction in both height and biomass ($P < 0.05$, Figure 16) relative to the unamended treatment. Biomass is a better metric of growth than height in non-tree species, so compost is considered the only amendment that showed significant improvement.

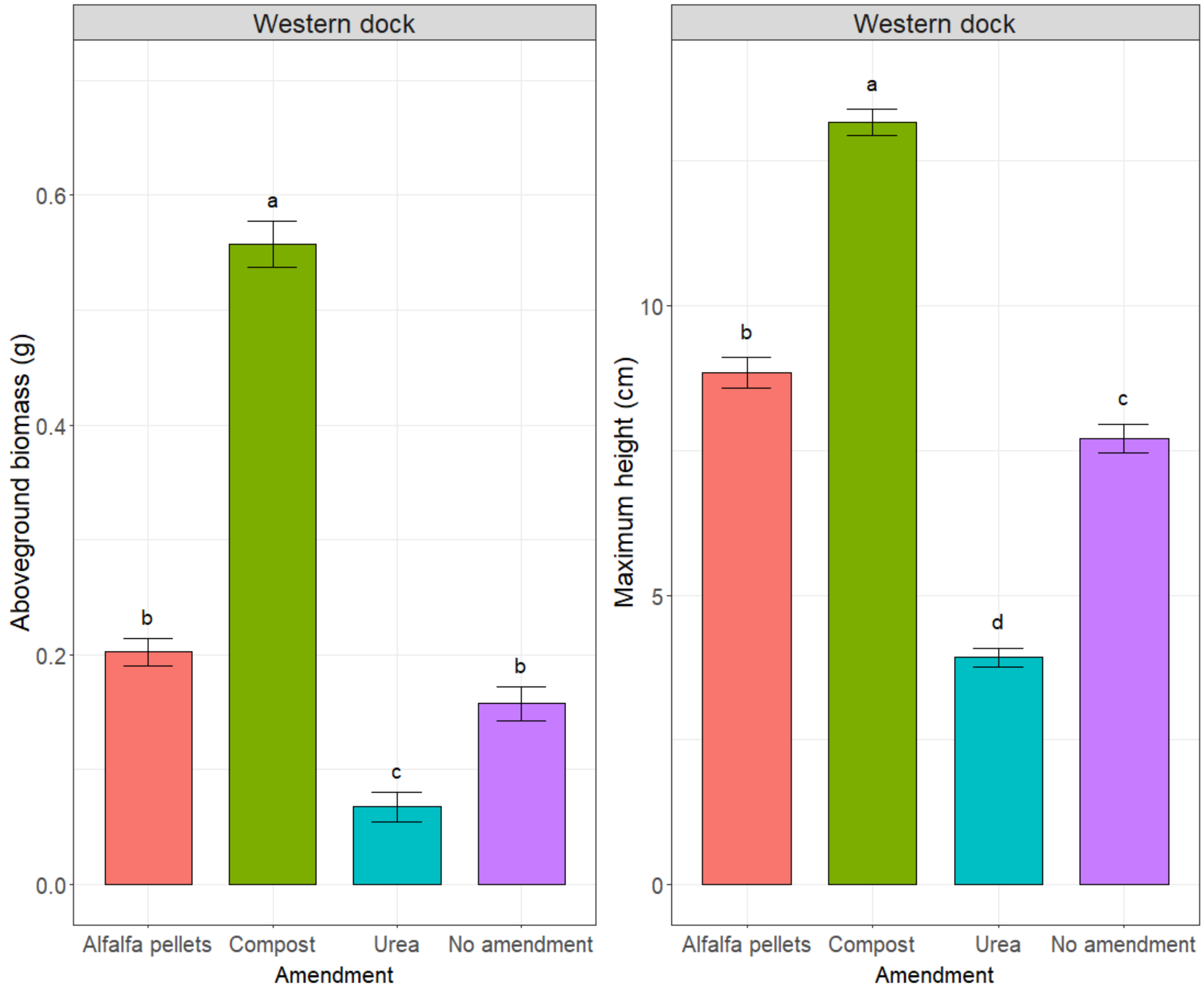

Figure 17:Mean aboveground biomass and maximum height of *R. occidentalis* (western dock), planted in artificial soil prototype of 0 and 1.5 SFR, amended with 3 amendments (alfalfa pellets, compost, and urea). Error bars represent one standard error of the mean (± SE, n = 4). Different letters indicate a significant difference ($p < 0.05$) amongst different amendments.

5 CONCLUSIONS

This project has demonstrated the repeatability and reproducibility of the developed protocols for the mixing and production of an artificial soil prototype using FFT with sand addition and the ability of three native plant species to germinate, survive and grow in these substrates. None of the amendments tested had a significant impact on flocculation performance, indicating that in-line addition of an amendment may be feasible. The artificial soil prototype with no sand addition (SFR 0.0) had the highest NWR but with a low final solids content and a very fine particle size distribution. The artificial soil prototype with SFR 3.0 was highly sandy, and difficult to produce with poor release water quality. The SFR 1.5 produced a well flocculated product with a higher solids content though lower NWR value from the SFR 0.0. The SFR 1.5 was most characteristically aligned to Luvisols in terms of sand and clay content.

It should also be emphasized that sand contributes no nutritional value to the artificial soils, and in fact serves to dilute the existing nutritional content of FFT with amendments. Therefore, it would be worthwhile for future studies to consider compensating any artificial soils with added sand with additional nutrient amendments. Furthermore, the sand used in this study significantly increased the electrical conductivity (salt content) of the mixtures. Plants start to struggle when the EC is above 4 as it was for all the sand-amended tailings in this study. The presence of extra salt in the sand may explain why no benefit to sand addition was found in the growth study.

There was an observable increase in aboveground biomass of slender wheatgrass, sandbar willow, and western dock with the application of compost, and with urea for sandbar willow only. Compost appeared to be the most consistent of all three amendments in terms of improving growth of tested species during this short-term (6 week) growth trial. Alfalfa pellets were initially inhibitory to species, particularly forthe germination of slender wheatgrass, but this effect appeared to dissipate over time. A longer growth trial may have demonstrated greater growth improvements with alfalfa.It is notable that aside from the compost-amended treatment, the observed growth rates of the plants in this trial were much slower than previously observed in greenhouse studies with fertilizer additions into treated tailings. In these previous trials, a starter fertilizer blend of macro/micronutrients was added. However, no secondary fertilization to balance potential deficiencies in other macro or micronutrients was utilized in this study. Compost was the only amendment used in this study that contained a wider range of macro/micronutrients, including phosphorous (which can increase nitrogen uptake by plants), while urea and alfalfa pellets were providing a source of nitrogen (and carbon in the case of alfalfa) only. It is speculated that the nitrogen contained in urea and alfalfa was also less readily available to plants initially due to a slower process of breaking down, which would have further contributed to the differences observed.

The results observed from this study were interesting. However, a longer-term study should be undertaken to test the limitation of secondary nutrients as well as to better understand nutrient fluxes over longer time periods. Secondly, as the inhibitory effects of alfalfa pellets have previously been observed to dissipate with time, the six-week period of this trial was insufficient to allow for a full evaluation of this amendment. Alfalfa may also have benefited plants with a greater "resting" period ahead of plant establishment to allow for adverse chemical effects to dissipate. Therefore, there is a need to test the suggestion that the inhibitory effect of alfalfa pellets is short-lived and can be corrected with pre-planting irrigation to dilute the effects of the allelopathic chemicals. Thirdly, the water chemistry of release water from different combinations of amendments and SFR needs to be further studied to understand if there are any impacts on species growth. By creating a final substrate that is reclamation ready, this approach could be applied as a surface capping technique overtop of already existing soft tailings deposits, but further study is required.

6 IMPLICATIONS FOR TAILINGS MANAGEMENT

Reclaiming tailings as part of a functional boreal ecosystem is the goal for mine closure. From a practical perspective this means that the majority of the disturbed land must be reclaimed into an upland forest while a minority of the area is transformed into lakes and wetlands. Currently approved tailings plans have a significant reliance on deep deposits which will either be converted to lakes or be capped and converted to upland forest. The use of end pit lakes containing FFT has not yet been fully approved by the regulator and the techniques currently available for capping these deep soft deposits are extremely expensive. The addition of plants to the surface of a soft deposit may provide a less costly, more acceptable treatment method.

In the earlier Bugs & Veggies study conducted by NAIT (Collins et al., 2019) on thickened tailings and centrifuge cake it was found that both grasses and willows could be planted to good effect on treated tailings. The total water able to be removed from tailings by grasses was approximately twice as much as the water removed from tailings through evaporation alone, whereas the willows could remove approximately 1.5 times the amount of water removable by evaporation alone. Furthermore, grasses were found to dewater tailings down to 30cm whereas willows were found to dewater tailings down to 65 cm. In centrifuge cake, the grasses dewatered the tailings to a liquidity index of ~0.89 whereas the willows dewatered the tailings to a liquidity index of ~0.33. In TT the dewatering of the tailings was to a liquidity index of 1.15 for the grasses and 0.5 for the willow. The study also found that the growth and water use of grasses planted in the sandier TT was significantly greater than in the centrifuge cake, though minimal differences were noted for the willow.

In addition, both the grasses and the willows provided roots which acted to bind the tailings together more effectively than simple drying. Plant-treated tailings were found to have significantly different texture and higher strengths than the control tailings. This means the plants may be able to help create truly stackable tailings by minimizing the formation/risk of weak zones in the deposit. Western dock, while very effective at dewatering/handling large wet patches, does not have the fine root structure of grasses or willows and is less drought tolerant, therefore it may have limited use in this type of application independently though it could be considered in combination with grasses as a mitigation measure against flooding.

For a capping strategy, a combination of the three plants placed on a fresh tailings deposit may be effective. The western dock can help rapidly dewater wetter, low lying areas where water recharge is rapid. The grasses can provide strength and stability in the dryer edges and minimize erosion. The willows can provide significant strength increases and were found to generate strength well over 20kPa at the surface of the treated tailings and greater than 2kPa (peak) approximately 40cm below the surface in just a short growing trial. It is anticipated that much greater strengths could be obtained by longer growth trials, especially with the addition of appropriate nutrients. If proven, these strengths are in the target range for capping activities.

Similar results were found after one growing season at field trials at CNRL, though surface water management was identified as potential challenge (Smith et al., 2018).

The results of this study indicate that the addition of a nutrient could be easily incorporated in-line with minimal impact to the flocculation process. This provides a way of getting nutrients to the deposit without requiring site access. In addition, there may be a benefit in having the nutrients incorporated in more than the top 10-15 cm of soil as is typical for surface applications. This benefit will need to be tested in future trials. The final limitation for a capping strategy is how to safely deploy the plants onto a soft deposit. This matter is being investigated by Dr. Schoonmaker in collaboration with Dr. Beier and Dr. Lipsett at the University of Alberta. One promising technique is to lay out a willow cutting mat to allow new willows to sucker from there.

Apart from use as a capping strategy there may be a benefit of using plants in a sacrificial manner. One potential scenario that could be explored is to plant a series of willows prior to depositing tailings and adding tailings over them. If the deposition rate is kept lower than the growth rate it may be possible to create significantly stronger deposits than can currently be achieved with standard placement techniques. This application would require longer-term survival of the plants and would need to be tested for feasibility.

7 RECOMMENDED NEXT STEPS

The outperformance of compost-amended FFT could be due to the presence of other macro/micronutrients, as observed growth rates were much slower than what has been observed in previous greenhouse studies where a starter fertilizer blend of macro/micronutrients was added. Therefore, there is a need to test this limitation of a secondary nutrient. Secondly, as the inhibitory effects of alfalfa pellets have been observed to dissipate over time in the past, the short six-week growth period of this trial did not allow for a full evaluation. Further examination of literature, and some of our preliminary works notes this effect, but there is a need to test the suggestion that the inhibitory effect of alfalfa pellets is short-lived and can be corrected with irrigation and planting of other crop species with higher tolerance. Thirdly, the short time period of the study did not allow for a full evaluation of the influence of SFR on plant growth and the salt content of the sand used meant the results of salt and sand were convoluted with each other. It is recommended that a longer growth period be used to evaluate the impact of sand content (comparing SFR 0 and SFR 1.5). It is also recommended that the EC of the SFR 0.0 and SFR 1.5 be controlled to be less than an EC of 4 dS m^{-1}. Finally, due to the significantly larger volumes of artificial soils required for a longer growth trial (20L vs 1L), it is recommended that the ease of additive addition be tested in an in-line process rather than in the batch conditions used in this study.

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APPENDIX A: DETAILED PROCEDURES FOR PRODUCING ARTIFICIAL SOILS AT THREE SFRS

Protocol ID	Process
5	1) Subsample 300 g of homogenous FFT into a small metal beaker 2) Add amendments & mix for 1 min at 320 rpm under a jar-tester 3) Rapidly injectappropriate amount of A3338 polymer solution at 0.45 wt% 4) 1 second after injection, reduce speed to 50 rpm 5) Mix 20 seconds at 50 rpm 6) Mix 2:40 minutes at 10 rpm with spatula insertion at 5-second intervals 7) Mix 30 seconds at 5 rpm with spatula insertion at 5-second intervals 8) Remove blade and transfer contents into bucket + sieve
6	1) Subsample 300 g of homogenous FFT into a small metal beaker 2) Add amendments & mix for 1 min at 320 rpm under a jar-tester 3) Rapidly injectappropriate amount of A3338 polymer solution at 0.45 wt% 4) 2 seconds after injection, change speed to 50 rpm 5) Mix 20 seconds at 50 rpm 6) Mix 3 minutes at 10 rpm with spatula insertion at 5-second intervals 7) Mix 30 seconds at 5 rpm with spatula insertion at 5-second intervals 8) Remove blade and transfer contents into bucket + sieve
7	1) Subsample 300 g of homogenous FFT into a small metal beaker 2) Add amendments & mix for 1 min at 320rpm under a jar-tester 3) Rapidly injectappropriate amount of A3338 polymer solution at 0.45 wt% 4) 7 seconds after injection, change speed to 50 rpm 5) Mix 10 seconds at 50 rpm 6) Mix 2:20 minutes at 10 rpm with spatula insertion at 5-second intervals 7) Remove blade and transfer contents into bucket + sieve

Table A1: Initial protocols tested for SFR 0.0 300g release watertrials

Table A2: Initial protocols tested for SFR 1.5 300g release watertrials

Protocol ID	Process
3	1) Subsample 214g of homogenous FFT and 86g of homogenous sand into a small metal beaker 2) Add amendments & mix for 5 min at 270rpm under an overhead mixer with a jar-tester blade 3) Rapidly injectappropriate amount of A3338 polymer solution at 0.45 wt% 4) 3 seconds after injection, change speed to 30rpm 5) Mix 55 seconds at 30rpm with a spatula only holding in place acting as a baffle 6) **Quickly** remove the blade from the beaker and transfer FFT and sand mixture onto a bucket + sieve
4	1) Subsample 214g of homogenous FFT and 86g of homogenous sand into a small metal beaker 2) Add amendments & mix for 5 min at 275rpmunder a jar-tester 3) Rapidly injectappropriate amount of A3338 polymer solution at 0.45 wt% 4) 3 seconds after injection, change speed to 10rpm 5) Mix 1 minute at 1rpm with manual spatula control 6) Remove the blade from the beaker and transfer the FFT and sand mixture onto a bucket + sieve

Table A3: Initial protocols tested for SFR 3.0 300g release watertrials

Protocol ID	Process
8	1) Subsample 167 g of homogenous FFT and 133 g of homogenous sand into a 4” metal beaker 2) Add amendments & mix for 5 min at 275 rpm under a jar tester 3) Add A3338 polymer in one shot 4) Exactly 2 seconds after injection, change speed to 10 rpm 5) Mix 58 seconds at 10 rpm with a spatula inserted at 5-second intervals 6) Remove the blade from the beaker and transfer the FFT and sand mixture onto a bucket + sieve
9	1) Subsample 334 g of homogenous FFT into a 4” metal beaker 2) Follow protocol 6 mixing conditions 3) Add 266 g of homogenous sand to the flocs, use a spatula to mix sand and FFT as homogenously together as possible. 4) Remove the blade from the beaker and transfer the FFT and sand mixture onto a bucket + sieve

A.1 Protocol for production at SFR 0.0

1) Mix pail of FFT using a drill mixer until homogenous. Determine the slurry density and weigh enough FFT to make 1 L into a 6” metal beaker. Weigh the appropriate mass of nutrient amendment chosen and add to the subsample.
2) Place the subsample underneath the overhead mixer with mixing blade clearance of 0.5 cm from beaker bottom, allow to mix for 1 min at250 rpm. Prepare a plastic syringe with the appropriate amount of 0.45 wt% A3338 polymer
3) After the 1 min of mixing is completed, inject polymer solution in a one-shot motion as fast as possible, directly into FFT. Exactly 3 seconds after the polymer has been injected, stop mixing.
4) Preset mixer speed to 30 rpm, introduce spatula into the beaker positioned such that it is touching the beaker bottom while avoiding the spinning blade. Start mixer at the preset 30 rpm.
5) Move spatula back and forth along a ~120° arc along the edge of the beaker, cycling twice per second for ten seconds. Use the spatula to ensure flocs are moved throughout the mixing container. Repeat step 5 for 1.5- 2 minutes.
6) After ~1.5-2 minutes, the flocs will noticeably compress as water is released. Stop mixing, and wait 1 minute, allowing water to release from flocs. If operator judges more conditioning is required, continue to step 7. Otherwise, if the flocs look compressed and lots of water has been released, skip to step 8.
7) Turn the mixer on at30 rpm, holding the spatula in place against the outside wall of the beaker. After ~3-10 full turns of the blade (depending on how sheared the flocs are at this step), stop mixing and allow 30 seconds for the water to release. Repeat if necessary.
8) Dislodge any floc solids and remove blade from the beaker. Transfer all contents of the beaker onto a sieve + bucket. Use a spatula to create a hole in the center of the flocs approximately 2.5 cm in diameter and create channels where water may pool on top of flocs. Cover with plastic wrap.

A.2 Protocol for production at SFR 1.5

1) Mix pail of FFT using a drill mixer until homogenous. Determine the slurry density. Weigh enough FFT and sand to make 1 L slurry at SFR 1.5 into a 6” metal beaker. Weigh the appropriate mass of nutrient amendment chosen and add to the subsample.
2) Place the subsample underneath the overhead mixer with mixing blade clearance of 0.5 cm from beaker bottom, allow to mix for 1 min at 165 rpm. Prepare a plastic syringe with the appropriate amount of 0.45 wt% A3338 polymer
3) Stop mixing and use a spatula to scrape the inside edge and bottom of the beaker a couple of times, allowing any clumps of sand to break down. Continue mixing at 165 rpm for another 2 minutes.
4) After 3 minutes of mixing are complete, inject polymer as a quick, continuous motion directly into the FFT. Immediately after the polymer has been injected, stop mixing.
5) Preset mixer speed to 20 rpm, and introduce spatula into the beaker positioned such that it is touching the beaker bottom while avoiding the spinning blade. Start mixer at the preset 20 rpm.

6) Move spatula back and forth along a ~120° arc along the edge of the beaker, cycling twice per second for ten seconds. Use the spatula to ensure flocs are moved throughout the mixing container.
7) The flocs will quickly develop high yield stress and begin to stick to the walls of the beaker. Use the spatula to dislodge the flocs from the beaker sides and back into the mixing zone.
8) The flocs will eventually take on a highly textured, dry appearance. Allow for 2-3 more full spins of the blade while scraping the beaker with the spatula, and stop mixing
9) Wait 30 seconds, allowing water to release from flocs. If operator judges that more conditioning is necessary, continue to step 10. Otherwise, if the flocs are highly textured and water releases quickly, skip to step 11.
10) Turn the mixer on at 10 rpm, holding the spatula in place against the outside wall of the beaker. After 2 full turns of the blade, stop mixing and allow 10 seconds for the water to release. Repeat if necessary.
11) Dislodge any floc solids and remove blade from the beaker. Transfer all contents of the beaker onto a sieve + bucket. Use a spatula to create a hole in the center of the flocs approximately 2.5 cm in diameter and create channels where water may pool on top of flocs. Cover with plastic wrap.

A.3 Protocol for production at SFR 3.0

1) Mix pail of FFT using a drill mixer until homogenous. Determine the slurry density. Weigh enough FFT and sand to make 1 L slurry at SFR 3.0. Add the FFT to a 6” metal beaker, but do not add the sand. Weigh the appropriate mass of nutrient amendment chosen and add to the subsample.
2) Place the subsample underneath the overhead mixer with mixing blade clearance of 0.5 cm from beaker bottom, allow to mix for 1 min at 160 rpm. Prepare a plastic syringe with the appropriate amount of 0.45 wt% A3338 polymer.
3) After 3 minutes of mixing are complete, inject polymer as a quick, continuous motion directly into the FFT. Wait 5 seconds after the polymer has been injected, stop mixing.
4) Preset mixer speed to 30 rpm and introduce spatula into the beaker positioned such that it is touching the beaker bottom while avoiding the spinning blade. Start mixer at the preset 30 rpm
5) Move spatula back and forth along a ~120° arc along the edge of the beaker, cycling twice per second for ten seconds. Use the spatula to ensure flocs are moved throughout the mixing container
6) After ~1.5-2 minutes, the flocs will noticeably compress as water is released. Stop mixing.
7) Wait 1 minute, allowing water to release from flocs. If operator judges more conditioning is required, continue to step 8. Otherwise, if the flocs look compressed and lots of water has been released, skip to step 9.
8) Turn the mixer on at 30 rpm, holding the spatula in place against the outside wall of the beaker. After ~2-5 full turns of the blade, stop mixing and allow 30 seconds for water to release. Repeat if necessary.
9) Dislodge any floc solids and remove blade from the beaker. Decant all released water onto a sieve + bucket.

10) Add of the sand measured in step 1 to decanted flocs. Use a large spatula to manually mix flocs and sand until homogenous (~1.5 min). Pour flocs and sand mixture onto a sieve + bucket. Use a spatula to create a hole in the center of the flocs approximately 2.5 cm in diameter and create channels where water may pool on top of flocs. Cover with plastic wrap.

APPENDIX B: EFFECT OF AMENDMENTS ON FLOCCULATION KPIS IN MIXING STUDY

Table B1: Effect of amendments on net water release, solids content in flocs, and clay-based polymer dosage required for optimal flocculation in the mixing study (n=4)

Amendment	**SFR**	**Average NWR [%]**	**St.Dev. NWR [%]**	**Average Floc Solid% [%]**	**St.Dev. Floc Solid% [%]**	**Average Dosage [gtonne^{-1}]**	**St.Dev. Dosage [gtonne^{-1}]**
Alfalfa	0.0	0.3257	0.0136	0.3558	0.0057	1300.41	100.03
Blank	0.0	0.3394	0.0060	0.3599	0.0133	1300.41	100.03
Compost	0.0	0.3562	0.0139	0.3654	0.0027	1300.41	100.03
LOFe	0.0	0.3775	0.0036	0.3663	0.0032	1400.44	0.00
Organix	0.0	0.3523	0.0197	0.3561	0.0039	1400.44	0.00
Urea	0.0	0.3451	0.0100	0.3581	0.0036	1250.39	86.63
Urea+Alfalfa	0.0	0.3277	0.0297	0.3595	0.0112	1267.06	94.31
Alfalfa	1.5	0.0905	0.0558	0.5059	0.0079	1556.04	31.44
Blank	1.5	0.1001	0.0381	0.5059	0.0066	1500.47	44.74
Compost	1.5	0.0837	0.0537	0.5051	0.0042	1567.16	33.34
Urea	1.5	0.1025	0.0583	0.5075	0.0051	1567.16	33.34
Alfalfa	3.0	0.1210	0.0199	0.6082	0.0197	700.22	0.00
Blank	3.0	0.1894	0.0237	0.5107	0.0062	1818.75	0.00
Compost	3.0	0.1593	0.0322	0.6321	0.0200	700.22	0.00
Urea	3.0	0.1622	0.0112	0.6343	0.0196	691.88	14.44

Table B2: Effect of amendments on water clarity and water colour in the mixing study (n=4)

Amendment	**SFR**	**Avg**	**St.Dev. Colour**	**Avg Clarity**	**St.Dev. Clarity**

		Colour			
Alfalfa	0.0	3.75	0.43	13.00	4.64
Blank	0.0	3.75	0.43	9.25	4.32
Compost	0.0	3.00	0.00	9.50	9.50
LOFe	0.0	3.00	0.00	16.67	0.47
Organix	0.0	3.00	1.00	17.00	5.00
Urea	0.0	3.75	0.43	11.00	4.30
Urea+Alfalfa	0.0	3.00	0.82	14.67	5.44
Alfalfa	1.5	2.33	0.94	15.33	20.98
Blank	1.5	1.90	1.22	13.40	13.49
Compost	1.5	2.75	0.43	2.50	1.66
Urea	1.5	2.75	0.43	2.25	1.09
Alfalfa	3.0	3.00	0.00	1.75	1.09
Blank	3.0	3.00	0.00	1.00	0.00
Compost	3.0	3.00	0.00	1.75	1.09
Urea	3.0	3.00	0.00	1.00	1.00

APPENDIX C: PHOTOS FROM GREENHOUSE POTTIING TRIAL

(a)

(b)

(d)

(e)

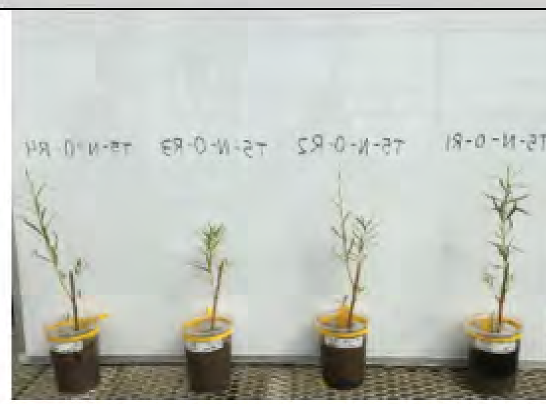


Figure C1: Photos of *S. interior* (sandbar willow) grown in artificial soil prototype at 0 SFR: (a) 0 SFR+ compost (b) 0 SFR+ urea (c) 0 SFR+ alfalfa pellets, (d) 0 SFR+ no amendment after harvest from May 9, 2019

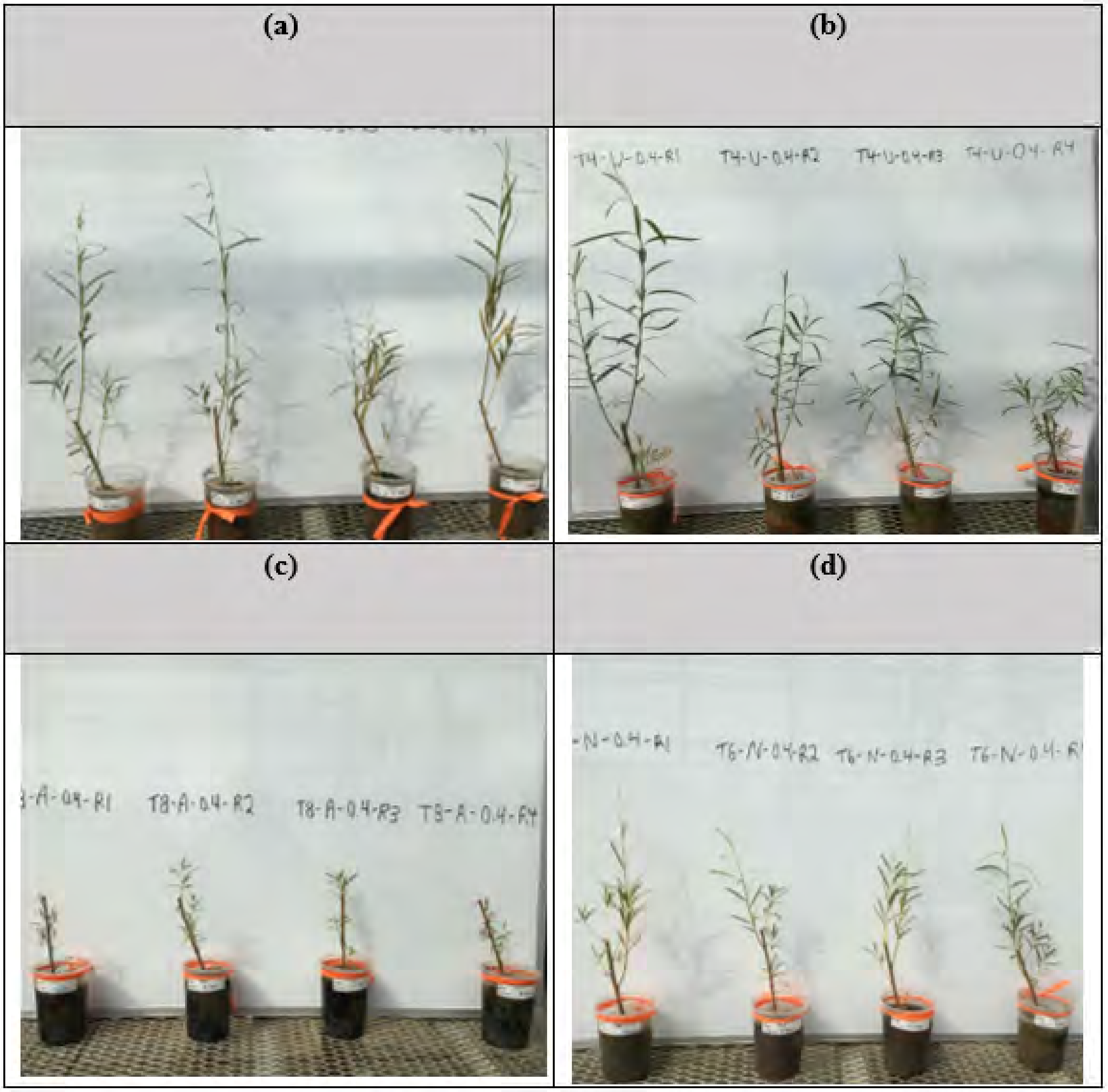


Figure C2:Photos of *S. interior* (sandbar willow) grown in artificial soil prototype at 1.5 SFR: (a) 1.5 SFR+ compost (b) 1.5 SFR+ urea (c) 1.5 SFR+ alfalfa pellets, (d) 1.5 SFR+ no amendment after harvest from May 9, 2019

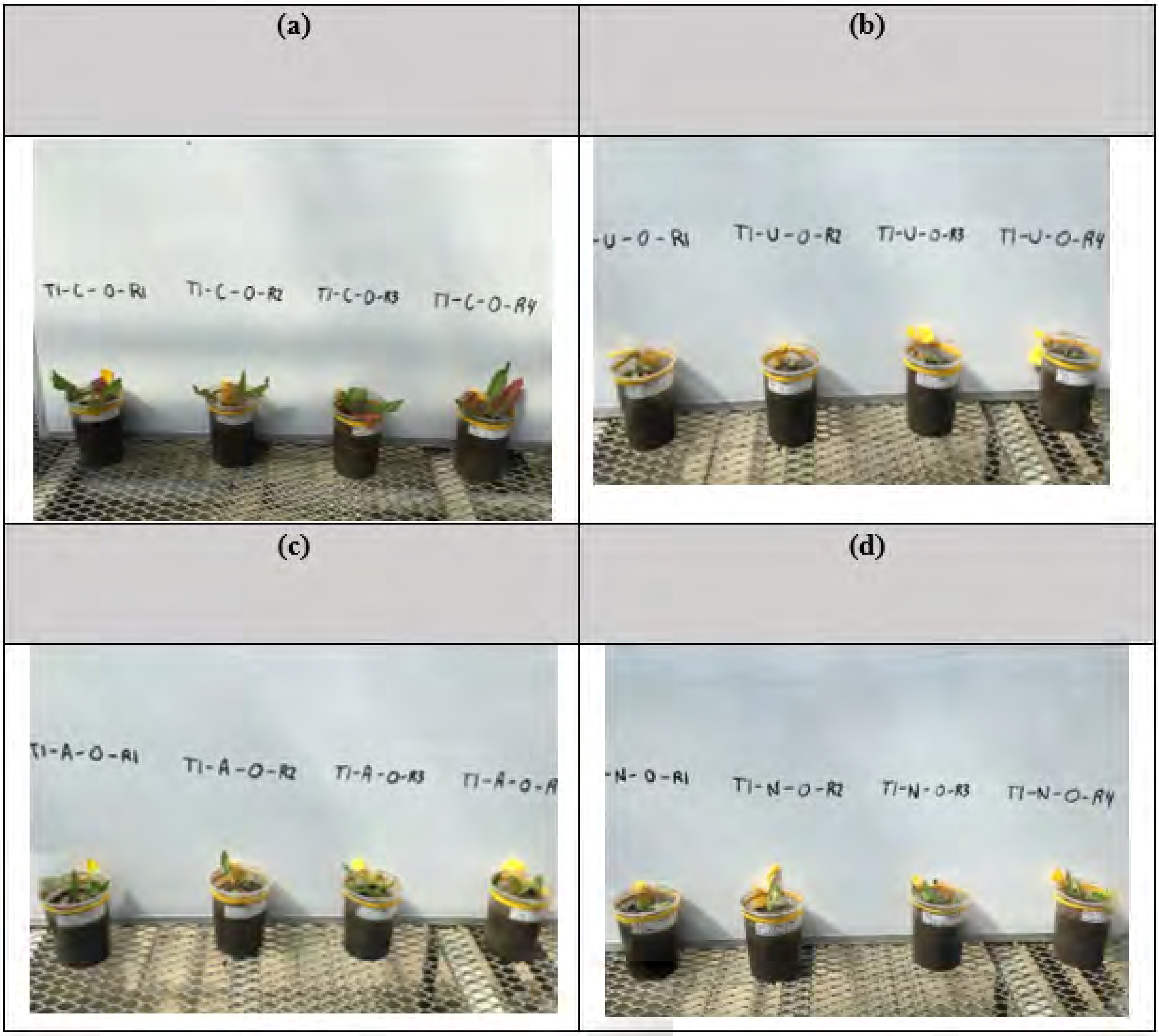


Figure C3: Photos of *R. occidentalis* (western dock) grown in artificial soil prototype at 0 SFR: (a) 0 SFR+ compost (b) 0 SFR+ urea (c) 0 SFR+ alfalfa pellets, (d) 0 SFR+ no amendment after harvest from May 9, 2019

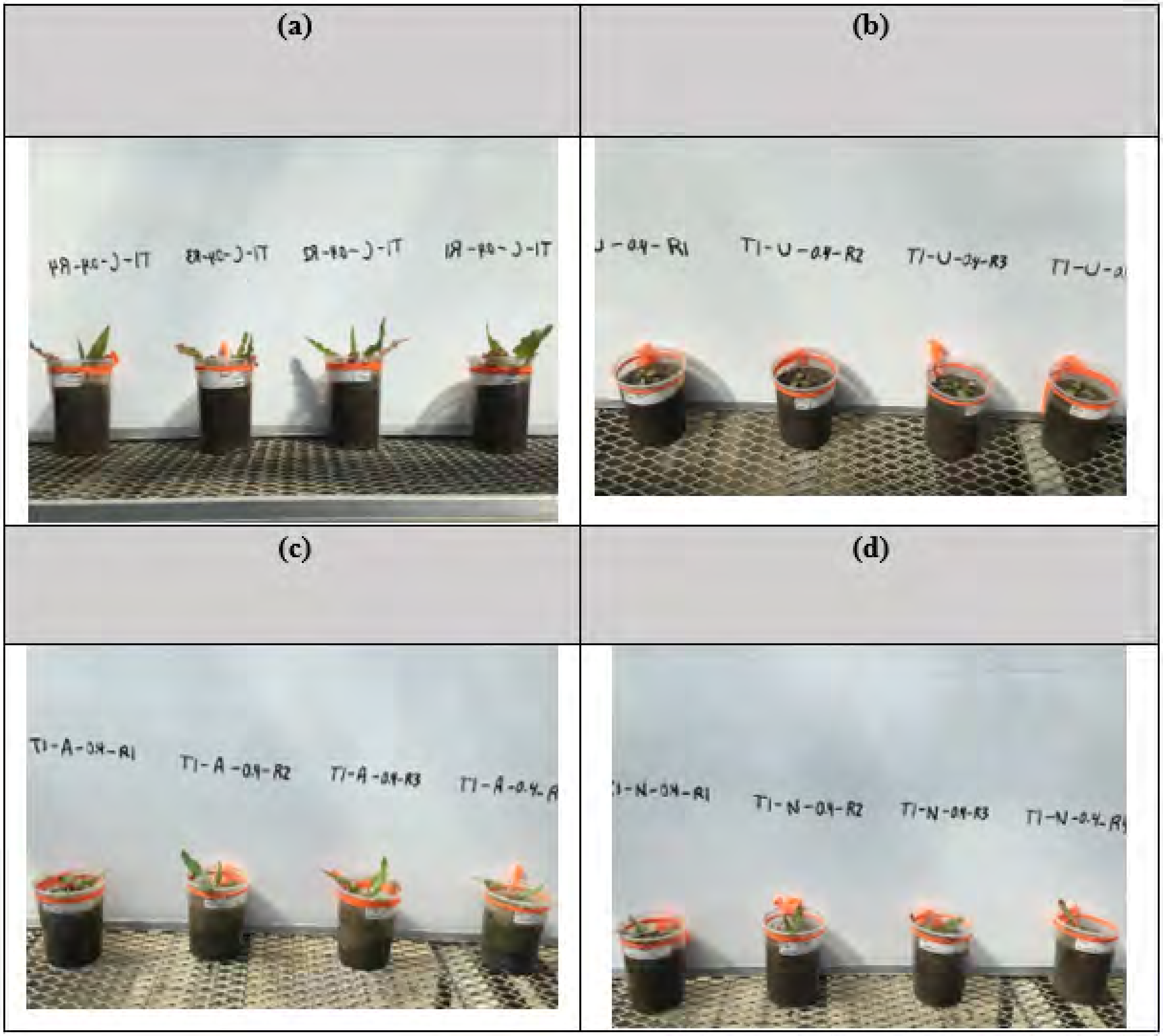
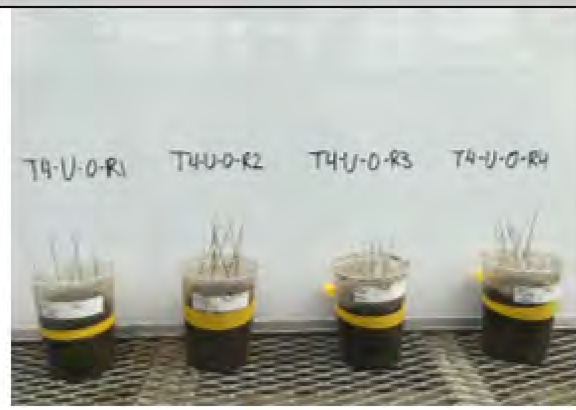


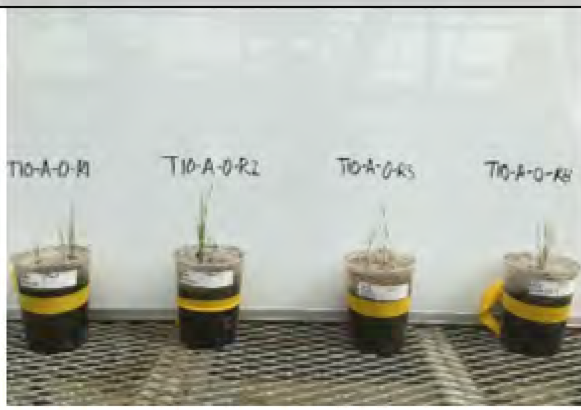
Figure C4:Photos of *R. occidentalis* (western dock) grown in artificial soil prototype at 1.5 SFR: (a) 1.5 SFR+ compost (b) 1.5 SFR+ urea (c) 1.5 SFR+ alfalfa pellets, (d) 1.5 SFR+ no amendment after harvest from May 9, 2019

(a)

(b)



(c)



(d)

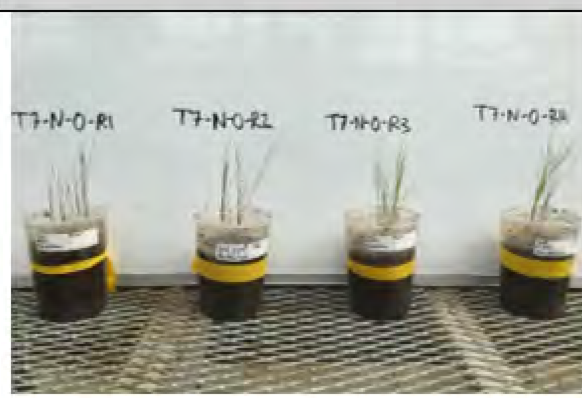


Figure C5:Photos of *E. trachycaulus*(slender wheatgrass) grown in artificial soil prototype at 0 SFR: (a) 0 SFR+ compost (b) 0 SFR+ urea (c) 0 SFR+ alfalfa pellets, (d) 0 SFR+ no amendment after harvest from May 9, 2019

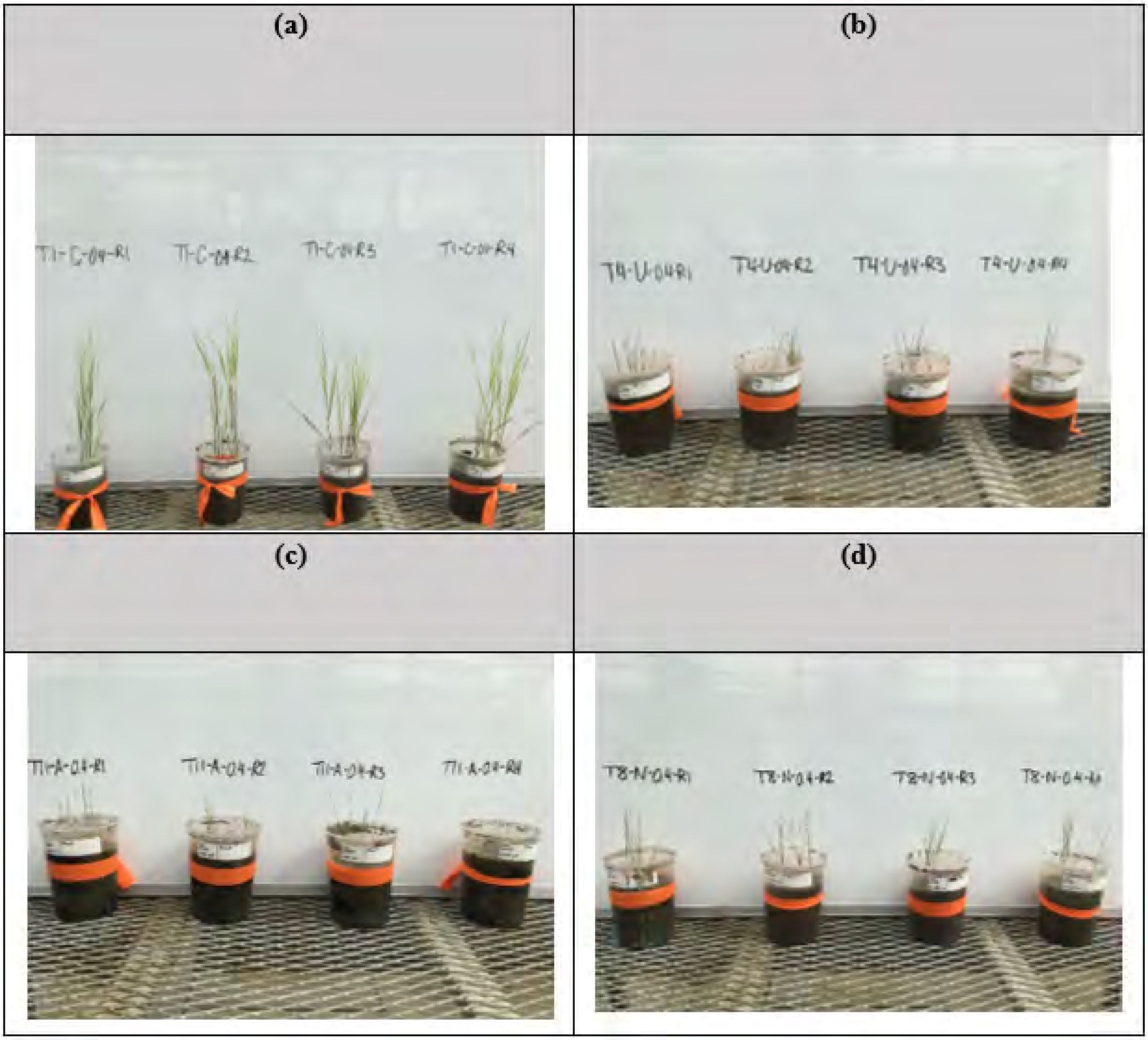


Figure C6: Photos of *E. trachycaulus* (slender wheatgrass) grown in artificial soil prototype at 1.5 SFR: (a) 1.5 SFR+ compost (b) 1.5 SFR+ urea (c) 1.5 SFR+ alfalfa pellets, (d) 1.5 SFR+ no amendment after harvest from May 9, 2019

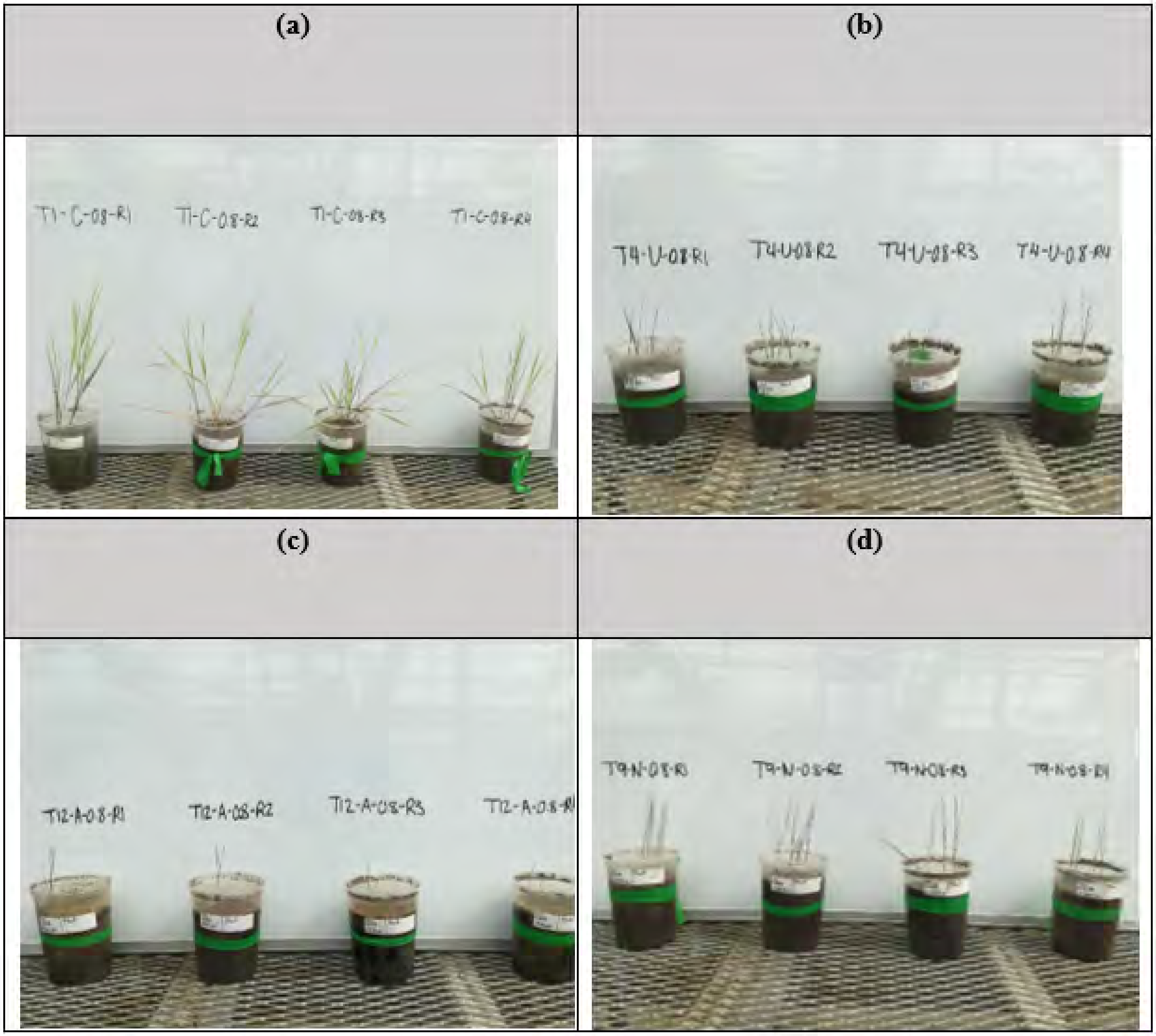


Figure C7: Photos of *E. trachycaulus* (slender wheatgrass) grown in artificial soil prototype at 3.0 SFR: (a) 3.0 SFR+ compost (b) 3.0 SFR+ urea (c) 3.0 SFR+ alfalfa pellets, (d) 3.0 SFR+ no amendment after harvest from May 9, 2019

APPENDIX D:LIST OF PUBLICATIONS AND PATENT FILING/APPLICATION

None