BIOSALIX: Mine reclamation using fabricated soils and organic residuals to augment soil quality

Emissions Reduction Alberta: Final Outcomes Report

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PROJECT DESCRIPTION

Coal mine development in North America is facing pressure due to shifts to alternative, lower emission fuels for power generation along with more restrictive policies on expansion of existing coal mines and new mine approvals. While these shifts will lead to reduced emissions, closing mines disrupts the rural communities which establish and thrive economically through mine development. These closures also present significant environmental challenges to reclaiming large areas of land typical of prairie coal mine operations.

The BIOSALIX project has its genesis as an innovative solution at the nexus of the key challenges of large scale mine reclamation, biosolids management, climate change mitigation, and energy transition. These challenges were addressed via the establishment of a short-rotation coppice willow plantation. SYLVIS Environmental Services formed a collaborative group including EPCOR Water Services, Westmoreland Mining, Natural Resources Canada – Canadian Forest Service, and Bionera Resources Inc. to implement the project vision. The project received funding from the Natural Resources Canada Clean Growth Program, the Emissions Reductions Alberta Partnership Intake Program and Alberta Innovates granting agencies.

BIOSALIX is anchored in the beneficial use of biosolids to improve willow establishment by amending marginally productive soils characteristic of reclaimed mines and to augment existing soil resources. To achieve this goal, approximately 12,000 dry tonnes of biosolids were transported from EPCOR's Gold Bar Wastewater Treatment Plant to Westmoreland's Paintearth Mine near Forestburg, Alberta. Biosolids were applied to a spectrum of reclamation areas to facilitate growth of willows and rectify reclamation trajectories via amendment addition to improve soil tilth, fertility, and organic matter status. Willows were planted into biosolids amended soils at rates up to 20,000 stems per hectare using specialized planting equipment in combination with conventional agricultural practices. The project relied on contributions of trained mine operators and local planting crews, providing diversified training and economic development opportunities within the regional labour force.

Shifting sands during the execution of the project included a global pandemic, extreme climatic conditions (i.e., wet and dry, hot and cold), and unanticipated early coal production cessation at the project site – reinforcing the timely nature of the BIOSALIX concept and successes that have been achieved. Addressing challenges allowed for learning key lessons about implementation of the BIOSALIX concept, including

- the need for intensive site characterizations when working on mine sites,
- accounting for numerous cumulative stressors that affect willow establishment,
- recognizing that a longer time frame is required for developing and operationally validating a biologically based concept to allow for iterative collection of knowledge and lessons learned across growing seasons.

Stands of willows exceeding two metres in height are now growing in marginal, disturbed prairie soils and more than 500 hectares of mined land at Paintearth have been amended with biosolids. Direct benefits of the project extend beyond the beneficial use of biosolids, reclamation of mine land, and diversification of the regional economy. The system is contributing to climate change mitigation efforts as it met carbon sequestration targets related to biosolids application and continues to strive towards those targets for willow development. The system has also helped to re-establish local biodiversity, providing fodder and habitat for wild animals such as pronghorns and rabbits.

A shift from coal use in Alberta accelerated the need for mines to address land reclamation for large production areas and evolving economic realities. The system fostered within the BIOSALIX project presents a unique means of confronting these realities, especially in conjunction with the lessons learned and knowledge gained from the initial operationalization of the concept. The main takeaways from the project are:

- Biosolids amendments are an effective tool for supporting positive reclamation outcomes.
- It is feasible to advance the technology readiness level of the BIOSALIX concept, but more time is required.
- Execution of the extension activities allowed for identifying critical stressors impacting willow establishment outcomes.
- The willow plantation establishment outcomes reflect the specific circumstances of this project and should not be broadly applied to other projects and sites looking to explore or advance a similar concept.

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EXECUTIVE SUMMARY

BIOSALIX is an innovative project that is designed to demonstrate an alternative means of achieving equivalent capability for reclaimed land with no adverse impacts to the environment. BIOSALIX addresses two broad challenges: the need to reclaim land that has been mined and the need to manage increased organic residuals created as populations of urban areas grow. The project uses municipal biosolids from the Edmonton region as a soil amendment to improve soil tilth and enhance conventional reclamation at a prairie coal mine. With productive soils in place, the site supports the establishment of a short rotation coppice (SRC) willow plantation. These systems generate a sustainable crop which can be harvested on a continuous basis, providing a carbon source for ongoing reclamation or a feedstock for composting, bioenergy, and bioproducts.

In addition to resolving multiple environmental challenges related to mining and municipal organics management, the BIOSALIX project contributes to the mitigation of climate change via reduction of greenhouse gas emissions and the revision of rural local economies via a renewable bioeconomy. Willow plantations actively sequester carbon below ground and above ground in biomass. While the above ground biomass is regularly harvested and fed into a bioeconomy supply chain, the below ground biomass accumulates over time. BIOSALIX fills the vacuum created by the acceleration of coal mine closure, which results in unforeseen stress on the reclamation process and co-incident acceleration of job losses, without adequate time to transition and shift the local economy or re-train the workforce.

The key technology gap that BIOSALIX seeks to address is the merging of using biosolids to build and enhance soils, with the establishment of a non-conventional woody biomass agricultural crop in a mine reclamation setting. BIOSALIX also aims to verify the carbon sequestration potential of the biosolids and woody biomass system, as well as to fill scientific, technical, and socio-economic gaps for multiple stakeholders. These technology gaps were addressed through the project's four main objectives, each with its own performance metric:

1. Develop an innovative system for coal mine reclamation using short rotation coppice (SRC) willows and municipal biosolids, which is valuable across all potential reclamation scenarios, but has additional value where mines are challenged by topsoil quality and quantity deficiencies. *Performance metric:* Achieve approximately 240 ha of reclamation on the mine site within the project timeframe.
2. Address the needs of municipalities to find cost-effective and environmentally safe methods for beneficial use of biosolids and wastewater from municipal wastewater treatment systems. *Performance metric:* Utilize approximately 4,000 dry tonnes (dt) of biosolids per year in reclamation processes (2019 – 2021).
3. Achieve a carbon sequestration system through below ground (soil) carbon, while also producing valuable woody biomass, a change agent for the establishment of a renewable economy. *Performance metric:* Develop a system capable of sequestering approximately 540 t CO2e soil carbon per hectare (ha) of established plantation area over a 30-year timeframe.

4. Measure economic diversification to the local mining community as a result of the project. *Performance metric:* Achieve approximately 12 local person-years of employment throughout the duration of the project.

The BIOSALIX project aimed to amend previously mined land with biosolids and plant an SRC willow crop on 500 ha of Paintearth Mine (PEM) over three years. Biosolids were applied on reclaimed areas of the mine as either (1) a topsoil amendment, (2) directly to subsoil to build topsoil, and (3) blended with subsoil and woodchips to reduce the volume of subsoil needed for reclamation. Over 15,000 dry tonnes of biosolids were applied to over 800 ha of land at PEM from 2019 – 2021, exceeding both the target metrics for biosolids utilization and reclamation, and successfully achieving the first two objectives. The biosolids amended soils were planted with cuttings of SRC willow in the spring of each project year. Over 500 ha of land was planted with willow over the course of the project.

The BIOSALIX project was able to exceed its benchmark of 12 person-years of employment over the course of the project by nearly two-fold, successfully achieving the fourth objective.

Preliminary carbon calculations have confirmed that the BIOSALIX system can achieve the targeted carbon sequestration on a per hectare basis. Although this metric could not be established within the project timeframe, the project provides a proof-of-concept for successful implementation of this system in mine reclamation.

The original BIOSALIX concept anticipated the outcome of a large, thriving plantation that PEM would take over management of to diversify reclamation options and secure a new source of income at the site. Unfortunately, the project has not reached that stage at this juncture. Despite the 2022 – 2023 extension addressing the issues identified upon conclusion of the initial 2019 – 2021 phase of the project, the goal of firming up the viability and scalability of the concept was not achieved and there are still unanswered questions. There are some pockets of willows planted over the last couple of years that are being maintained and indicate the potential for success; however, there is widespread failure of the 2023 planted area. The cause of the failure has been preliminarily diagnosed and addressing additional lessons learned to reach implementation at an operational scale is pending.

Various research and monitoring activities occurred during the BIOSALIX project to address multiple technology gaps. Highlights from the results of these activities include:

- Stockpiling biosolids at an all-weather stockpile pad found no adverse effects to underlying soil quality.
- Blending soil with biosolids and woodchips can reduce the quantity of soil required for reclamation by nearly 30% while meeting soil quality benchmarks.
- Soils amended with biosolids had marked increases in available nitrogen, phosphorous, and sulfur.
- Subsoil amended with biosolids can provide similar outcomes for soil quality and willow growth as topsoil amended with biosolids.
- Biosolids addition can upgrade unsuitable subsoil by reducing the sodium adsorption ratio and adding organic matter.

- Cytospora canker was found to be the most prevalent disease among willow plantations in Alberta.
- Higher stocking levels can improve yields of willow clones of smaller stature and of taller, larger diameter clones.
- Solid biofuels (wood chips and wood pellets) offer the most viable short-term opportunities for woody biomass in the region, while gaseous biofuels, liquid biofuels and biochar are the most viable in the medium-term.
- The BIOSALIX project at its current scale, which was less than 10 percent of the site, was able to replace 8.3% of economic activity at PEM.

The results of this project indicate that the nexus of benefits for Albertans related to this project may be realized, but it will have to be within other projects at this site or other sites, building on the foundation of valuable lessons learned.

Key lessons learned, which can be applied to any similar future projects are as follows:

- Site related factors play a critical role in the outcome of willow plantations, and intensive site characterization prior to site selection is necessary understand the stressors and challenging conditions present and take them into consideration during planning and execution of plantation establishment.
- When establishing willow on sites with multiple concurrent stressors, adequate moisture is critical, and a trade-off exists between optimal weed management and willow stress when using chemical weed management approaches.
- Future projects should consider a longer time frame for willow plantation establishment with more modest annual planting targets to allow for iterative collection of knowledge and application of lessons learned.

1 PROJECT DESCRIPTION

1.1 Introduction

The BIOSALIX project brings together two societal/industrial challenges, addressing them simultaneously to achieve significant carbon capture through biogenic carbon sequestration. Our approach is also structured to provide socio-economic benefits to mining communities threatened with the sunset of coal mines.

Prairie coal mine closures are being accelerated through provincial and federal policies aimed at reducing climate change and decreasing greenhouse gas (GHG) emissions from energy generation. This is the first societal/industrial challenge. The neighbouring communities that have supported these mines are threatened by the accelerated closure. Without an effective transition from mining to diverse employment opportunities, the resource-driven economies of small rural towns throughout the prairies and Canada will sunset with the resource industry they were built to support.

As municipalities grow and expand, the quantity of organic residuals produced by the populace increases. There is an ongoing challenge to develop high impact beneficial uses for these organics on a scale that is sustainable for large cities. This is the second societal/industrial challenge. The beneficial use of organic residuals, specifically municipal biosolids, the digested and stabilized solid produced by municipal wastewater treatment, has proven potential to positively contribute to carbon sequestration in both soil and plants.

Through these challenges, the BIOSALIX team sees an opportunity to achieve an outcome that achieves federal and provincial carbon strategy policy targets, provides a sustainable management option for municipal biosolids, and offers the prospect of community transition and growth from a mining hub into a clean tech nexus. BIOSALIX is an innovative mine reclamation/biomass production process using municipal biosolids as both an amendment and a feedstock in topsoil fabrication at a prairie coal mine in Alberta. This process augments reclamation practices to optimize and enhance soil organic carbon stocks and biomass stocks in disturbed coal mine lands.

The combination of the shortened mining timeline and the loss of revenue from coal reserves left in-situ affects the situation in several ways:

- It reduces the funds and time available to diversify the local economy to provide socio-economic stability.
- It strains capacity to find suitable resources for reclamation, including high quality topsoil (which is degraded and/or in short supply at some mines).
- Rural communities are forced to rapidly transition the economy with limited time and resources.

BIOSALIX fills the vacuum created by the acceleration of coal mine closure, which results in unforeseen stress on the reclamation process, and co-incident acceleration of job losses, without adequate time to transition and shift the local economy or re-train the workforce. It addresses the needs of growing municipalities by sustaining rural communities with new, clean, and renewable employment opportunities, based first on the novel reclamation process, and later, on the use of the reclamation process product – willow biomass – as the foundation of a new sustainable economy based on renewable resources that form a cornerstone for innovation.

The BIOSALIX process uses the residuals resource in the highest, best use conceivable – combining carbon sequestration, nutrient recycling, and long term soil productivity at large scale, especially in areas with marginal soils.

1.2 Background

BIOSALIX uses an innovative mine reclamation/biomass production process where municipal biosolids are both a soil amendment and a feedstock in topsoil fabrication. The BIOSALIX process augments reclamation practices to enhance soil organic carbon stocks and produce a woody biomass crop on previously mined land.

Standard reclamation processes at prairie coal mines typically include the following activities:

1. Replacement of overburden
2. Contouring
3. Subsoil placement
4. Topsoil placement
5. Revegetation

Topsoil and subsoil are salvaged prior to mining and stored in stockpiles until needed for reclamation. Reclamation challenges can include insufficient volumes of topsoil and/or subsoil to meet the required replacement depth, and poor soil quality with limited organic matter and nutrients to support revegetation.

Biosolids are used to address these challenges in three separate ways:

- As an amendment to already placed topsoil, applied at agronomic rates providing organic matter and nutrients to support plant growth.
- Applied directly to subsoil, at soil building rates providing organic matter equivalent to that of topsoil.
- As a feedstock for a fabricated soil, blended with a mineral source and a woody biomass source, which could be used in place of topsoil or subsoil.

The sites are revegetated to a short-rotation coppice (SRC) willow crop planted with a stand density of approximately 14,000 stems per hectare. SRC willow crops can be harvested every 3 – 4 years. During the harvest, the above ground woody biomass is removed to 10 cm above the ground, however the stool (the below ground portion) remains intact and alive. After harvest, the willows grow back in the next season from the stool (a process known as coppicing), typically with a higher stem density than previously observed. The harvest cycle can be repeated 8 – 10 times, giving the stand an effective lifespan of 25 – 35 years.

The SRC willow crop can provide two key benefits over revegetation to a conventional agricultural crop:

1. enhanced carbon sequestration (through greater below ground growth, and little disturbance of soil)
2. economic diversification via biomass production

Once established, an SRC willow crop can be harvested and maintained with minimal soil disturbance, allowing for accumulation of biogenic carbon in the soil. Additions of biosolids to the crop after each harvest cycle further promotes carbon sequestration by directly adding organic matter to the soil, and by adding nutrients which promote biomass growth.

Once harvested, the woody biomass can be used as a carbon feedstock to fabricate additional soil for reclamation. Other opportunities for the biomass include use as a composting feedstock, or as a bioenergy feedstock. With the development of a diverse end-use market, the BIOSALIX system aims to transform a sunsetting coal mine into a hub for a new bioeconomy.

1.2.1 Operational implementation of the technology in mine reclamation

The BIOSALIX project is both a methodological leap forward in mine reclamation philosophy and process, and a new process, being the first demonstration of high-rate biosolids applications and the establishment of a non-conventional woody biomass agricultural crop in a mine reclamation setting in Alberta.

In reclamation, the key objective is the certification of the reclamation cost-effectiveness, to release the reclamation bond capital. As such, the principal challenge associated with the BIOSALIX system is the cost of biomass system establishment, and the management of biosolids as a component of the soil placement/amendment process. This project aims to demonstrate that investment in reclamation using a technology designed to develop the site as both a ‘carbon farm’ and a renewable biomass feedstock producer has significant advantages that overcome its initial setup costs, forming a business case for the transformational change. The demonstration has been designed on a large scale to provide an opportunity to assess the qualitative and quantitative components of this process including technical, logistical, and economic feasibility of this practice on an operational scale over an appropriate timeframe.

Traditionally, mine reclamation practices involve importing topsoil for any topsoil deficits, which is a costly and environmentally unfriendly route. This ultimately creates another land disturbance from where the topsoil was mined. The BIOSALIX project will allow for mines to produce biomass to support their own internal reclamation efforts by growing feedstocks that can be used in combination with biosolids to ‘blend and extend’ existing topsoil resources, thereby avoiding unsustainable options for increasing the externally sourced soil volume demand for reclamation. It is estimated that up to 10% more topsoil can be conserved using this innovative reclamation method, as compared to existing practices.

1.2.2 Verification of carbon sequestration potential

This project involves the modification and improvement of existing reclamation practices to achieve significantly greater long-term soil organic carbon stocks and long-term renewable biomass feedstock product on currently unproductive mine land. This transformational change of existing reclamation practices will bring significant, quantifiable carbon sequestration which will be measured over the span of the project. It is conservatively estimated that the BIOSALIX system will capture 14 tonnes of carbon per ha per year.

1.2.3 Socio-economic impacts

Harnessing a solution to numerous socio-environmental challenges that have been carefully studied by the project research teams, this project fills important scientific, technical, and socio-economic gaps for multiple stakeholders (governments, corporations, communities, and policymakers), which will enable its commercialization:

- Provincial coal reduction strategies and climate change mitigation goals are achieved.
- Municipalities and large utilities with growing organic residuals management burdens seek diversification and increased resilience through beneficial management of residuals and biosolids.
- Small municipalities proximate to mines benefit from knowledge transfer applicable to their biosolids and effluent management. This can stretch infrastructure asset lifespan, reducing rural municipal financial burden while providing value to the municipality and the clean economy.
- Mines overcome reclamation and socio-economic challenges, accelerated by policy decisions to reduce carbon emissions from coal-fired electricity on a much shorter timeframe throughout Alberta.
- The solution improves the sequestration of biogenic carbon on the landscape.
- The socio-economic outlook for mining communities is improved through increased employment and skill-building.
- A nexus and feedstock from which renewable energy and bioproducts can be piloted and realized for national benefit is provided.

1.2.4 Project team

The BIOSALIX concept emerged as a collaboration between SYLVIS Environmental, EPCOR Water Services Inc., Westmoreland Mining LLC., Bionera Resources, and Natural Resources Canada – Canadian Forest Service. This collaboration brought together expertise in beneficial residuals management, SRC willow establishment and management, SRC willow and carbon related research, and mine reclamation.

1.3 Project Objectives

At the onset of the project, four objectives were identified:

- Develop an innovative system for coal mine reclamation using SRC willows and municipal biosolids, which is valuable across all potential reclamation scenarios, but has additional value where mines are challenged by topsoil quality and quantity deficiencies.
- Address the needs of municipalities to find cost-effective and environmentally safe methods for beneficial use of biosolids and wastewater from municipal wastewater treatment systems.

- Achieve a carbon sequestration system through below ground (soil) carbon, while also producing valuable woody biomass, a change agent for the establishment of a renewable economy.
- Measure economic diversification to the local mining community as a result of the project.

These objectives and their associated performance metrics were consistently revisited with the lens of considering unforeseen challenges related to the global pandemic, the transition from coal powered energy production, and a series of extreme weather events. These challenges varied from regulatory review and approval delays to increased costs for operating safely due to a lack of available personnel and equipment resources. Despite these challenges, the project was moved forward safely with pivots to the operational schedule and activities to adjust to changing circumstances.

It became apparent during the 2021 field season that the willow establishment targets for the project would not be met. Establishment levels for the 2021 areas and retainment levels for the 2020 areas were flagged as areas of concern mid-season. At that time, less than 10% of the targeted plantation area was deemed as having strong potential for successful establishment and future growth.

An action plan was developed in late 2021 by the project team, engaging the expertise of the Steering Committee members to assess the status of the project and identify a path forward. The consensus of the group was that there is a lot of knowledge to be gained and potential value to fully capitalizing upon the lessons learned from the initial part of the project. The action plan included a no-cost two-year extension to facilitate achieving the pillars of a re-framed definition of success:

- Build knowledge about the implementation of SRC willow plantations in Alberta.
- Demonstrate operational capacity and replicability for areas of success.

1.4 Performance/Success Metrics

Progress towards the project objectives was measured using the following success metrics:

- Achieve approximately 500 hectares (ha) of reclamation on the mine site within the project timeframe.
- Utilize approximately 4,000 dry tonnes (dt) of biosolids per year in reclamation processes.
- Develop a system capable of achieving up to 190,000 t CO_2e soil carbon sequestration over a 30 year timeframe.
- Achieve approximately 12 local person-years of employment throughout the duration of the project (a person-year is defined as the equivalent of one person's full-time employment for one year. Twelve person-years means that the sum of employment would equal 12 full time employment opportunities for one year. Permutations of this might be 4 full time employees over three years, as an example.).

Two of the success metrics were modified for the project extension to the following:

- Achieve approximately 240 ha of reclamation on the mine site within the project timeframe.
- Develop a system capable of sequestering approximately 540 t CO_2e soil carbon per hectare (ha) of established plantation area over a 30-year timeframe.

1.5 Project Changes

Over the course of the BIOSALIX project, changes were made to respond to emerging challenges. Some of the key changes in the project plan are outlined below:

- Biosolids transport schedule was accelerated to align with changes in EPCOR's dewatering schedule.
- Planting targets were modified annually to make up for any shortfalls in previous years
- Planned equipment purchases were delayed allowing more time to select the best possible equipment to meet the project's needs. Additional equipment, such as a tine cultivator and rock picker were identified as important following challenges encountered during the first operational season.
- The most significant change within the project was the two-year extension and associated action plan. This included changes to two of the success metrics, as described in Section 1.4.
- Funds allocated for willow plantation establishment and ongoing plantation management work not completed were reallocated for preparing and turning over project areas to the landowner.
- Planned greenhouse gas verification and reporting was deemed unnecessary due to the deviations in execution of the project and unanticipated outcomes of willow plantation establishment. Similarly, the commercialization and technology transfer report was no longer relevant as there was no change in the technology readiness level.

The primary change of note in the composition of project team is the purchase of Bionera Resources Inc. by Groupe Ramo Inc. (Ramo) in the fall of 2022. This change was considered beneficial to the BIOSALIX project with the additional willow management experience and resources provided by Ramo.

1.6 Technology Risks

At the onset of the project, eight key risks were identified, ranked, discussed, and assigned mitigation measures.

1.6.1 Project feasibility

The tight timeframes required to conduct biosolids applications and complete planting each year was identified as a low likelihood risk. The assigned mitigation measure was the ability to shift the timeline to achieve project goals and outcomes as needed. The project team was confident with the track record by both SYLVIS and Bionera to be able to overcome obstacles to achieve project timelines.

This mitigation measure was utilized successfully to complete the biosolids application related outcomes, and to meet the overall planting targets for the project. One unforeseen aspect of the project feasibility risk assessment was integrating the mine's reclamation and soil placement activities with biosolids applications and willow planting. In some cases, biosolids applications and planting had to occur immediately after topsoil placement, which resulted in extremely soft and challenging ground conditions. Being able to complete planting in the target planting window was additionally challenged by weather conditions that impact both field trafficability and the soil conditions required for early willow establishment (also see climatic risk).

1.6.2 Regulatory risk

As the ability to apply biosolids for mine reclamation falls outside of Alberta's biosolids guidelines, and requires regulatory authorization, the risk of not receiving such authorization was identified as a low likelihood risk. The mitigation measure put in place was to obtain authorization prior to project commencement. SYLVIS relied on previously demonstrated success in the biosolids authorization process. The mitigation measure for this risk proved successful, as Paintearth Mine received authorization to utilize biosolids shortly before the planned start for biosolids transport, in June 2019. One unforeseen aspect of regulatory risk was the timeline for authorization of the subsoil demonstrations, which were authorized separately on a site-by-site basis. These took more time than planned and resulted in unanticipated project delays.

1.6.3 Climatic risk

Severe climatic events following willow planting, such as severe drought, heavy hail, and severe winter cold without snow cover were identified as low likelihood risks. Climatic risk was identified as one variable that could not be managed through operation care and due diligence. Any areas lost to severe climatic events would be replanted in the following year, where possible, or result in a decreased carbon sequestration potential for the project overall.

This risk became one of the primary reasons for failure in willow establishment, and an additional mitigation measure – irrigation was identified prior to the BIOSALIX extension. The ability to irrigate required the completion of regulatory and logistical steps; as a result, irrigation could not be utilized in time to mitigate the effects of drought during execution of the BIOSALIX extension.

Excessive or prolonged rain events, resulting in delays to biosolids application and planting was identified as medium likelihood. Mitigation measures for this risk were to provide additional equipment and operators for biosolids application. It was assumed that a mine reclamation setting would provide more flexibility for timing of applications compared to agriculture. The mitigation measures for this risk were successful in allowing for the completion of biosolids applications, but the risk assessment did not foresee the impact of rain on willow planting activities. Additional mitigation measures were put in place for this challenge, such as the use of a lighter planting unit for wet ground and diverting planting teams to gap planting and weed maintenance when unable to plant.

1.6.4 Technical risk

Technical risk was identified as low likelihood given the following: (1) proof-of-concept has been demonstrated through biosolids application to reclamation areas at the prescribed quantities on a smaller scale; and (2) willow biomass stock selection and planting has been demonstrated in past and current projects. Mitigation measures for this risk were to follow best management practices for the application of biosolids to land. One unforeseen aspect of this risk was the additional challenge of completing biosolids applications and willow planting in a mine reclamation setting in a drought-prone area, which added challenges related to both climate and soil conditions.

1.6.5 Pest incursion risk

The risk of pest incursion resulting in decline of willow health was identified as a low to medium likelihood risk. Mitigation measures for this risk included adding diversity to the system through planting multiple varieties of willow to add resilience to the overall plantation through genetic diversity. This mitigation measure appeared to be successful, as insect pests did not have a significant effect on plantation health. Unforeseen risks related to pest incursion included ungulate browsing and fungal pathogens, both of which added to cumulative stress on the plantation, particularly when environmental stressors, such as heat or low moisture were also present. Additional mitigation measures for dealing with cumulative stressors, which rely primarily on access to irrigation water, have been proposed, and are discussed further in this report.

1.6.6 Financial risk

Financial risk related to the high cost of establishing a willow plantation over and above standard reclamation practices was identified as a medium likelihood risk for mine sites. Mitigation for this risk included a comprehensive understanding of the costs of all components of the project through relatable experience. This mitigation measure was partially successful, with budgets increased to a certain degree but not sufficiently to overcome challenges during execution of planting. Additional planting funding was secured during the extension phase to facilitate implementation of lessons learned and knowledge gained during the initial phase of the project. Demonstration of the benefits of the system is required to be able to provide a positive business case to other mine sites.

1.6.7 Market adoption/commercialization risk

Market adoption and commercialization was identified as a risk with medium likelihood, and as the principal point of uncertainty in the project concept. Mitigation measures for this risk included research aspects within the project for market development, and by having advisors from regulatory, mining, and biosolids management sectors available to provide input on mechanisms to improve uptake. Although the market research indicated limited immediate market opportunities for willow biomass, market adoption and commercialization could not be pursued fully within the scope of this project due to the challenges related to willow establishment.

2 PROJECT WORK SCOPE

2.1 Technology Development, Installation and Commissioning

2.1.1 General project description

The original scope of the BIOSALIX project aimed to amend previously mined land with biosolids and plant an SRC willow crop on 500 ha of mine land over three years from 2019 to 2021. Paintearth Mine (PEM) is in Central Alberta, south of the Village of Forestburg, approximately 190 km from the City of Edmonton. The mine has a footprint of over 6,000 ha, consisting mostly of crop and grazing land. PEM is owned and operated by Westmoreland Mining Holdings LLC (Westmoreland), and its Canadian subsidiary Prairie Mines & Royalty ULC. This site was an active mine until March 2020 and continued to provide coal to the Battle River Generating Station until 2021. Currently, operations at PEM include mining of landfilled coal ash for cement fabrication and reclamation of previously mined land.

2.1.2 Regulatory

The use of biosolids to reclaim mine land is a relatively novel concept in Alberta, as most biosolids are applied to agricultural land, stored in wastewater lagoons, or composted. Prior to the commencement of the project, PEM amended its *Environmental Protection and Enhancement Act* operating approval to allow for use of biosolids in reclamation. This amendment allowed biosolids to be applied to topsoil following existing Guidelines for the application of biosolids to agricultural land. The use of biosolids at soil building rates, or as a feedstock in a fabricated soil, required additional approval from the Alberta Energy Regulator (AER) on a site-by-site basis. The BIOSALIX team submitted and received approval from the AER for three different demonstration sites over the course of the project.

2.1.3 Site selection and characterization

Potential project sites were identified by PEM, which included:

- historically reclaimed land with reclamation challenges such as lack of topsoil, or low organic matter and nutrients
- recently reclaimed land with placed subsoil and topsoil
- land undergoing reclamation, without placed subsoil and/or topsoil

All sites were characterized prior to commencement of operations to confirm suitability for biosolids and willow planting. Site characterization included the following activities:

- soil sampling and analyses for nutrients, organic matter, pH, salinity, and trace elements
- mapping of site features such as water bodies, slope, underground utilities, depressional areas, and operational hazards
- determination of biosolids application rates

2.1.4 Biosolids application

The biosolids used in this project were generated by EPCOR Water Services Inc. (EPCOR), one of the key project partners. Biosolids were transported to site in the summer and fall of each year from 2019 – 2021. The original project plan was to transport 4,000 dt per year over the three years, for a total of 12,000 dt of material. This schedule was accelerated to 6,000 dt per year over two years to better meet EPCOR's biosolids management needs. Additional to the project, another almost 3,600 dry tonnes were delivered and managed at the mine in 2021. Although not part of the funded project, these biosolids were intended to be used primarily for soil fabrication, to be able to meet one of the main project obligations to PEM. Due to a reduction in the size of available area for soil fabrication, the project team had to re-allocate biosolids to contingency areas. In all, over 62,000 bulk tonnes of dewatered biosolids were transported to PEM over the three years, which is equivalent to over 15,000 dry tonnes (dt) of biosolids.

Biosolids transported to the site were stockpiled prior to applying to land. In 2019 and 2020, not all biosolids transported could be applied prior to winter. These biosolids were overwintered in stockpiles and applied the following spring.

The location of all 2019 to 2021 biosolids application sites at PEM is shown in Figure A 1, Appendix A. The application type, area applied, and biosolids tonnage for 2019 through 2021 is summarized in Table 2.1, below.

Table 2.1: Summary of biosolids applications at Paintearth Mine from 2019-2021.

Year	Biosolids Application Type	Area (ha)	Total Biosolids Applied (dt)
2019	Topsoil Amendment	142.9	2,565
2020	Topsoil Amendment	431.8	6,999
	Subsoil Application	56.8	2,006
2021[b]	Topsoil Amendment	148.4	3,168
	Subsoil Application	11.0	332
	Subsoil Blend and Extend	6.4	685
Total		**797.3[a]**	**15,755**

a) Approximately 7.8 ha was applied twice, once in 2020 and again in 2021, in the West Pit Subsoil demonstration site as per the operational schedule.
b) Delivered and applied external to the funded project. For information only.

Biosolids were used in one of three ways:

- applied as a topsoil amendment
- applied directly to subsoil as an alternative to topsoil placement
- used as a feedstock in soil fabrication (subsoil blend and extend)

All sites that received biosolids as a topsoil amendment had been identified by PEM as having poor fertility or other challenges to meeting reclamation outcomes. Of these sites, 60% were planted with SRC willow. The remaining 40%, although not part of the BIOSALIX system, received the same reclamation benefits from biosolids and can be used as control areas to quantify the benefits of biosolids. Of the total biosolids applied, 12,732 dt were applied as a topsoil amendment to 723 ha of mine land.

An additional 2,338 dt of biosolids were applied directly to subsoil over 68 ha of mine land at two demonstration areas. Applications directly to subsoil demonstrated the ability of biosolids to build subsoil into topsoil. These demonstration areas were implemented in late 2020, with willows planted in 2021. These demonstrations are described in more detail in Section 2.2.3.

The remaining 685 dt of biosolids were used to fabricate a blended subsoil, also referred to as subsoil blend and extend. The soil fabrication portion of the BIOSALIX project was implemented in 2021, one growing season later and smaller than intended due to regulatory and logistical challenges. The blended subsoil demonstration area will not be planted with SRC willow. Subsoil fabrication was identified as an opportunity to add direct (via addressing subsoil quality and quantity deficiencies outlined in the mine closure plan) and indirect (via the development of best practices for operational scale soil blending) value to mine reclamation and carbon sequestration activities on site. In total, 2,900 m^3 (685 dt) of biosolids and 3,300 m^3 of woody biomass were mixed with 15,000 m^3 of subsoil, resulting in a 29% reduction of required subsoil volume in the blend and extend site.

Overall, biosolids were applied to nearly 800 ha of land at PEM for the purposes of enhancement of reclamation. Over 630 ha were reclaimed as part of the funded project. This exceeds the project target of reclaiming 500 ha of land by 26%.

2.1.5 Willow planting and stand management

The original project target was to plant and establish a 500 ha SRC willow plantation within the project's 3-year timeline. The original planting targets and the actual gross planted areas for the first three years of the project are summarized in Table 2.2.

Table 2.2: Planned and actual areas planted with SRC willow for 2019 – 2021.

Year	Target Area (ha)	Planted Area (ha)
2019	80	60
2020	220	191
2021	256	253
TOTAL		**504**

Note: Target areas were set at the start of each planting year to meet a total of 500 ha plantation. The original planting targets for 2019 – 2021, respectively were 80 ha, 210 ha, and 210 ha.

Each year of planting encountered unique challenges related to weather, site conditions, and personnel availability. Although planting did not meet targeted areas in 2019 and 2020, planting targets were adjusted each year to maintain the trajectory of 500 ha total plantation area, and the lessons learned in each planting year were applied in the subsequent years. Overall, the BIOSALIX project met the target of 500 ha of planted area, but some of this area includes willows that were tilled under and replanted in subsequent years due to poor survival.

Plantation survival was assessed at the end of each growing season. Plantation areas with poor survival and low prospects for canopy closure were tilled under and prepared for replanting.

Plantation management to achieve retention was a major barrier for the plantation contractor. Over the first three years, a total of 504 ha was planted, with a gross area of approximately 60 ha retained at the end of 2021 for future management (Figure A 2, Appendix A).

Several key challenges were identified that impeded plantation success in the first three years of the project, which included the following:

- The COVID-19 pandemic had unforeseen impacts requiring additional planning and protective equipment, as well as regular changes to safety policies and procedures.
- There was difficulty hiring and retaining skilled and unskilled staff due to the remote location and seasonal nature of the work, resulting in knowledge gaps and inadequate management and planning.
- Willows were planted late in the growing season, which reduced their chances of surviving the winter into the second growing season.
- Insufficient resources, both labour and equipment were devoted to weed management in newly planted and second-year plantation areas. Once weeds proliferated within a plantation, they became impossible to manage without tilling under the whole area.
- Willows planted in 2021 were subject to an extreme heat wave shortly after planting, which led to the failure of much of the planted area that year.

At the end of 2021, the BIOSALIX team developed an action plan to plant 150 ha from 2022 – 2023, with a focus on plantation establishment and retention by applying the lessons learned during the first 3 years. A total of 156 ha of willow was planted during this 2-year period (Table 2.3).

Table 2.3: Planned and actual areas planted with SRC willow for 2022 – 2023.

Year	Target Area (ha)	Planted Area (ha)
2022	50	37
2023	90	119
TOTAL		**156**

Promising results were seen in the first year of the extension, with 21 ha of the 37 ha planted surviving into their second growing season. In 2023, spring drought, in combination with other stressors, led to mass failure of over 100 of the 119 ha planted that year. To date, approximately 50 ha of plantation is currently classified as surviving, but much of this is fragmented, with heterogeneous willow density and growth, and distributed across the mine site (Figure A 3, Appendix A).

2.2 Methodology

The BIOSALIX project enabled many opportunities for research and monitoring, which occurred over the course of the project. The following sections describe the primary research activities conducted over the course of the project. The results of these research and monitoring activities will be discussed in Section 2.3.

2.2.1 Soil amendment environmental monitoring

In addition to the site characterization carried out prior to biosolids applications, SYLVIS conducted an environmental monitoring program involving post-application soil sampling one year following applications. Post-application monitoring was carried out at all sites with biosolids applied as a topsoil amendment in 2019 and 2020. Wherever possible, samples were collected from within 5 metres of pre-application soil sampling locations to facilitate comparison between the two datasets. Samples were analyzed for pH, nutrients, and trace elements.

2.2.2 Stockpile monitoring study

Stockpiling is critical for the operational efficiency of dewatered biosolids land application. Typically, biosolids are stockpiled on a portion of a field that is to receive biosolids amendment, but during wet weather, these fields may not be accessible for transport trucks delivering biosolids. Stockpiling biosolids on an all-weather pad allows transport to continue uninterrupted. SYLVIS conducted a stockpile monitoring study to provide the regulator with data on the potential for environmental impacts of stockpiling biosolids on an all-weather pad.

The all-weather stockpile (AWS) at PEM was constructed on compacted overburden and treated road stabilizers to desiccate clay platelets and allow the soil to settle, harden, and seal. The products are biodegradable and use the natural clay in the soil as the binding agent.

Soil sampling was conducted to monitor the environmental impacts of storing biosolids at the AWS. Samples were analyzed for constituents that could be indicative of biosolids (nutrients, trace elements). Baseline samples were collected in June 2019, prior to any biosolids being stockpiled at the site. Biosolids were stored in the stockpile through 2019, and it was fully emptied by May 2020.

Two follow-up soil sampling events were completed in 2020. Samples were collected up to a depth of 40 cm. Deeper samples could not be collected due to the compacted nature of the AWS pad.

2.2.3 Subsoil demonstration monitoring

Biosolids can be applied directly to subsoil as an alternative to topsoil placement. Once vegetated, the amended subsoil can develop the same characteristics as topsoil over time. Biosolids are applied at higher than agronomic rates to add sufficient organic matter to encourage this process. This reclamation technique has been demonstrated successfully at other mine sites but has never been done in conjunction with willow biomass establishment. This reclamation technique was implemented in two areas at PEM in combination with the BIOSALIX process, referred to here as the subsoil demonstration areas. Research and monitoring were conducted in these areas to test different application rates, and consecutive applications over multiple years, on soil development, vegetation survival and growth, and downslope water quality.

The first subsoil demonstration area is a 32 ha site known as Section 13/18. Biosolids were applied in 2020 at three application rates: 25 dt/ha, 50 dt/ha, and 75 dt/ha, with willows planted during the 2021 operational season. Site monitoring included water sampling from the end-pit lakes directly downslope of the authorization area, vegetation growth and survival assessment, and soil sampling for two growing seasons following biosolids applications. Willows were planted in the first year of the trial but had very poor survival. The willows were not replanted, and vegetation monitoring could only be completed for one growing season.

The second of the subsoil demonstration areas is a 24.8 ha site known as West Pit Subsoil (WPSS). The site was divided into different treatment areas, which received either a single biosolids application at 25 dt/ha, or two applications of biosolids at 25 dt/ha over consecutive growing seasons. Biosolids were applied in 2020 and 2021. Willows were planted in the first year of the trial, and then turned under and replanted in the second year due to poor survival. Monitoring activities in WPSS included soil sampling and vegetation monitoring for two growing seasons following biosolids applications. To assess the success of the WPSS demonstration monitoring was also conducted at an adjacent reference site, known as Section 15, which received topsoil addition and biosolids.

2.2.4 Subsoil and biosolids blending

An alternative reclamation practice using biosolids is to fabricate soil by blending biosolids with other materials, typically a mineral feedstock, and a feedstock with a high carbon to nitrogen (C:N) ratio, such as woodchips. Precise feedstock ratios can be used to design a soil that meets the needs of a particular site. Fabricating soils with biosolids is a common practice in other areas but has never been implemented on a mine site in Alberta.

As PEM has identified a need for suitable subsoil for reclamation, a pilot project was developed to extend subsoil resources by blending subsoil with biosolids and woody biomass, fabricating a “blended subsoil” that meets reclamation quality requirements. PEM received regulatory approval for this demonstration in April 2021 for an area of the mine known as the East Pit. Research and monitoring were developed to test the quality and capability of the blended subsoil against standard suitable subsoil and to test the effectiveness of different operational methods.

Following an initial site assessment, PEM identified a 6.4 ha area that would be operationally feasible to carry out the subsoil blending activities, while the remaining 22.7 ha in the East Pit area would undergo standard reclamation and serve as a large control area.

Operational activities commenced in May 2021, with subsoil delivered in windrows to the project area. Due to poor site conditions, windrow dimensions exceeded the operational capabilities of the windrow turner originally intended for use in the project. The 6.4 ha site was separated into three treatment areas with alternative subsoil blending methodologies.

Prior to blending, feedstocks were sampled at a rate of one composite sample per 5,000 m^3 to monitor quality and to adjust the mix ratio as needed. In the first treatment area, biosolids and woody biomass were bucket mixed with windrowed subsoil using a front-end loader. The mixed windrows were leveled with a bulldozer. The approximate blend ratio (by volume) was 1:1.1:5 (biosolids: woody biomass: subsoil). Following leveling, the area was worked with an agricultural tillage disk to further mix the material.

For the remaining area, subsoil windrows were levelled prior to biosolids and woody biomass deliveries. The remaining feedstock material was surface applied in lifts, alternating biosolids and woody biomass, and incorporated with the levelled subsoil using agricultural tillage equipment. The blend ratios for these two areas were 1:1.2:5 (1.8 ha) and 1:1.1:5.5 (2.3 ha) (biosolids: woody biomass: subsoil).

The blended subsoil was sampled at a rate of one sample per 5,000 m^3 of material and compared to the mine's subsoil quality standards. The site was topsoiled and seeded with an agricultural crop in the spring of 2023. Preliminary monitoring of soil and vegetation was completed in late summer 2023, and PEM will conduct final monitoring on the success of the trial as part of their standard reclamation monitoring activities.

2.2.5 Biomass market analysis

As a part of the BIOSALIX initiative, SYLVIS approached Innotech Alberta's Bio-Industrial Research & Development (BIRD) team to conduct an independent third-party evaluation of end-use opportunities for willow biomass produced at PEM. This study explored market opportunities for bioenergy, biorefinery, biochemical, and bioproduct applications of willow biomass. In simple terms, the study aimed to answer the following question: *What product(s) could economically be produced from the willow biomass grown at the BIOSALIX project?* Several metrics were identified to determine if an opportunity was economically viable for the BIOSALIX project: (1) a market for the biomass is immediately available; (2) the end user is close to the BIOSALIX site in Forestburg to reduce transportation costs; (3) the end user would take most, or all the annual biomass produced; and (4) the purchase price would exceed or offset BIOSALIX production costs.

With these metrics in mind, the BIRD team conducted a broad literature scan to determine the industrial and commercial sectors in which woody biomass in general, and willow biomass specifically, is used. Following the broad scan, a detailed description of potential opportunities in each of the sectors was developed from the literature. Each opportunity was ranked using an analytical hierarchy approach to help guide the selection of opportunities for future integration into the BIOSALIX initiative.

2.2.6 NRC-CFS research

Researchers from the Natural Resources Canada – Canadian Forest Service (NRC-CFS) Northern Forestry Centre (NoFC) and the Canadian Wood Fibre Centre (CWFC) led the research aspect of the BIOSALIX project. Research was conducted in four key areas: growth and yield monitoring, insect and disease monitoring, cumulative carbon assessments, and expansion of biomass projects to other communities. Annual project reports from NRC-CFS are found in Appendix Three.

Growth and yield monitoring was conducted by the CWFC at the PEM site starting in 2019. Fifty plot locations were established in 2019 to assess willow growth and biomass production for a 3-year period. These plots were established in tandem with carbon soil sampling points to measure above- and below-ground carbon biomass. All plots were impacted by either weed control or retreatment of the planted area due to poor performance, which reduced the number of plots from

50 to 35 in 2020. Height and diameter of the tallest stem in each plot, along with the number of live and dead stems for each plant were recorded. Biomass samples were collected at the end of each successive growing season, starting in 2020. Because the PEM plantation was still in its infancy in 2019, willow assessments were also conducted at well-established plantations located in Keoma, Ohaton, and Beaverlodge, Alberta. The data collected from all four sites will be used to inform future willow variety selection and contribute to total cumulative carbon estimates on site. In addition to growth and yield plots, common garden planting trials were initiated at PEM and the Keoma plantation. Sixteen willow clones were planted at each location on soils treated with and without municipal biosolids. The common garden trials were also initiated to inform future willow variety selection and quantify the effects of geographic location and site on willow clone performance.

For the second component, NoFC researchers travelled to the Keoma and Ohaton willow plantations in 2019 to conduct insect and disease surveys, with all surveys cancelled in 2020 due to the COVID-19 pandemic. In 2021, less intensive surveys were carried out at Keoma, Ohaton, Beaverlodge, and Paintearth. In 2019, NoFC researchers assessed insects, pathogens, animal pests, and abiotic factors affecting tree health via visual inspections of 13 willow clones at the Keoma site and 4 clones at the Ohaton site. For each willow clone, three or four replicates, from a total of 100 trees, were individually assessed for general overall health and for signs and symptoms of disease agents. Trees were scored on a six-point scale for overall health, and a five-point scale for the severity of the agents/conditions affecting the trees (Table 2.4). The goal is to aid practitioners in identifying insect and disease pests that could affect plantation integrity and performance and, subsequently, help to ensure practitioners employ the appropriate management and mitigation strategies.

Table 2.4: Health and severity scales used to assess willows for insects, disease, and other conditions at Ohaton and Keoma plantations in 2019.

Scale[a]	Overall Health	Severity
0	0% affected (perfect health)	-
1	1-25% affected	trace (1-5% affected)
2	26-50% affected	light (6-25%)
3	51-75% affected	moderate (26-50%)
4	75-99% affected	heavy (51-75%)
5	100% affected (dead)	severe (76-100%)

a) Scales obtained from the Canadian Forest Service CGP BIOSALIX Project Report 2019.

In 2021, surveys were conducted at the plot level instead of individual stem surveys. Plots were scored on the same scale as in 2021, based on detailed visual inspections. This provided overall plot scores as in 2019, but with out measures of variance.

The third component of the NRC-CFS research involved cumulative carbon assessment of SRC willow plantations used in conjunction with municipal biosolids application for coal mine reclamation and improvement of marginal soils. In this research, carbon is assessed via three major pools: biomass (above- and below-ground), litter (particularly for deciduous species) and soil organic matter. Carbon monitoring parameters are selected to measure and monitor carbon indicators reflecting stored carbon pools, transfers, inputs, and losses at each site (Table 2.5).

Table 2.5: Carbon monitoring parameters used and frequency to be measured at each site.

	Parameter	Method	Frequency
Biomass	Above-ground Biomass Components (Mg C ha^{-1} y^{-1})		
	Planted Tree Volume (m^3/ha)	Calculated using counts, width, and associated expansion factors	Annual
	Below-ground Biomass Components (Mg C ha^{-1} y^{-1})		
	Root Production (kg C/m^2)	Estimated – using species specific root:shoot and expansion factors based on aboveground biomass	Annual
Dead organic matter	Litter (kg ha^{-1})	Measured – Litter Traps 0.5 m^2 (four each per plot), total organic carbon from LECO total carbon combustion to CO^2 and analysis by infrared detector	Annual
Soil	Soil Organic Carbon (Mg CO_2e ha^{-1})	Measured – Bulk Density and total organic carbon from LECO total carbon combustion to CO_2 (0-30 cm)	Baseline and at the end of study
Respiration	Total Soil Respiration (Mg CO_2e ha^{-1})	Excluded as this parameter is difficult to calculate over time with reasonable certainty	N/A

Note: Table obtained from the NRC-CFS BIOSALIX Project Report 2019.

A total of 162 and 94 sampling points were sampled in 2019 and 2020, respectively, prior to biosolids applications to quantify baseline soil carbon pools. Further sampling was conducted in 2021 following biosolids applications. Growth and yield data collected by researchers performing willow assessments were used to quantify above-ground biomass. NoFC and CWFC researchers' aim is to determine the impact on soil carbon and the total cumulative carbon (CO_2 equivalent) within these plantations. This work will also provide a basis for determining and developing quantification protocols under the Alberta Regulatory framework.

The fourth aspect of this research program involved exploring the potential for increasing the regional wood biomass supply to expand the biomass nexus created by the BIOSALIX project. NoFC and CWFC researchers determined potential communities of interest within a 100 km radius of PEM for establishing short rotation willow plantations as a mechanism for processing of municipal sewage wastewater. All lagoon treatment systems within a 100 km radius of the mine were identified, and associated communities were approached to explain the concept of wastewater irrigated willows and determine their interest in pursuing this as a wastewater utilization strategy. This has the potential to reduce community wastewater treatment costs and the impacts of mine closure by producing additional biomass for the PEM woody biomass hub.

2.2.7 Improvements in willow establishment and management

Bionera investigated the failure-to-thrive of the 2023 planted areas with a focus on ascertaining what, if any, impacts the following factors may have played:

- salinity in soils
- insects (i.e., cutworm damage)
- herbicides (i.e., chemical damage)
- pathogens (i.e., bacterial or fungal damage)
- climate (e.g., drought)

A collaborative investigation with NRC-CFS was completed to identify evidence of insect damage in the failed plantation areas. The results of this investigation concluded that no evidence of inspect damage was present, and that the most likely cause of the shoot damage was from herbicide splash during heavy rains. Following initial testing of soils and vegetation, and analyses of local weather patterns, an establishment trial was implemented with the purpose of replicating the outcomes observed following willow planting and determining factors meaningfully contributing to those outcomes. From August 14 – 16, 2023, four plots each were established in two different fields that had willow establishment failures. Each plot was 2.7 m long by 9.9 m wide and had a 10 m buffer from adjacent plots. Within each field, one plot was a control while the other three received various herbicide treatments. Within each plot, rooted and unrooted cuttings, treated and untreated with fungicide, and various willow varieties were represented. All plots were irrigated regularly (e.g., during planting and on weekly or as-required basis) while herbicide applications were completed on August 17 and fungicide applications on August 22.

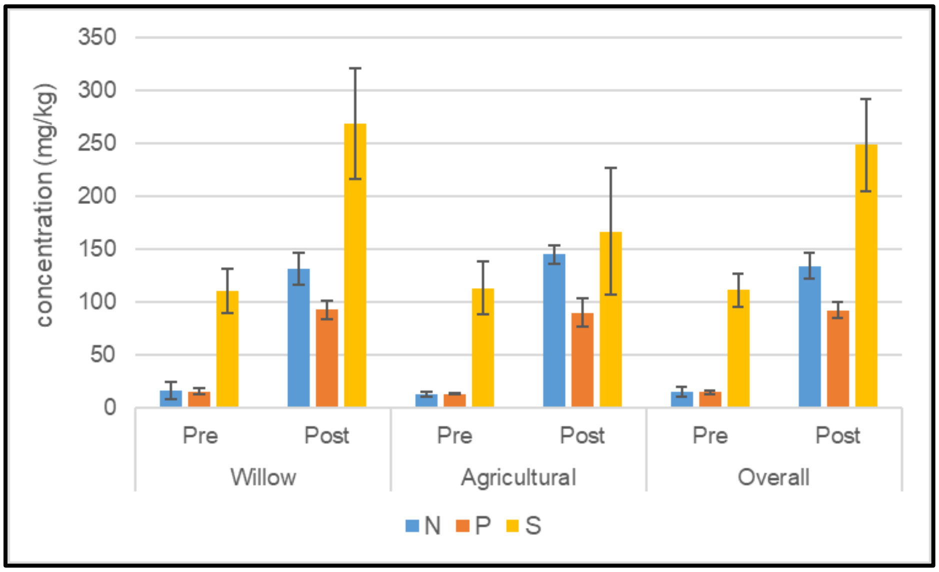
Trial disadvantages, including the late summer timing and 5-week duration of the trial were identified; however, the potential value of collecting preliminary data regarding factors negatively influencing willow establishment was deemed to outweigh the trial weaknesses.

2.3 Results

2.3.1 Soil amendment environmental monitoring

Soil samples collected before and one growing season after biosolids applications in the willow sites and agricultural control sites indicated an eight-fold increase in available nitrogen and a five-fold increase in available phosphorous in the top 15 cm of soil (Figure 2.1). These results were consistent in both the willow sites and the agricultural sites. The concentration of available sulfate-S increased by about 1.2 times following biosolids application, but this change only appears to be significant in the willow fields and not the agricultural fields.

Figure 2.1: Average available nutrient concentrations of nitrate + ammonium-N (N), phosphorous (P), and sulfate-S (S) in soil pre- and one growing season post-amendment with biosolids at Paintearth Mine. Error bars represent standard error of the mean.



2.3.2 Stockpile monitoring study

Results from the follow-up sampling conducted at the AWS in 2020 are presented by sampling depth in Table 2.6. These results were compared to the baseline data to determine whether there were any significant changes in soil nutrient concentrations or soil salinity following stockpiling activities.

Table 2.6: Select mean soil nutrient and salinity parameters analyzed in the stockpile monitoring study.

Constituent	Baseline Sampling			Follow-up Sampling			Units
	0 – 15cm	15 – 30cm	30 – 60cm	0 – 15cm	15 – 30cm	30 – 40cm	
Salinity							
Electrical Conductivity	3.45	4.22	2.75	5.53	6.22	NR	dS/m
pH	8.00	8.0	8.5	7.80	7.5	NR	pH
Nutrients							
Total Nitrogen	0.14	0.10	0.10	0.15	0.13	NR	%
Total Phosphorous	481	468	456	440	460	NR	µg/g
Available Nutrients							
Ammonium – NH_4^+	0.5	< 0.5	2.0	5.2	0.5	NR	µg/g
Nitrate – NO_3^-	3	4	3	9	13	NR	µg/g
Phosphorus	< 9	6	5	< 5	< 5	NR	µg/g
Potassium	197	206	230	221	183	NR	µg/g
Sodium	1,746	2,237	2,677	3,390	2,200	NR	µg/g
Chloride	7.5	6.0	6.0	9	12	NR	µg/g

Note: NR=Not Reported. Soil conditions did not allow for sample collection at this depth.

Some minor increases in nitrogen concentrations (total N, ammonium-N, nitrate-N) were observed in the follow-up data. This variance is expected due to the difference in nitrogen content between material, i.e., biosolids versus mine spoils. However, there is no leaching to depth, with total nitrogen concentrations increasing by only 0.01 and 0.03% in the 0 – 15 and 15 – 30 cm depths, respectively. Other nutrient concentrations (total and available phosphorous, total and available potassium, available sulphate, calcium, and magnesium) did not increase from the baseline levels.

Follow-up sampling also showed an increase in salinity levels, with electrical conductivity (EC) and available chloride concentrations increasing at the 0 – 15 cm and 15 – 30 cm depths, as well as available sodium concentrations showing a slight change in the 0 – 15 cm depth. These minor changes may be related to the surface soil treatments applied to the AWS, which contain mineral and chloride compounds.

Auger refusal in the AWS, at 40 cm below ground surface, during follow-up sampling demonstrates the presence of a compacted layer that would limit infiltration and downward movement of nutrients. This further supports that none of the changes from background levels indicate an increase in environmental risk due to the stockpile activities within the AWS.

Given the results presented, the monitoring study was successful in demonstrating that stockpiling of dewatered biosolids at the PEM within an all-weather stockpile, undertaken in accordance with best management practices, is protective of the environment.

2.3.3 Subsoil demonstration results

The results of the Section 13/18 Subsoil Demonstration indicate that biosolids can upgrade unsuitable subsoil for use as either topsoil or subsoil by reducing the sodium adsorption ratio (SAR) and adding organic matter (Table 2.7). Biosolids additions can also increase available nitrogen and phosphorous in the soil from a deficient range to a high range for at least the first growing season following applications. The addition of biosolids did increase the electrical conductivity of the soil (EC), but the effect appears temporary as EC began to decrease after the second growing seasons. Biosolids additions also did not result in any significant accumulation of trace elements in the soil.

Due to extreme heat and drought shortly after willow planting in 2021, the site had little to no vegetation uptake of nutrients throughout 2021 and early 2022, which may have led to movement of nitrate-N into the deeper soil layers in the 75 dt/ha treatment area, and to an increase in nutrients in the end-pit lakes adjacent to the site. Under these extreme circumstances, the assumptions for nutrient removal by vegetation could not be met at the higher application rates.

The results of this trial support the use of biosolids amended subsoil as an alternative to topsoil placement for reclamation. Recommendations for future implementation include the use of subsoil with lower salinity, particularly when applying biosolids at higher rates, and to ensure that vegetative growth is established after application to keep the soil covered, avoid soil erosion, and ensure vegetative uptake of available nutrients to avoid nutrient loss or movement off site or through the soil profile. In a willow system, this could be done using an annual crop as a tool to utilize excess nitrogen during the first growing season of willow growth, or alternative management practices. Larger buffers from sensitive water features and ensuring that these buffers are fully vegetated may further mitigate the risk of nutrient movement into downslope water bodies. With these additional mitigation measures in place, biosolids applications directly to subsoil at the rates used in this trial can be a useful and environmentally protective tool for solving reclamation challenges.

Table 2.7: Average soil quality criteria and soil quality rating[a] in the 0 – 15 cm profile across all treatments in Section 13/18 before and after biosolids applications. The bolded rating indicates the overall, or most limiting, soil rating for each sampling event.

Year	Organic Carbon (%)	Texture[b]	EC (dS/m)	Saturation (%)	SAR	pH
Topsoil Ratings, Plains Region						
Good	> 2	L, SL, SiL	< 2	30 – 60	< 4	6.5 – 7.5
Fair	1 – 2	CL, SCL, SiCL	2 – 4	20 – 30, 60 – 80	4 – 8	5.5 – 6.4, 7.6 – 8.4
Poor	< 1	LS, SiC, C, S, HC	4 – 8	15 – 20, 80 – 120	8 – 12	4.5 – 5.4, 8.5 – 9.0
Unsuitable			> 8	< 15, > 120	> 12	< 4.5, > 9.0
Pre-Application						
2020	1.13 *Fair*	SCL *Fair*	4.99 *Poor*	77 *Fair*	15.1 ***Unsuitable***	8.1 *Fair*
Post-Application						
2020	1.44 *Fair*	SCL *Fair*	6.47 *Poor*	78 *Fair*	15.9 ***Unsuitable***	8.1 *Fair*
2021	2.05 *Good*	SCL *Fair*	7.77 ***Poor***	65 *Fair*	11.5 ***Poor***	7.8 *Fair*
2022	1.60 *Fair*	SCL *Fair*	5.80 ***Poor***	58 *Good*	9.4 ***Poor***	7.7 *Fair*

a) Criteria for evaluating suitability of topsoil in the Plains Region, from Table 6 of Soil Quality Criteria Relative to Disturbance and Reclamation.

b) L = loam, SL = sandy loam, SiL = silt loam, CL = clay loam, SCL = sandy clay loam, SiCL = silt clay loam, LS = loamy sand, SiC = silty clay, C = clay, S = sand, HC = heavy clay

The results of the West Pit Subsoil monitoring indicate that subsoil amended with biosolids can provide similar outcomes for soil quality and willow growth as topsoil amended with biosolids. In particular, the addition of biosolids to subsoil increased the concentration of available nutrients from deficient or marginal to adequate for crop growth. Biosolids addition did not contribute to significant accumulation of trace elements in the soil, and did result in small, but not significant, reductions in soil SAR. The biosolids amended subsoil had no negative impact on willow establishment and growth as compared to biosolids amended topsoil (Table 2.8). The biosolids amended subsoil had a lower quality standard as compared to the amended topsoil, but still met criteria to be suitable for use as a topsoil.

Table 2.8: Average willow height and survival percentage in the WPSS subsoil demonstration area and an adjacent topsoil area. Due to low survival in 2021, willows were replanted in 2022.

Year	Site	Application Rate	Survival (%)	Average Height (m)
2021	Subsoil	25 dt/ha	31.1	0.04
	Topsoil		21.3	0.27
2022	Subsoil	25 dt/ha	72.0	0.36
		50 dt/ha	63.8	0.32
	Topsoil	25 dt/ha	23.2	0.16

2.3.4 Subsoil and biosolids blending results

The blending methods used in subsoil and biosolids blending activities were a result of operational constraints associated with the site itself. The windrow turner, which was initially slated to be used in the project, was proven to achieve the best texture and quality material. A crucial lesson learned from this project, specifically, was the necessity for proper windrow sizing and relatively level and dry site conditions. Nonetheless, the subsoil blending activity at PEM was successful in achieving the desired results, even with the challenges presented and the alternate blending methodologies used.

The subsoil blend and extend activity demonstrated that a blended subsoil can be used as a reclamation alternative by meeting quality standards and extending existing subsoil resources on site. Results from the blended subsoil samples indicate that the material achieved quality targets, including pH within an optimal range of 6.5 – 8.5, trace elements below 75% of regulatory soil limits, and SAR and EC within suitable ranges for reclamation soils.

Overall, a total of 15,002 m^3 of subsoil, 2,900 m^3 of biosolids, and 3,300 m^3 subsoil were placed over the 6.4 ha demonstration area at an optimal placement depth of 0.33 m. Using standard reclamation, a total of 20,790 m^3 of subsoil would be required to achieve the same depth. Blending the subsoil with biosolids and woody biomass resulted in a 29% reduction in the required subsoil volume.

2.3.5 Biomass market assessment

Innotech Alberta's BIRD team identified a full suite of end-use opportunities for willow biomass produced at the PEM site. Four broad categories, or sectors, were identified for willow end-use. These include Biofuels, Forest Products, Bioproducts and Specialty Products. Within these sectors, 16 potential product opportunities were also identified, including wood chips, wood pellets, liquid and gaseous biofuels, pulp and paper, lignin, biochemicals, wellness and personal products, and several others.

With all options identified, the BIRD team created a prioritized list of short-and medium-term opportunities for the BIOSALIX biomass using an analytical hierarchy approach. Based on the opportunity scan, solid biofuels (wood chips and wood pellets) offer the two most viable short-term opportunities that can be efficiently implemented into the BIOSALIX project initiative within

3 to 5 years, as existing end-users are within a relatively short distance from the plantation and would likely be able to take the full annual production.

Gaseous biofuels, liquid biofuels, and biochar were the three most viable medium-term opportunities, as potential end-users exist for these opportunities who are currently using alternative sources. These opportunities could be implemented in 5 to 10 years, as further discussions would be required to determine whether they would be willing to use willow biomass in their processes. These potential end-users, both of which are biofuel plants located in Slave Lake and Edmonton, are currently in construction and demonstration phases, respectively.

In addition to the opportunities scan, the BIRD team provided suggestions for next steps for commercializing the PEM biomass. These suggestions included contacting potential end-users, such as ranches, zoos, biofuel facilities, municipalities, and counties that may be interested in purchasing the bio-products, as well as monitoring new developments in markets and industries in Alberta and beyond on a continuous basis. Additionally, suggestions were made to help to increase the marketability of the biomass products and raise awareness of the BIOSALIX project in Alberta and more broadly.

While there are few end-use options in the vicinity of PEM today, the presence of a large-scale source of woody biomass could spark the development of new industries in the future that offer higher, better uses for woody biomass.

2.3.6 NRC-CFS research

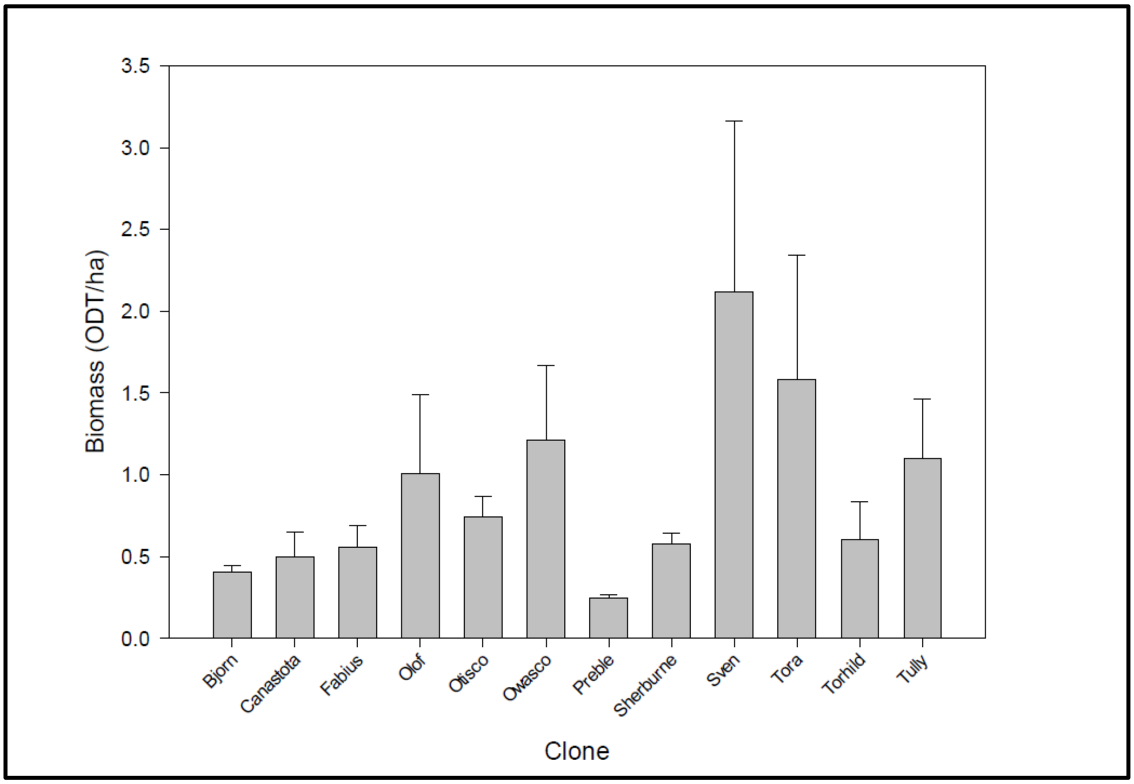
The following section will summarize key findings in two of the four components related to the BIOSALIX project, where NRC-CFS was able to report results.

Growth and yield data collected in 2019 and 2020 at PEM reveal that Sven and Tora varieties produce the most aboveground biomass, while Preble was consistently found to have the lowest biomass values. Of the established stands at PEM, the two that appear to have the most growth are Preble, which may indicate that the low biomass varieties are more suited to the conditions at PEM. Figure 2.2 summarizes average biomass for the 12 clones surveyed at PEM in 2020.

Stocking levels were also compared between 2019 and 2020, which indicated a significant reduction in stocking for all clones at PEM. However, some of this is likely attributed to researchers having to re-establish plots in 2020. Nonetheless, all clones show poorer performance after the first year, with an overall average stocking level of 63% in 2020, down from 84% in 2019.

In addition to PEM data, supplemental biomass data were collected at the Keoma plantation to infer expected 3-year-old harvestable biomass yields at the PEM site and identify high biomass production clones. The data revealed that Preble, with its moderate height and diameter values, performed the best due to its abundance of both live and dead stems. The report also indicated that stocking levels at the Keoma plantation were consistently high, with an overall average of 88% in 2020 and 83% in 2019. NRC-CFS researchers indicated that higher stocking levels can ensure higher productivity of clones of smaller stature and can subsequently improve yields of taller and larger diameter clones. The number of stems per plant, however, does not necessarily indicate high biomass yields.

Figure 2.2: Average biomass (oven-dry tonnes - ODT/ha) of live stems per plant by clone at Paintearth in 2020 planted in 2019 (error bars indicate standard error). Figure obtained from the NRC-CFS BIOSALIX Progress Report 2020.



Due to late and varied planting timing of the common garden trials, only 4 plots planted at the Keoma and PEM sites in 2020 had good establishment. Much of this was due to the timing of planting. It was also noted that more weed pressure was observed in the biosolids treated areas, which may be an indirect effect of biosolids application and a contributing factor to poor growth. As a result, all four common gardens were replanted and surveyed in 2021. Personal communication with the NRC-CFS researchers indicates that the common garden established at the Ohaton site in 2021 has 97% survival, while the PEM garden has 65% (with biosolids fertilization) and 69% (without biosolids fertilization). The researchers indicated that lower success rates at the PEM site are due to browsing by deer and pronghorn. As with the challenges associated with establishing and maintaining the overall willow plantation at PEM, long-term survival of the common garden could not be achieved. The installation of a new common garden was attempted in 2023, but this area was part of the over 100 ha of planted area that failed in early 2023.

The 2019 insect and disease surveys from the Keoma and Ohaton plantations revealed a total of 1 stem disease agent, 31 insect and mite pests, 5 vertebrates, and 3 abiotic agents, with more species of pests found at the Keoma plantation than the Ohaton plantation. These higher pest counts at the Keoma plantation were likely due to the more extensive surveys carried out at the site given the higher variety of clones present.

The most abundant disease noted at both the Keoma and Ohaton plantations was the Cytospora canker. It was also noted as one of the most severe and serious agents affecting the willows. Additional investigative work was carried out by a separate group of NRC-CFS researchers at the Keoma plantation in 2020, which revealed that over 50% of stems in four of the seven clones surveyed were killed by Cytospora infection.

In 2021, 3 stem disease agents, 42 insect and mite pests, 3 vertebrates, and 3 abiotic agents were found across four sites surveyed (Keoma, Ohaton, Beaverlodge, and Paintearth). The highest diversity of pest was found in Keoma, as in 2019, which is most likely due to the higher diversity of willows and larger extent of surveys. Cytospora canker continued to be the most important disease agent identified across all sites surveyed in 2021.

2.3.7 Improvements in willow establishment and management

Initial exploration of the suspected factors indicated that soil salinity played a role in establishment outcomes, with a salt concentration of 400 parts per million (ppm) or higher assessed as uninhabitable at the project site. In collaboration with NRC-CFS, Bionera assessed that insects were not contributing factors to the 2023 failure-to-thrive as cutworms (the main suspected culprit) were not found in the soil in any stage of development. Observations on the remaining factors of herbicides, pathogens, and climate were obtained from the establishment trial.

Bionera replicated the main observation of the 2023 failure-to-thrive to some extent in both trial fields: planting stock that has developed roots and shoots with the shoots terminating and shrivelling at the ground surface (Photograph 12, Appendix B).

The preliminary results from the trial indicated that, while the difficult conditions encountered at the mine likely contributed to a general difficulty in rooting, moisture is a main limiting factor at the site; there is a cost to plant vitality of using pre-emergent herbicide to control weeds; and that pathogen influences are mitigated by fungicide. For fungicide application, it was noted that the two different pre-emergent herbicides trialled selectively mitigated mortality depending upon the fungal pathogen present in the soil. Overall, these factors were noted as being part of a larger pool of cumulative stressors impacting plantation establishment outcomes. Solutions identified as having a strong potential to positively influence establishment outcomes include:

- ensure water availability prior to planting in the climate at the project site
- assess sites for pathogens when completing site characterization
- adjust the timing of pre-emergent applications to take place prior to planting
- treat cuttings to increase pathogen resistance
- use rooted cuttings and revert to mechanical management of weeds until willows are thriving in climate-stressed conditions

2.4 Project Outcomes

Objective 1: Develop an innovative system for coal mine reclamation using SRC willows and municipal biosolids, which is valuable across all potential reclamation scenarios, but has additional value where mines are challenged by topsoil quality and quantity deficiencies

The BIOSALIX project demonstrated proof-of-concept for an innovative mine reclamation system using short-rotation coppice willows and municipal biosolids; however, the full-scale operational implementation of the concept could not be achieved due to challenges related to the establishment and survival of the SRC willows.

The success metric for this objective was to achieve 500 ha of land reclaimed, with a concurrent goal of that area being converted to willow plantation on a gross plantation area basis. While the project reached 800 ha of land that achieved enhanced reclamation with biosolids, and achieved over 500 ha of willows planted, the current estimate for surviving plantation area upon completion of the project is less than 10% of the target. The multitude of contributing factors include those from outside the project team's control (e.g., higher temperatures or drier soil conditions) as well as some from within the project team's control (e.g., planting time or weed management by the willow contractor). Key learnings related to these factors and the risks to willow plantation establishment at an operational scale are described in Section 4.1.

Objective 2: Address the needs of municipalities to find cost-effective and environmentally safe methods for beneficial use of biosolids and wastewater from municipal wastewater treatment systems

One success metric of this objective was to utilize approximately 4,000 dt of biosolids per year in the reclamation process. This metric was met and exceeded: 6,000 dt of biosolids per year were used in reclamation in 2019 and 2020, and an additional 3,672 dt was utilized in 2021 for the subsoil blend and extend demonstration and agricultural fields. The project addressed the need of EPCOR to find a cost-effective and environmentally safe method for beneficial use of biosolids.

Objective 3: Achieve a carbon sequestration system through below ground (soil) carbon, while also producing valuable woody biomass, a change agent for the establishment of a renewable economy

The success metric for this objective was to develop a system capable of soil carbon sequestration of up to 190,000 t CO_2e over a 30-year timeframe. This metric has not been met but has been demonstrated that it is possible at a per hectare basis, even slightly exceeding the originally projected per-hectare sequestration estimates. Further details on carbon sequestration are provided in Section 5.1.

Objective 4: Measure economic diversification to the local mining community as a result of the project.

The success metric for this objective was to achieve approximately 12 person-years of employment throughout the duration of the project. The success metric was met and exceeded, as 21 person-years of employment were created from 2019 – 2021 (Table 2.9).

Table 2.9: Total hours of direct employment and equivalent person-years for the BIOSALIX project from 2019-2021. A person-year is calculated based on a 40-hour work week over 52 weeks.

Job Description	2019		2020		2021	
	Hours	Person-Years	Hours	Person-Years	Hours	Person-Years
Project Manager/ Qualified Professional	1,733	0.9	3,209	1.6	4,245	2.1
Environmental Technician	1,946	1.0	2,190	1.1	1,952	1.0
Equipment Operator/ Maintenance	1,557	0.8	6,373	3.1	2,721	1.4
Field Supervisor	1,517	0.8	2,298	1.2	3,392	1.7
Skilled Labour	1,700	0.9	3,585	1.8	3,257	1.6
Total	8,453	4.4	17,655	8.8	15,567	7.8

The potential for economic diversification was measured in a report produced by the Canadian Forest Service. This report analyzed two scenarios for possible replacement of economic activity due to closure of the mine. The first scenario includes the economic impact of the BIOSALIX pilot project undertaken in 2019 and 2020, with the second scenario calculating the potential income generated if the project were to replace the mine entirely. Using 2016 sector dependence census data, as well as employment information supplied by SYLVIS, the current pilot program replaces 8.3% of economic activity generated by the mine, while a full replacement of the mine site would generate up to 30% of economic activity and employ 13 full-time workers over the 30-year lifespan of the willow crop.

Though not a full replacement, this is still recognized as a substantial benefit, given the relatively small total economy generated by the region. Other complementary activities on the mine site, such as the mining and processing of historically stored fly ash operated by ASHCOR Technologies, would also contribute to new economic activity. If most employees are based in the village of Forestburg, this project offers a strong improvement for the village's local economy, specifically. Furthermore, given that mine reclamation is a necessary process, this project provides both environmental and economic benefits to the mining community, while simultaneously achieving reclamation targets. Additionally, the added value of using biosolids as a nutrient source and providing quality worker training are appreciable assets not included in the above scenarios. The NRC-CFS report indicates that training employees could be a means of furthering future economic diversification in other similar operations.

Objective 5: Build knowledge about the implementation of SRC willow plantations in Alberta in order to demonstrate operational capacity and replicability

The final success metric was developed as part of the action plan within the project extension, which included revised success metrics for the objectives that were not achieved within the core project. These revised success metrics were to achieve approximately 240 ha of reclamation on the site with SRC willow, and to develop a system capable of sequestering approximately 540 t CO2e soil carbon per hectare of established plantation area over a 30-year timeframe.

The successful establishment of the 2022 plantation areas utilizing the proposed establishment and weed management prescriptions demonstrated that the knowledge gained, and lessons learned can lead to success.

To date, less than 50 ha of surviving plantation is present across the mine site, which includes a combination of legacy areas planted prior to the extension, 2022 surviving areas, and small areas of 2023 willows. Although the projections for CO_2 sequestration on a per hectare basis still stand, this objective has not been met as the project could not demonstrate long-term survival of the plantations beyond the second growing season, the remaining willow area is small and fragmented, and the additional management does not meet the original assumptions for the projections.

3 COMMERCIALIZATION

At project onset, the Technology Readiness Level (TRL) was set between 7 and 8. The purpose of the BIOSALIX project and the planned size and scope was to achieve operational efficiencies and be able to achieve TRL 9 for full implementation by project completion. The primary system need to achieve technology readiness was the specific combination of biosolids management and willow establishment in a mine reclamation setting, and at an operational scale.

TRL advancement could not be achieved for this project, primarily due to being unable to meet success at the requisite scale needed for commercialization. The small areas of success achieved from the 2022 planted areas indicate that advancement may still be possible, but the challenges in 2023 shed light on additional risks to success that were not fully understood at the onset of the project. Additional mitigation measures such as irrigation, use of rooted cuttings, and/or fungicide have not been tested at scale, and the overall impact of these measures on the financial feasibility of the BIOSALIX concept is uncertain.

The lessons learned over the course of the BIOSALIX project have clarified that the technology was at TRL 7 at commencement, and that the current TRL remains at 7.

4 LESSONS LEARNED

4.1 De-risking of SRC Willow Establishment

One of the key lessons learned within BIOSALIX is that establishing SRC willow on marginal lands has many inherent risks to long-term success. These challenges are best summarized in three overarching categories of lessons learned: site selection, cumulative stressors, and project timeframe.

4.1.1 Site selection

Sound site selection and preparation is a key factor in successful willow establishment. There are numerous site-related factors that will impact the timing, duration, and success of planting, as well as the survival and establishment of the planted cuttings.

- Stressors such as high salinity, high pathogen load, or a prolific weed seed bank can have the greatest impact on establishment.
- Mine sites have unique site challenges, such as poor soil quality due to changing reclamation standards, poor soil stability on freshly topsoiled sites, presence of rocks and boulders that result in equipment damage and planting delays.

The key recommendation related to site selection is to complete intensive site characterization to understand the stressors and challenging conditions present and take them into consideration during planning and execution of plantation establishment.

4.1.2 Cumulative stressors

There are numerous, interrelated stressors for willow establishment. These can be related to site characteristics or environmental conditions.

- Weed competition can significantly affect establishment, and weeds become more difficult to manage if not dealt with early during establishment.
- Moisture timing and amount is particularly critical and has cascading impacts that need to be controlled for.
- Even under optimum moisture conditions, warm soil can impact rooting success, and promote the growth of soil-borne fungal pathogens.
- Chemical weed management, particularly the use of pre-emergent herbicide, will result in some increased mortality and reduced health of newly planted cuttings.
- Browsing by ungulates is an additional stressor that can be difficult to control for in large plantations.

When multiple stressors are present concurrently, this can result in mass failure to thrive. As moisture appears to be the main limiting factor for establishment success, the key recommendation for managing cumulative stressors are as follows:

- Ensure adequate moisture is accessible when required. Access to irrigation is necessary under potentially hot and dry climates.
- Willows should not be planted in soils where the salt content exceeds 400 ppm
- Planting should occur under cool, moist conditions, if possible.
- Weed control is essential early in the season and needs to be maintained to reduce competition. Eliminating perennial grass load is particularly important.
- Two broad-spectrum burn-down herbicide applications should occur prior to spring pre-planting tillage and bed preparation.
- Sites should be assessed for pathogens prior to selection. In areas where fungal pathogen load is high, the use of fungicide or rooted cuttings significantly improves the outcomes of establishment.

- Pre-emergent herbicide, which was previously prescribed immediately after planting to improve is effectiveness, will result in less stress on willows if applied before planting and after willows have hardened off in the fall.
- Under climatically stressful conditions, mechanical weed management should be prioritized over chemical until willows are thriving.
- End of season plantation mowing followed by a fall application of pre-emergent herbicide demonstrated success in lowering weed pressure in the second year after establishment.

4.1.3 Project timeframe

The limitations of working within the Alberta growing season mean that any setbacks in establishment can postpone project success by a year or more.

- There is a narrow planting window that optimizes sufficient growth of willow biomass to ensure winter survival.
- The planting window is sensitive to weather events; planting cannot occur under saturated soil conditions, and hot and dry conditions at planting time can prevent establishment of cuttings or exacerbate other stressors.
- There is a narrow window to initiate effective weed management immediately after planting and at the start of the second growing season, which is critical to willow survival.
- Establishing and managing large areas of plantation requires intensive staffing over a relatively short period of time, this level of staffing can be difficult to achieve consistently from year to year.

Any future projects should consider a longer time frame for project development including operational validation and plantation establishment, e.g., 10 years instead of 3 years, with more modest annual planting targets, e.g., 30 – 50 hectares per year. This will allow for iterative collection of knowledge and application of lessons learned across growing seasons, while also reducing the risks associated with unusual conditions, for example, extreme climatic events.

4.2 Use of Biosolids in Mine Reclamation

The BIOSALIX project was an opportunity to utilize several different biosolids reclamation techniques at an operational scale on a mine site in Alberta, with positive reclamation outcomes for mine sites challenged with topsoil or subsoil shortages, or poor quality topsoil on legacy reclaimed areas. Regulatory and operational key learnings are as follows:

- Reclamation with biosolids presents a suite of equipment and techniques that are fundamentally different from typical operations at a mine site. Mine operators can be hesitant to work with biosolids if they are unfamiliar with the material. Obtaining buy-in from the mine operators by explaining in detail the nature of biosolids and the goal of the process can increase operational efficiency, improve record-keeping, and enhance on-site safety culture.

- The authorization process to allow biosolids use outside of current guidelines (e.g., the subsoil demonstrations and subsoil and biosolids blending) can take a lot of time and represents a significant uncertainty for biosolids management projects on mine sites. Authorizations should be developed as early as possible. Any mine that chooses to utilize biosolids as an alternative to topsoil or subsoil placement must have a demonstrated shortage of suitable topsoil or subsoil.
- A windrow turner is ideal for blending feedstocks together into a consistent, high-quality soil, but requires placed windrows to have specific dimensions, which may be difficult to produce using large rock trucks or on uneven or soft terrain.

5 ENVIRONMENTAL BENEFITS

5.1 Emissions Reduction Impact

The main greenhouse gas verification component of the project was the baseline sampling scope-of-work completed by NRC-CFS. The intention was to complete a comprehensive baseline sampling campaign and return 10 years later for follow-up sampling to calculate both the direct and indirect carbon sequestration in the BIOSALIX system. The baseline sampling was completed early in the project with both sampling and lab analyses impacted by the COVID-19 pandemic.

At the close of the 2019 – 2021 phase of the project, the NRC-CFS baseline analyses were not available, so SYLVIS carefully evaluated available data with a focus on aligning procurement and post-application sampling for biosolids applications with existing willow areas to assess the direct carbon sequestration potential due to biosolids additions to mine soils. While the reduced number of samples, short timeframe over which samples were collected, and non-linear progression of project areas along the BIOSALIX concept timeline were noted by the team at SYLVIS, the analyses indicated a 0.4% and 0.3% increase in the mean (geometric mean) soil organic carbon in the topsoil (0 – 0.15 m) and upper subsoil (0.15 – 0.3 m), respectively (Table 5.1). Assuming a soil bulk density of 1.4 t/m^3, and repeated applications of biosolids every three years, this increase corresponded with a predicted direct sequestration of 540 t CO_2e per hectare over a 30-year timeframe. This projection was higher than the per hectare forecast at project commencement of 380 t CO2e, but the project did not have sufficient established willow area to achieve the targeted intensity of 190,000 t CO2e soil carbon sequestration over a 30-year timeframe.

Table 5.1: Average changes in soil organic carbon, and respective tonnes of CO_2e from 0 – 15 cm and 15 – 30 cm depths on BIOSALIX project sites amended with biosolids.

	Pre-Application (2019)			**Post-Application (2020)**			**Change**
Layer	TOC (%)	SD (%)	t CO_2e/ha	TOC (%)	SD (%)	t CO_2e/ha	t CO_2e/ha
0 – 15 cm	2.9%	0.4	223.3	3.3%	0.4	254.1	30.8
15 – 30 cm	2.4%	0.8	184.8	2.7%	0.7	207.9	23.1
Sum	-	-	**408.1**	-	-	**462**	**53.9**

Note: SD = standard deviation. Calculation of t CO_2e assumes an average soil bulk density of 1.4 t/m^3.

Some limitations of these preliminary calculations include an assumed average soil bulk density, a low sample size per unit area, and an assumption of linear increase in soil carbon over time with repeat biosolids applications. Also missing from the projections is the contribution of the willow biomass crop to soil carbon sequestration over time through litter deposition and fine-root turnover.

As the current remaining willow plantation areas are not suitable for ongoing management with repeat biosolids applications due to their limited size and fragmented nature, these per-hectare sequestration projections cannot be applied for this project. Furthermore, additional management activities not originally planned within the system, such as early coppicing of willows, additional tillage and re-planting of the same areas add confounding factors to the sequestration projection. Therefore, the BIOSALIX project will not be able to achieve the projected GHG reductions, and any further verification will not be pursued within the context of this project.

Although this project could not achieve any meaningful GHG reductions, these preliminary data suggest that significant carbon sequestration within this system is possible upon successful willow establishment at a suitable scale to allow for biosolids management and willow harvesting at the intended 3-year cycle. This is a significant knowledge contribution for funding bodies that may evaluate future applications for similar projects. Specifically, proposal assessors may confirm that the magnitude of targeted outcomes aligns with scale of the project, appropriate risks and mitigation strategies are identified for fostering willow plantation establishment success, and research and sampling plans for carbon sequestration verification are incorporated to further advance understanding of this aspect of plantation establishment. It also provides a real-world, operational-scale comparative, and prairie-climate-specific estimate for results from other projects.

5.2 Other Environmental Impacts

The BIOSALIX project was the first of its kind in a mine reclamation context and its execution provided important information for successful implementation of such projects on mine sites.

BIOSALIX provided a regulatory pathway for other mine sites to implement similar projects. The results of the all-weather stockpile monitoring study, for example, provided regulators with data to support that permanent biosolids stockpiles, when constructed to selected specifications, can be used over subsequent years without any downward migration of nutrients or trace elements towards groundwater. The results of the subsoil application and subsoil blending demonstration monitoring programs will inform regulators on the benefits and environmental protectiveness of these types of biosolids applications on other mine sites.

The immediate results of the subsoil blending demonstration has already led to the initiation of a similar project at another Alberta mine site. The operational lessons learned from this project can be applied to this, and future projects.

6 ECONOMIC AND SOCIAL IMPACTS

In addition to the employment outcomes described in Section 2.4, the project has had the following benefits:

- Biosolids applications to the agricultural crop fields on the mine site improve soil fertility, which can subsequently improve yields and reduce fertilizer costs to the farmers operating on the mine site.
- The blend and extend activity has verified that a mine can reduce their reclamation soil volume requirements by 29% by blending subsoil with biosolids and woodchips.

7 SCIENTIFIC ACHIEVEMENTS

7.1 Presentations and Conference Showcases

- 10th Clean Energy Ministerial and 4th Mission Innovation Showcase. Exhibitor.
- ERA Spark 2019. BIOSALIX: Growing Carbon Positive Ecosystems, Transforming Reclamation Challenges, Creating Clean Growth Opportunities. October 30, 2019.
- BioFest 2021. Visionary Restoration Narratives: Tools That Solve Bigger Problems Than Our Own. September 21, 2021.
- WEF Residuals and Biosolids Conference. Techniques in Restoration and Reclamation of Surface Mines Achieve a Powerfully Layered Narrative of Benefit for Municipal Biosolids and Mines Alike…So What's Stopping Us? May 26, 2022.
- Canadian Biosolids and Residuals Conference. Reimagining Mine Reclamation with Willows, Biosolids, and Climate Change Mitigation: The BIOSALIX Story. September 18-21, 2022.
- BC TRCR Mine Reclamation Symposium. Mine Reclamation to Achieve a Narrative of Layered Co-Benefit. September 22, 2022.
- CLRA Alberta Chapter AGM & Conference. Beneficial Use of Municipal Biosolids in Reclamation to Achieve Co-Benefits for Mines and Municipal Biosolids Generators. February 24, 2023.

7.2 Reports

- Natural Resources Canada. Clean Growth Program BIOSALIX Project Progress Report 2019. June 26, 2020.
- Natural Resources Canada. Clean Growth Program BIOSALIX Project Progress Report 2020. April 14, 2021.
- Innotech Alberta. SRC Willow Biomass Value Proposition Final Report. November 12, 2021.
- Natural Resources Canada, Pest surveys of willow plantations in central Alberta, 2019 and 2021 – Final Report. June 2022.
- Natural Resources Canada. 2023. Investigation Report: Damaged Willow Shoots at Ramo Paintearth Plantation.

8 OVERALL CONCLUSIONS

The primary outcome of this project was a proof-of-concept for the BIOSALIX system in mine reclamation. Results from this project will inform regulators and mines on best practices for using biosolids in reclamation. They will also provide information to future project teams and proposal reviewers regarding the scope, risks, challenges, and potential for similar projects. The subsoil blending portion of the project demonstrated that residuals such as biosolids and woodchips can be used to reduce the quantity of soil required for reclamation by nearly 30%. This concept can be applied at other mine sites facing shortfalls of topsoil and/or subsoil. The BIOSALIX project was also able to collect important socio-economic data on the implications of such projects to communities if implemented at a larger scale.

The BIOSALIX project met its core objective of diversifying biosolids end-use for mine reclamation. It provided proof-of-concept for establishing SRC willow on mine land reclaimed with biosolids that can sequester 540 tonnes of CO_2e on a per hectare basis over the lifetime of the plantation.

Despite the knowledge gained and lessons learned, the project was unable to bring the concept beyond the initial TRL of 7. If anything, the project helped shed light on multiple critical challenges associated with willow establishment in the mine reclamation context within Alberta.

The project fell well short of its original goal of a 500 ha SRC willow plantation established over three years, with only 50 ha of dispersed and varied-density willow plantation area remaining at the end of 2023. Multiple challenges affected this success metric: extreme weather events, cumulative and previously unidentified biological stressors, limited staff and resource availability due to the global pandemic, and early coal mine closure were the primary factors.

The BIOSALIX project has economic, environmental, and social benefits. The project resulted in the equivalent of 21 full-time jobs over the course of its initial three years. It has demonstrated an economic alternative to soil importation for mines with soil shortfalls for reclamation and has also demonstrated an alternative biosolids end-use for major generators in Alberta. The socio-economic benefits within the local community include the opportunity to subcontract or rent equipment to the project, and reduced fertilizer costs and improved soil quality for the agricultural control areas. In addition to the carbon sequestration potential, the project has the added environmental benefits of improved soil quality and fertility, and recycling of nutrients and organic matter.

The key learnings from this project were related to de-risking the willow establishment process. From the initial three-year phase of the project, more modest annual planting targets, dedicated resource allocation to both planting and weed management, and adjustments to weed management and planting techniques and timing were among the key learnings. The extension added key learnings of increased timelines for these sorts of projects, impacts of complex cumulative stressors on willow establishment, and additional requirements for site characterization for the climate and mine site conditions encountered during this project.

Overarching takeaways from the project are:

- Biosolids amendments are an effective tool for supporting positive reclamation outcomes.
- It is feasible to advance the technology readiness level of the BIOSALIX concept, but more time is required.
- Execution of the extension activities allowed for identifying critical stressors impacting willow establishment outcomes.
- The plantation establishment outcomes reflect the circumstances of this project and should not be broadly applied to other sites and projects looking to explore or advance a similar concept.

8.1 Next Steps

The unanticipated outcomes for the willow plantation at the end of 2023 have necessitated changes in planned follow-up activities upon project completion.

- The 2024 operational season, which was to focus on maintenance of established willow plantation, and particularly the stands planted in 2023, has been removed from the scope-of-work for the BIOSALIX project.
- Funds received for establishing plantation area (i.e., planting and maintaining) that will not be completed will be reallocated to preparing and turning over all BIOSALIX project areas to Westmoreland in 2024. The project areas without established area will be turned over in Spring 2024. The areas with willow will remain in place through the 2024 growing season and a decision regarding their fate will be made thereafter.
- Comprehensive GHG reporting and verification will not occur because deviations in execution of the project (e.g., additional tillage and multiple plantings in some areas) and outcomes (e.g., heterogenous willow cover in established plantation areas) do not allow for claiming against the initial project assertions or verification of the carbon sequestration potential of the concept.
- Commercialization and technology transfer reporting will not be applicable as the anticipated increase in technology readiness level during the course of the BIOSALIX project did not occur. The BIOSALIX concept has not yet been fully realized and any future building upon lessons learned will take place outside of this project with different project proponents, funding, and scopes-of-work.

Follow-up reclamation projects at other mine sites, utilizing biosolids and organic residuals, are being developed based on the outcomes of the biosolids demonstration projects at Paintearth Mine. Planning and regulatory authorization at two mines sites in Alberta has been completed, with operational work anticipated in 2024.

9 COMMUNICATIONS PLAN

Knowledge dissemination for the project has occurred as part of the conference attendance, external reports and media mentions described in Section 7. Due to the small amount of established plantation area and the standing plan to return all project areas to traditional reclamation trajectories, it is not anticipated that there will be future developments and outcomes to communicate. SYLVIS and Bionera, as key project partners, have agreed either party receiving a media or other query regarding the project will address the query and inform the other key partner. Any unanticipated developments or outcomes will be captured in required post-project reporting for the funding bodies.

APPENDIX A – FIGURES

Figure A 1: Overview of BIOSALIX biosolids application sites showing areas applied in 2019-2021.

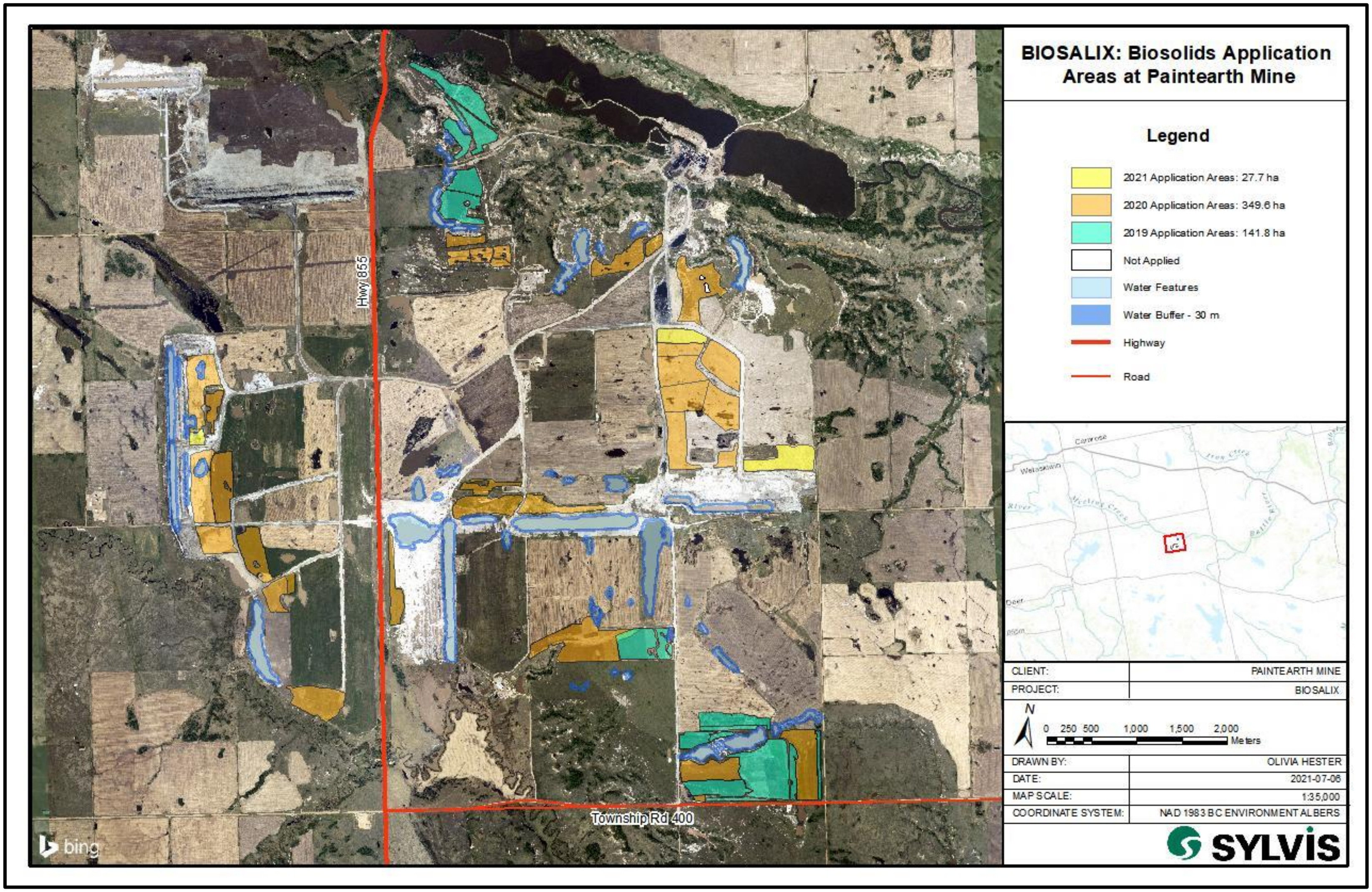


Figure A 2: Overview of BIOSALIX willow plantation area by year as of the end of 2021.

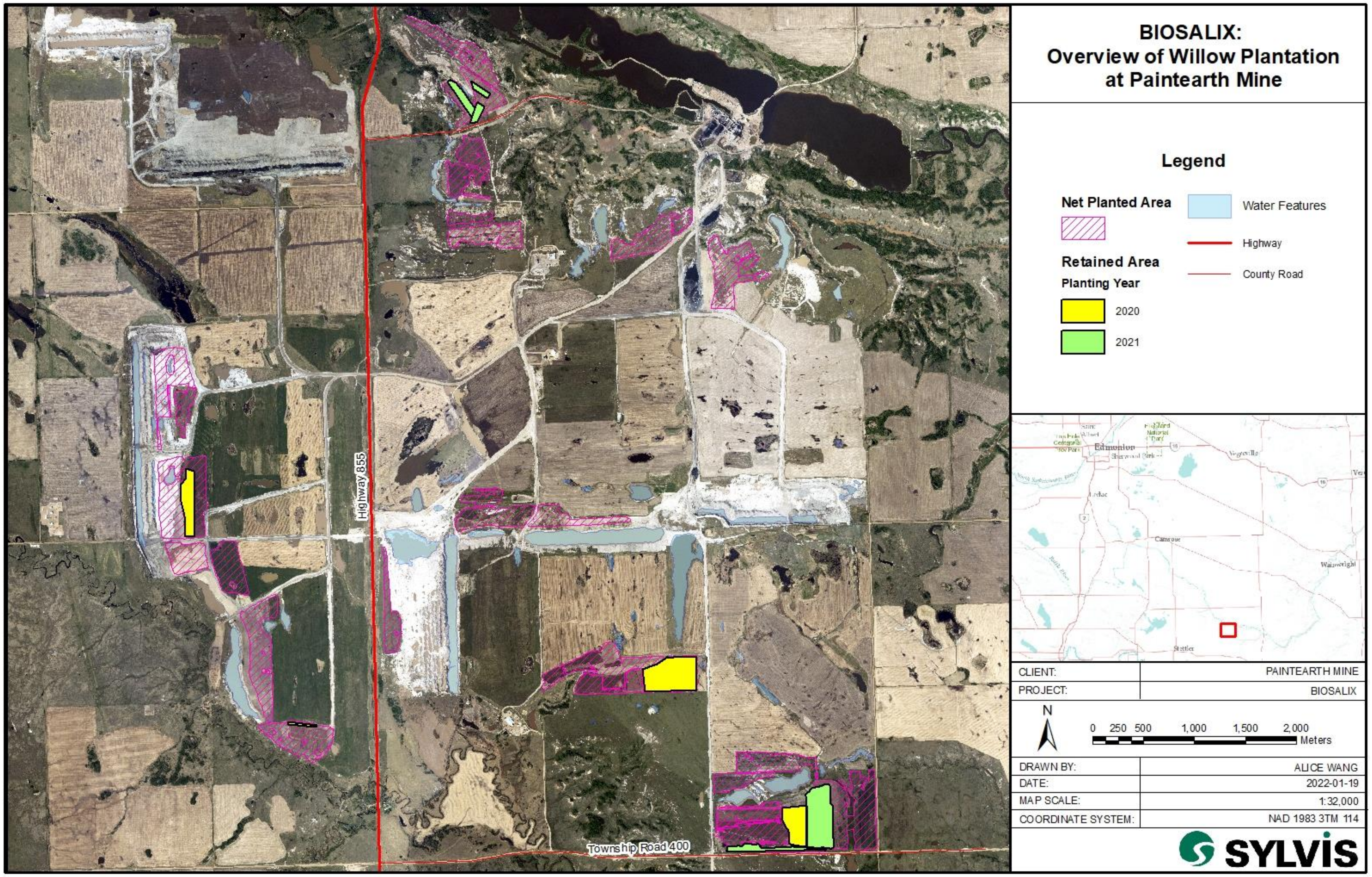
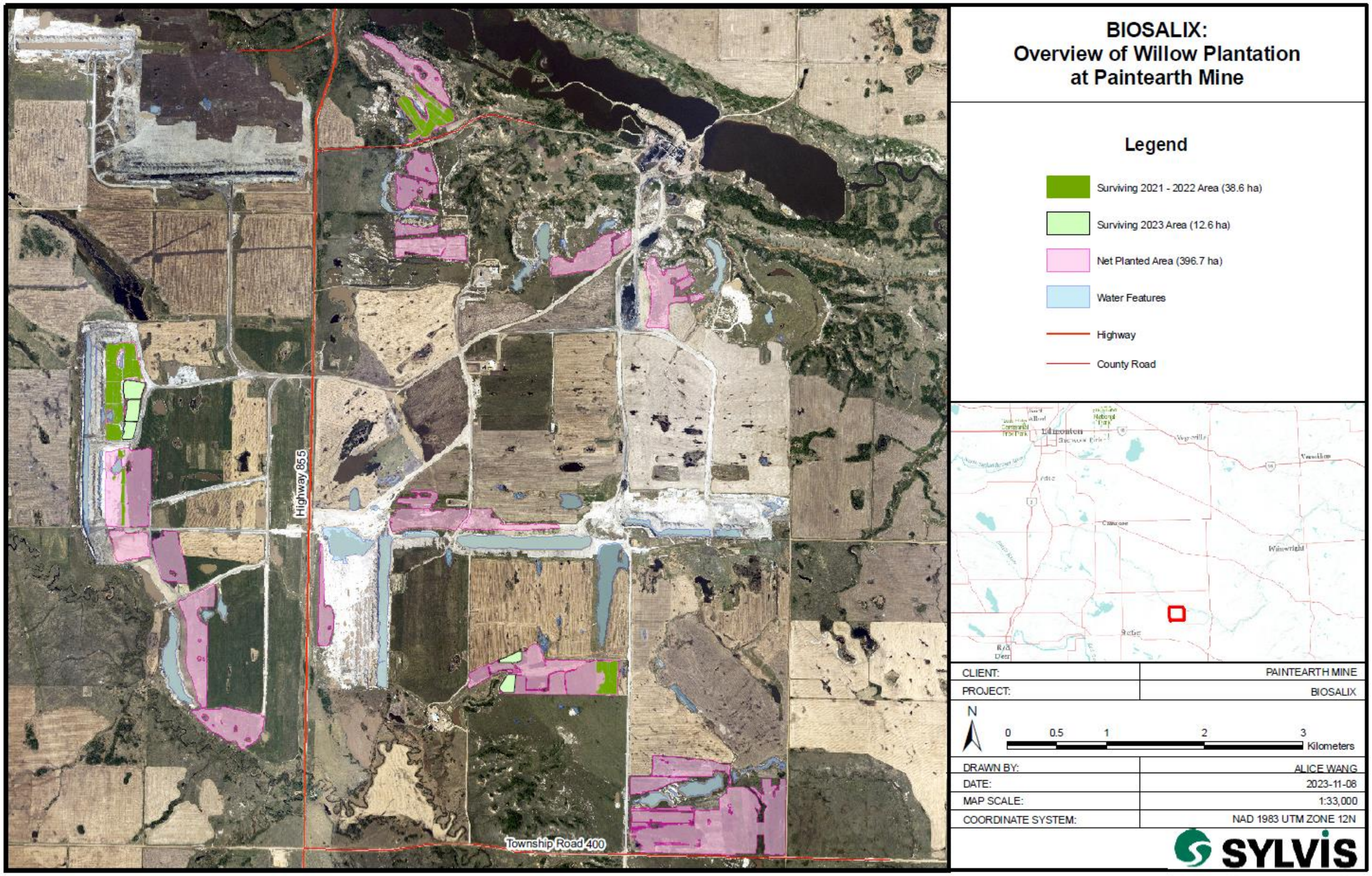


Figure A 3: Overview of BIOSALIX willow plantation area as of the end of 2023.



APPENDIX B – PHOTOGRAPHS

Photograph 1: Biosolids were applied and incorporated to amend over 800 ha of land at Paintearth Mine. This included historically reclaimed land that did not meet current reclamation standards. (August 2019)

Photograph 2: Biosolids were applied directly to subsoil as an alternative to topsoil placement. The organic matter and nutrients from the biosolids support vegetation growth, allowing the subsoil to develop into topsoil. (June 2020)

Photograph 3: Operational testing of the Frontier Soil Turner, one of the tested mixing techniques for the subsoil blend and extend activity. (September 2021)

Photograph 4: A planting crew operating an Egedal planter, which inserts willow whips vertically into the ground and cuts off a length of approximately 8 inches to create a billet. Approximately 1-2 inches of the billet is left protruding above the surface. (June 2021)

Photograph 5: The BIOSALIX willow billet planters, the first of their kind in North America, were piloted for the project. This planter lays the willow billets flat in the base of a furrow which is then covered with soil. (May 2021)

Photograph 6: Rows of healthy willows after their first season of growth. They range in height between 0.4 and 1.2 metres at this stage. (September 2020)

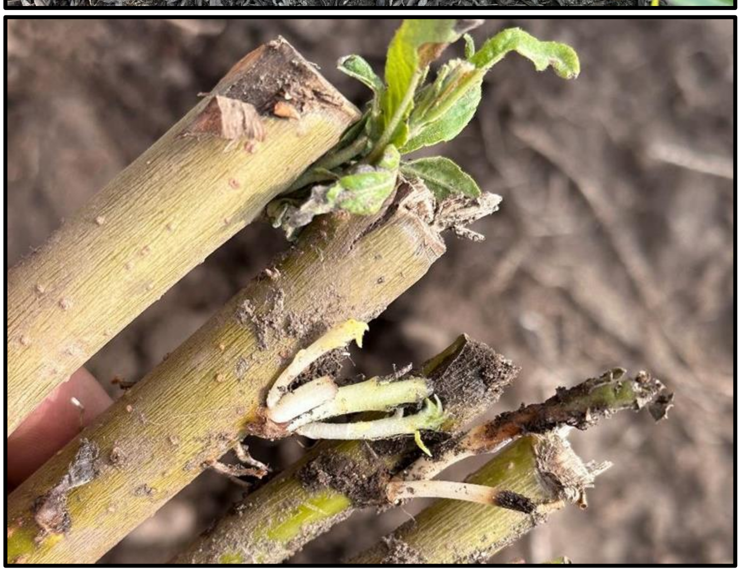
Photograph 7: An Emissions Reduction Alberta (ERA) video shoot to highlight the project as part of its web video series on game-changing activities in Alberta. (March 2021)

Photograph 8: Grazing by wildlife such as pronghorn, mule deer, and rabbits were one of the detrimental factors affecting willow establishment. (April 2021)

Photograph 9: Heat and low moisture conditions were an issue during the 2021 planting season. Billets planted during this time were scorched when exposed at the surface with successful shoots only noticed emerging from depth. (August 2021)

Photograph 10: A thriving stand of willows with effective weed control at the end of its first growing season during the project extension period. This demonstrates the outcomes of implementing early lessons learned about planting and weed management prescriptions. (September 2022)

Photograph 11: A leaf litter layer in a willow stand during its second growing season. Litter layer development is a key step in the BIOSALIX concept as soil develops with the addition of nutrients and organic matter. (August 2023)



Photograph 12: Failure-to-thrive symptoms for willow stock planted during the 2023 season. Roots and shoots develop on the billets with shoots terminating and shriveling at the ground surface prior to emergence from the soil. (Summer 2023)

Photograph 13: A thriving stand of willows at the end of their second year of growth. The surviving portion of the BIOSALIX willow stand provides proof-of-concept for successful implementation of the system. (September 2022)