

Effects of three site preparation treatments on mortality and growth of four
early-successional species on degraded sites

by

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ABSTRACT

Three site preparation treatments, straw (S), Meri-Crusher (MC), and coarse woody debris (CWD) in a 2x2x2 factorial testing four early-successional species for land restoration: *Betula papyrifera*, *B. populifolia*, *Alnus viridis ssp. crispa*, and *A. incana ssp. rugosa* were examined for mortality and growth. The study was conducted on three 25-year barren sites. Chapter 1 assessed summer 2021, winter, and spring frost heaved mortality. Greatest causes of mortality were frost heaved followed by summer drought. Overall, S reduced mortality by 27%, CWD by 19%, and MC increased by ~4%. When treatments were combined in any way, mortality dropped significantly indicative of an additive effect. Chapter 2 focused on growth measurements, in 2022, alders and birches had on average 3 and 1 stems, respectively. Alders averaged 11x more dry mass than birches. When site preparation treatments were combined alders stem mass mostly experienced synergistic while birches were largely additive growth.

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Table of Contents

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iii
Table of Contents.....	iv
List of Tables	vii
List of Symbols, Nomenclature or Abbreviations	xii
Introduction.....	1
Bibliography	7
 Chapter 1: Summer, winter, and spring frost heave mortality of four early-successional species on severely degraded sites using a factorial of three site preparation treatments.	12
Abstract	13
 Introduction.....	14
 Methodology and experimental design.....	18
Site preparation treatments	18
Plant materials.....	20
Soil Properties	21
Mortality assessment.....	22
Statistical analysis.....	22
Results.....	24
Discussion.....	42
Summer mortality	42
Winter mortality.....	44

Frost heave mortality	45
First full year mortality	48
Application.....	50
Bibliography	51
Chapter 2: Growth and biomass of four early-successional species on severely degraded sites using a factorial of three site preparation treatments.....	58
Abstract	59
Introduction.....	61
Methodology	64
Site preparation treatments	64
Plant materials.....	65
Soil Properties	66
Plant Measurements	66
Statistical analysis	67
Results.....	69
Soil Moisture.....	70
First Year	73
Second Year	77
Average stem count.....	81
Stem dry mass.....	83

Discussion	90
2021 Growing Season	90
2022 Growing Season	91
Application.....	95
Bibliography	97
Conclusion	102
Bibliography	104
Glossary	105
Curriculum Vitae	

List of Tables

Table 1 Species and provenance of seedling material used in the experiment.	21
Table 2. 2020 soil properties for three experimental sites on DND Base Gaagetown	25
Table 3. Site preparation treatments, species and site effects and interactions on summer 2021 mortality ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).	27
Table 4. Site preparation treatments, species and site effects and interactions on winter mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).	31
Table 5. Site preparation treatments, species and site effects and interactions on frost heaved mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).	34
Table 6. Site preparation treatments, species and site effects and interactions on total first year mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).	37
Table 7. Species and provenance seedling material used in the experiment.	65
Table 8. 2022 soil properties for three experimental sites on DND Base Gaagetown	70

Table 9. Site preparation treatments, species, and site effects and interactions on first year growth ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.....	74
Table 10. Site preparation treatments, species, and site effects and interactions on second year growth ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.....	78
Table 11. Site preparation treatments, species, and site effects and interactions on average stem count ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.....	81
Table 12. Site preparation treatments, species, and site effects and interactions on stem dry mass ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.....	83

List of Figures

Figure 1. Freshly created meri-crushed plot in September of 2020.....	18
Figure 2. Straw implementation and plots in September 2020.....	19
Figure 3. Freshly laid coarse woody debris plots in September 2020, in what would become site 1.....	20
Figure 4. Soil moisture content (A) Rainfall (mm) sourced from Fredericton area from April 1st, 2022 - September 30th, 2022. (B) Soil moisture readings in 2021 showing differences between straw and no straw coverage on dates where field assessments were done. Dates marked with * are significantly different $P < 0.05$. Note x-axis dates range differ.....	26
Figure 5. Summer 2021 mortality with (A) MC x S x Site interaction, (B) S x Site x Species interaction for species in DND base Gagetown. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$	29
Figure 6. Summer 2021 mortality with MC x S x CWD interaction for species in DND Base Gagetown	30
Figure 7. Winter mortality with Straw x CWD x Site interaction for species in DND base Gagetown	32
Figure 8. Winter mortality with (A) Site x CWD interaction, (B) Straw x CWD interaction, Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$	33
Figure 9. Frost heave mortality showing MC x S x CWD interaction for species in DND base Gagetown.....	35

Figure 10. Frost heave mortality showing Site x S interaction. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$.	36
Figure 11. Total first year mortality showing MC x S x CWD interaction for species in DND base Gagetown.	38
Figure 12. Total first year mortality showing (A) Species x Straw interaction, (B) Site x S interaction. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$.	39
Figure 13. Total mortality classified by period of death. A) Species broken down by when they died. B) Treatment types and their associated mortality.	41
Figure 14.. Soil moisture content (A) Rainfall (mm) sourced from Fredericton area from April 1st, 2022 - September 30th, 2022. (B) Soil moisture readings in 2021 showing differences between straw and no straw coverage on dates where field assessments were done. Dates marked with * are significantly different $P < 0.05$. Note x-axis dates range differ.	71
Figure 15. Soil moisture content. A) Rainfall (mm) sourced from Fredericton, NB. area from April 1st - Sept 30th. B) Soil moisture readings taken in 2022 showing differences between straw and no straw plots on dates when field assessments were done. Note: X-axis ranges differ.	72
Figure 16. First year growth (cm) showing A) species x S x CWD interaction. B) Site x S x CWD interaction.	76
Figure 17. Second year growth (cm) showing A) species x S x CWD interaction. B) Site x S x CWD interaction.	80

Figure 18. Number of stems showing a species x S x CWD interaction.	82
Figure 19. Stem dry mass ($\pm$ SE) showing A) Species x S x CWD interaction. B) Site x MC x Species interaction.	85
Figure 20. Stem dry mass ($\pm$ SE) for each treatment combination including an expected line assuming single treatment effects were additive for A) white birch B) gray birch. A and B have differing Y-axis.	87
Figure 21. Stem dry mass ($\pm$ SE) for each treatment combination including an expected line assuming single treatment effects were additive for A) green alder B) speckled alder. A and B have differing Y-axis.	89

List of Symbols, Nomenclature or Abbreviations

ANOVA: Analysis of variance

C: Carbon

Ca: Calcium

cm: Centimeters

CWD: Coarse woody debris

df: Degrees of Freedom

dm: Dry mass

DND: Department of National Defense

g: Grams

GA: Green alder

GB: Gray birch

ha: Hectares

K: Potassium

M: Meters

MC: Meri-crushed/ Meri-crusher

Mg: Magnesium

MS: Mean Square

N: Nitrogen

NCWD: No coarse woody debris

NMC: No Meri-crushing

NS: No straw

P: Phosphorus

pH: Acidity level (potential hydrogen)

p-value: An index measuring the strength of evidence against the null hypothesis (<0.05)

R^2 : Coefficient of determination

S: Straw

SA: Speckled alder

WB: White birch

VC: Variance component

μ : Overall mean

Introduction

During the 1990s military operations overseas demanded more training experience for their troops to be trained in desert like conditions. This demand was fulfilled in DND Base Gagetown by removing around 8000ha of soil down to bedrock and plowing the removed soil and vegetation into berm lines and using the freshly made scarred landscapes as simulations for combat. Once the need for these simulated landscapes lost importance, Base Gagetown was left with the problem of restoring the denuded areas and attempted to fix it, however, the loss of rooting networks holding down the soil soon led to massive amounts of erosion and unsuccessful planting efforts.

Landscapes in need of restoration originate from a multitude of practices but when an ecosystem is left barren and unable to return to its original state, a collection of problems for people trying to fix it are posed. The overarching aim of forest restoration is to restore the land's productivity by establishing an ecosystem composed of indigenous species, which will operate to deliver a range of economic and ecological benefits. (Grant and Koch 2007; Zipper et al. 2011b, Macdonald et al 2015). Mining operations are most akin to what has occurred on DND Base Gagetown, where the landscape needs revegetated but cannot restore itself in a timely manner since the rooting medium is either too poor or not present in large enough quantities to support larger vegetation. Unlike mining operations which over the past decades have been regulated (for example the Surface Mining Control and Reclamation Act (SMCRA), enacted in the United States in 1977, the Alberta Environmental Protection and Enhancement Act in 1993 to cover much of Canada's oil mining operations, and other such legislation existing all over the world),

the landscapes of DND Base Gagetown are not under such legislation. Following the auditor general's inspection in the early 2000's, the some 8000ha of denuded landscapes require restoration.

Rapid erosion from these sites creates more problems by removing growing media and increasing sedimentation in local waterways, negatively affecting aquatic environments (Patric 1976; Ryan 1991). A first look at reclamation led authorities to reduce the erosion that was further deteriorating the sites and plant grasses and legumes (Plass 1982; Chaney et al 1995; Torbertt & Burger 2000), however, the severely disturbed soils often were compacted, lacked water holding capacity and soil nutrients, leading to the inhibition of established forest cover due to severe competition (Jochimsen 1996; Bradshaw 1997; Angel et al 2005; Šourková 2005; Zipper et al 2011a). Focus shifted to create a rooting medium and a surface that would reduce erosion and promote re-colonization of native plants. Unlike the problems that landscapes post mining operations face, DND Base Gagetown faces insufficient soil since the topsoil and vegetation was plowed into berms to resemble desert conditions for training.

Barren sites like the ones on DND Base Gagetown face an number of problems. Unfavorable conditions for plant survival include summer heat and drought, nutrient deficiency, frost heave in shallow soils, and cold damage during the winter. Drought limits productivity of forests worldwide (Hinckley et al. 1981; Trenberth et al. 2014, Fathi & Tari 2016). The shallow soils observed on DND Base Gagetown often lack water retention capabilities and are quick to desiccate, resulting in high seedling mortality. Frost heaving occurs when ice forms within the soil surface layers and within wet soil, causing a volumetric expansion and lifting seedlings from their original planting

positions (Miller, 1980). Frost heave can cause young plants to be damaged or killed from root exposure, and frost heaved soil is susceptible to increased erosion (Brink et al 1967; Luoto & Seppälä 2000). A shallow soil and consequently a high-water table increases susceptibility to frost heaving from greater water concentrations near the soil surface (Bescow 1935; Kinoshita 1979; Sheng et al 2013). Much of the prior planting attempts in the barren sites have resulted in extremely high rates of frost heaved mortality.

Using early-successional deciduous species to return nutrients to the soil and eventually ameliorate the coarse substrate into a forest supporting substrate would be greatly accelerated since nutrient content and organics within hardwood forests are often greater than conifer forests (Son et al. 2007; Ste-Marie et al. 2007). Early successional trees are also known for their ability to succeed in open, post-disturbance landscapes (Fox 1984; Swanson et al. 2011). Some early successional species are known for relatively fast growth despite existing in harsh environments and their tendencies to be bio-accumulators (Lanner 1983; Fox 1984; Monsen 2004). Natural weathering and the expansion of rock fractures can be accelerated by the presence of roots and their associated fungi (Frazier & Graham, 2000; Landeweert et al., 2001). Additionally, mycorrhizal hyphae can colonize spaces inaccessible to roots (Bornyasz et al., 2005), further contributing to the process. Four early successional species from genus *Betula* and *Alnus* were of interest to use for reclaiming DND Base Gagetown: white birch (WB, *Betula papyrifera* (Marsh.)), gray birch (GB, *B. populifolia* (Marsh.)), speckled alder (SA, *Alnus incana* ssp. *rugosa* (Du Roi) R.T. Clausen), and green alder (GA, *A. viridis* ssp. *crispa* (Ait.) Turrill).

A successional restoration plan should begin with the development of soils and establishment of early successional native vegetation which should allow sites to eventually return to natural successional processes (Polster 1989; Macdonald 2015). To achieve this process, focus was put into three site preparation treatments: 1) a mechanical crusher to create a loose aggregate using a Meri-Crusher (MC) (MJ hydraulic 1.4 ST Meri-Crusher from Voukatti, Finland), 2) straw (S) coverage, and 3) coarse woody debris (CWD) coverage. Reintroduction of the original topsoil to barren sites can be a promising method to ameliorate poor soil, however the risk of erosion on the exposed soil should be controlled with a ground cover (Krindo 2005). The topsoil in DND Base Gagetown that was redistributed over the barren sites faced large losses in volume to erosion. Creating a new layer of soil for planting purposes therefore is the remaining option. Mechanically ripping a site has been shown to benefit seedling growth and survival (Lantagne & Burger 1983; Alcázar et al 2002). Mechanically ripping the top layer of aggregate creates a substrate which can be used to restore terrestrial ecosystems with little to no existing substrate available and is often better than bringing in soil from elsewhere (Reynold 1978; Ashby 2008; Polster, 2009). Benefits of ripping the soil include reducing compaction, improved root penetration, mitigation of soil erosion, and improving planter access (Richardson 1980; McMinn & Hedin 1990; Örlander 1990).

Following the redevelopment of the soil, focus should be put into revegetation (Alcázar et al 2002). CWD when used for reclamation can create protected microsites and enhance biodiversity, increase soil microbial activity, improve soil nutrient and water holding capacity, and increases surface roughness (Skousen et al 2011; Haskell et al 2012; Vinge & Pyper 2012; Brown & Naeth 2014). Additionally, CWD has been shown to

reduce frost heaving by insulating the ground and creating an overburden layer (Goulet 1995; Vinge & Pyper 2012). Straw coverage has benefits such as: reducing surface evaporation (Novak et al 2000), improve water infiltration (Adekalu et al 2007), increase moisture retention (Edwards et al 2000; Balwinder-Singh 2011; Rahma et al 2019), and can act as an insulator to help prevent frost heave (Liu et al 2014).

In the first chapter, mortality of the four early successional species WB, GB, GA, and SA was assessed over a full year. Three types of mortality were quantified and analyzed: summer 2021, winter, and frost heaved related mortality. Total first year mortality, the sum of the three mortalities, was also analyzed. Three site preparation treatments of MC, S, and CWD were used in a factorial design, producing 8 treatment combinations. While literature exists on the individual treatments, little to no literature exists discussing the effects of combining these treatments for reclamation purposes. Objectives for this chapter were to determine the effects that the treatments would have individually, as well in combination, on the mortality of the species across a full year. We hypothesized that when used, the treatments would have a positive effect and when used together, the effects may be additive or even synergistic. Additionally, differences between species would be of interest since, while all species are used for reclamation purposes, some may be better suited for the harsh degraded sites.

Chapter two utilizes the same experiment across a two-year timespan analyzing growth (cm), stem count, and stem dry mass (g). First year data contains only growth (cm), while second year data included growth (cm), stem count, and stem dry mass (g). Since alders are shrub species and birches are trees (Farrar 1995), stem dry mass and stem count are important to consider along with growth to see which species can capture

the degraded sites the best. Objectives in chapter two were to quantify, analyze, and understand the different treatment combinations and how they affected growth, stem count, and stem dry mass of the four species. We hypothesized that when used, the treatments would have a positive effect on the early successional species, and when used in combination the effects may be more than additive.

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Chapter 1: Summer, winter, and spring frost heave mortality of four early-successional species on severely degraded sites using a factorial of three site preparation treatments.

Abstract

Three site preparation treatments, straw (S), Meri-Crusher (MC), and coarse woody debris (CWD), were assessed in a 2 x 2 x 2 factorial design to examine the survival of four early-successional species: white birch (WB, *Betula papyrifera* Marsh), gray birch (GB, *Betula populifolia* Marsh), green alder (GA, *Alnus viridis* Vill. ssp. *crispa* Ait) and speckled alder (SA, *Alnus incana* L. ssp. *rugosa* Du Roi) used for restoration on sites barren for 25-years. Mortality was measured after three time periods, summer 2021, winter mortality, and frost heave mortality (spring 2022). Summer mortality was predominantly influenced by S treatments (reduced mortality) and their interactions. S interactions were not rank changes but magnitude effects. The species x straw interaction showed that SA had the greatest magnitude difference with 25% and 3.6% summer mortality for NS and S treatments, respectively. SA, a hydrophilic species, accounted for nearly half the total summer mortality and there were strong species effects and species interactions. The full combination of site preparation treatments had the lowest summer mortality at 1% with other site x species x site preparation treatments having up to 20% summer mortality. Winter mortality only effected 1.9% of the total sample size and there were no species effects or interactions, but contrary to other results S was the leading cause of mortality due to fungal presence found on expired seedlings. For frost heave mortality, it was clear that the S treatment was effective with 1.2% and 20.7% mortality for S and NS, respectively. MC alone had the greatest negative effect with 46.9% frost heave mortality, however, when interacting with S or CWD, the mortality decreased substantially. Frost heave had no species interactions and only a species effect with SA having the greatest mortality. Over the first full-year, MC alone

and control had the greatest mortality with 60% and 38%, respectively, after one year. One-year mortality showed S reduced mortality by 27%, CWD by 19%, and MC increased mortality by approximately 4%. When treatments were combined in any way, mortality dropped significantly showing an additive effect, with the three-combination treatment resulting in the lowest mortality with only 3.1%. Straw provided the strongest effect, both as an effective barrier to moisture evaporation providing up to 10% more soil moisture under dry conditions and provided an effective thermal barrier that substantially reduced the frost heave mortality.

Introduction

Barren landscapes such as former mine sites, severely disturbed, or waste deposit sites present severe challenges to restore ecological services. Rapid erosion from these sites creates more problems by removing soil and increasing sedimentation in local waterways, negatively affecting aquatic environments (Patric 1976; Ryan 1991). Severely disturbed soils are often compacted, lack water holding capacity and soil nutrients (Jochimsen, 1996, Bradshaw, 1997, Šourková 2005). Successional restoration should start with some development of soils and early successional native vegetation which should allow sites to eventually return to natural successional processes (Polster 1989). Returning nutrients to the soil and eventually ameliorating the coarse substrate into a forest supporting substrate could be accelerated by using early-successional hardwood species, as it has been shown that nutrient content and organics within hardwood forests are often greater than conifer forests (Son et al. 2007; Ste-Marie et al. 2007).

Reintroduction of original or new topsoil to barren sites can appear to be a promising method to ameliorate poor sites; however, there is a very high likelihood of more erosion (Skrindo 2005).

Seedlings in barren landscapes are often exposed to severe climatic conditions. Heat and drought in the summer, lack of nutrients, frost heave in shallow soils, and cold damage in the winter are unfavourable conditions for plant survival. Shallow soils lack water holding capacity and dry rapidly resulting in seedling mortality. In addition, shallow soil depth to bedrock and consequently high-water table increases susceptibility to frost heaving from greater water concentrations near the soil surface (Bescow 1935; Kinoshita 1979; Sheng et al 2013). Frost heave has two main effects. First young plants may be damaged or killed from root exposure. Secondly, soil that has been frost heaved is susceptible to erosion (Brink et al 1967; Luoto & Seppälä 2000). According to Graber (1971) four types of damage can occur to seedlings: 1) heaved out: lethal exposure of root system, 2) partial heave and exposed root damage is commonly found, 3) girdling of plant stems via mechanical damage caused by substrate abrasion on the epidermis and cambium, and 4) seedling decapitation: separation of plant parts such as the roots from the aboveground plant parts.

Early-successional species are known for their ability to grow in post-disturbance landscapes (Fox 1984; Swanson et al. 2011). They tend to grow rapidly which can help capture sites quickly. With their need for full sunlight, they are commonly used in land restoration (Lanner 1983; Fox 1984; Monsen 2004). Some early-successional species are known for relatively fast growth rates despite harsh conditions. We examined four such species: white birch (WB, *Betula papyrifera* Marsh), gray birch (GB, *Betula populifolia*

Marsh), green alder (GA, *Alnus viridis* Vill. ssp. *crispa* Ait) and speckled alder (SA, *Alnus incana* L. ssp. *rugose* Du Roi). All four species are classified as early-successional, relatively fast-growing species with relatively short lifespans (Farrar 1995). All four species have some histories in restoration efforts due to their ability to withstand and reclaim harsh sites (Hosie 1969; Vogel 1981; Lanner 1983; Fox 1984; Blundon 1990; Monsen 2004). White birch prefers deep, well-drained, rich soil, but can still compete in a wide range of soil types ranging from gravels to silts and organic bog to peat soils (Haeussler 1986). Gray birch grows best on a moist, well drained site, but is quite adaptable and can grow well on dry sandy or even gravelly soil (DeHond 1989; Chapman 1990). Green alders prefer moist sites but can tolerate dry sites with soil types from gravelly to sandy and will regularly be found on upland glacial till sites (Furlow 1979). Speckled alders compete best on wet sites, such as beside waterways, bogs, fens, but will also establish in mires with peaty soils (Armstrong 1982; Brisson 2006). In Minnesota, it was noted that speckled alder will grow in mesic to moist sites but was found more in moist sites (Bakuzis 1962).

In this study, we examined a three-site preparation factorial design: 1) site crusher to create a loose aggregate using a Meri-Crusher (MC) (MJ hydraulic 1.4 ST Meri-Crusher from Voukatti, Finland), 2) straw (S) coverage, and 3) coarse woody debris (CWD) coverage. The site crusher treatment involved mechanically ripping the top layer of aggregate to create a substrate which can be used to restore terrestrial ecosystems with little to no existing substrate available (Ashby 1997; Polster, 2009). Breaking *in situ* soil beds is better than replacing with soil from elsewhere (Lambermont & Lebon 1978) and benefits of ripping the soil include improved aeration, water infiltration, root penetration,

and mitigation of soil erosion (Richardson 1980). Straw coverage can affect the processes occurring in the top layer of the soil such as reducing surface evaporation (Novak et al 2000), improve water infiltration (Adekalu et al 2007), increase moisture retention (Edwards et al 2000; Balwinder-Singh 2011; Rahma et al 2019), and can act as an insulator and regulate extreme temperatures in the winter to help prevent frost heave of planted seedlings (Liu et al 2014). Coarse woody debris can create protected microsites and enhance biodiversity to a reclaimed site (Pyper M, 2012). The addition of CWD has been shown to decrease water loss and seedling desiccation by providing shelter from the elements (Jumpponen, 1999). There is a preponderance towards larger CWD as smaller pieces like mulch can draw what little available nitrogen from the soil via different fungi to fuel decomposition (Wells and Boddy, 1990).

Our goal was to quantify the effects on seedling mortality of three site preparation treatments in a factorial design resulting in eight separate treatments, using four early-successional species. We hypothesized that the presence of a treatment will have a positive effect on the survival and establishment of the seedlings. We also hypothesized that when site preparation treatments were used together their effects might be additive. In addition, we hypothesized that there will be species differences in survival. Our objective was to quantify mortality 1) over the first summer, 2) over the following winter and 3) mortality due to frost-heaving. In addition, we examined the combined full first-year mortality to assess the best practices and the best species to begin the restoration and forest succession process on highly disturbed sites.

Methodology and experimental design

Site preparation treatments

Three site preparation treatments MC, S and CWD were arranged in a factorial design resulting in eight site preparation treatments that were established on three sites at CFB Gagetown, NB, (45.68108, -66.50179). These eight treatments were replicated four times (blocks) on each site resulting in 32 plots per site. The MC treatment was created using a John Deere 200D excavator equipped with a MJ hydraulic 1.4 ST Meri-Crusher (Voukatti, Finland). The MC plots produced a 3.2m by 3.2m square of broken aggregate from the solid rock substrate (Fig. 1).



Figure 1. Freshly created meri-crushed plot in September of 2020

Straw bales on the back of a pickup truck bed were used to distribute straw over approximately 18m² of area or roughly 2 experimental plots to a depth of 5cm (Fig. 2).



Figure 2. Straw implementation and plots in September 2020

The CWD was sourced from the Department of National Defense (DND) near Gagetown, NB, using primarily GB. All CWD was processed into ~3m length to match the MC plots (Fig. 3). An average volume of $0.2033\text{m}^3 \pm 0.02\text{m}^3$ of CWD was applied to 48 plots. The placement of CWD was done last to hold the straw in place and the CWD was distributed over each plot in a north to south orientation to provide shade at different times of the day.



Figure 3. Freshly laid coarse woody debris plots in September 2020, in what would become site 1

Plant materials

Seedlings from the four tree species were grown from seed lots bulked from seed collected from sources listed in Table 1. WB, GB, and GA were grown during 2020 at the Atlantic Forestry Center (AFC), Fredericton, NB (45.93501, -66.65745) SA were grown in Scot and Stewart nurseries in Antigonish, Nova Scotia (45.53292, -61.86888). In January 2021 stems were cut to a height of roughly 10cm and packaged into boxes for frozen storage at - 4° C in AFC freezers. The seedlings were removed from frozen storage 3-4 days prior to planting to thaw out. Each experimental plot (32 plots x 3 sites = 96 plots) had four replicates of each species randomly planted in each plot May 7-8, 2021.

Table 1 Species and provenance of seedling material used in the experiment.

	Species	Source Year	Provenance	Country	Latitude (N)	Longitude (W)	Elevation (m)	
	<i>Betula papyrifera</i>	white birch	1998	Wayerton, NB	CAN	47.21667	-65.93333	300
	<i>Betula papyrifera</i>	white birch	1998	Jewetts Creek, NB	CAN	45.83333	-66.98333	50
	<i>Betula populifolia</i>	gray birch	2008	Newmarket, NB	CAN	45.80501	-66.95634	149
	<i>Betula populifolia</i>	gray birch	2008	Newmarket, NB	CAN	45.83147	-66.97115	130
	<i>Betula populifolia</i>	gray birch	2008	Newmarket, NB	CAN	45.8076	-66.96825	141
	<i>Betula populifolia</i>	gray birch	2008	Newmarket, NB	CAN	45.83486	-66.96272	125
	<i>Betula populifolia</i>	gray birch	1999	Bai-du-Vin, NB	CAN	47.03333	-65.16666	5
	<i>Alnus viridis ssp. crispa</i>	green alder	2002	West Quaco, NB	CAN	45.33	-65.53	65
	<i>Alnus viridis ssp. crispa</i>	green alder	1999	Lower Prince William, NB	CAN	45.87	-67	20
	<i>Alnus incana ssp. rugosa</i>	speckled alder	1983	Enmore, PEI	CAN	46.58	-64.05	10
	<i>Alnus incana ssp. rugosa</i>	speckled alder	1983	Valleyfield, PEI	CAN	46.13	-62.72	45
	<i>Alnus incana ssp. rugosa</i>	speckled alder	1983	Shediac, NB	CAN	46.23	-64.6	15

Note: NB, New Brunswick; PEI, Prince Edward Island

Soil Properties

For each plot, three depths to bedrock measurements were made using an iron rod gently hammered into the soil until it contacted the solid rock substrate. Soil samples were collected in October 2020 from 3 sites x 2 treatments MC, no MC (NMC) x 4 block replicates for a total of 24 total soil samples. Soil analysis included texture sand, silt, clay, and rock (%) and soil macronutrient analysis including organic matter; carbon (C), and nitrogen (N) using phosphorus (P) available potassium (K), calcium (Ca), magnesium (K), concentration, and pH by the Laboratory for Forest Soils and Environmental Quality at the University of New Brunswick using techniques as outlined in (Major et al. 2022). Soil bulk density assessment was made from 16 plots per site, 8 meri-crushed plots and 8 non-meri-crushed plots for a total of 48 samples in the fall of 2022. Table 2 provides a summary of soil properties among sites. Soil moisture (%) was measured periodically using a ML3 Theta Probe soil moisture sensor (Cambridge,

England), by recording three readings per plot, in two randomly selected blocks of each site, varying site order each time they were taken. Soil moisture readings were made on 13 collection dates ranging from March 3rd, 2021, to September 9th, 2021.

Mortality assessment

Survival assessments were performed at end of August 2021 for summer mortality, and April 2022 for frost heave mortality. The difference between mortality in autumn 2021 and spring frost heave was considered winter mortality.

Statistical analysis

The experiment was established as a randomized block design. Initial soil properties were subjected to analyses of variance (ANOVA), site and MC were fixed effects, block was a random effect. The following ANOVA model was used:

$$Y_{ijk} = \mu + B_i(S_j) + S_j + M_k + SM_{jk} + e_{ijk}$$

where Y_{ijk} is the dependent soil property trait of the i^{th} block, j^{th} site, and the k^{th} MC treatment, and μ is the overall mean. $B_i(S_j)$ is the random effect of block nested within site ($i = 1,2,3,4$), S_j is the effect of the j^{th} site ($j = 1,2,3$), M_k is the effect of the k^{th} MC treatment ($k = 1,2$), SM_{jk} is the interaction effect between j^{th} site effect and k^{th} MC treatment effect, and e_{ijk} is the random error component.

Available soil moisture in 2021 were subjected to analyses of variance (ANOVA), site, S, MC, and CWD were fixed effects, block was a random effect. The following ANOVA model was used:

$$Y_{ijklm} = \mu + B_i(T_j) + T_j + S_k + M_l + C_m + TS_{jk} + TM_{jl} + TC_{jm} + SM_{kl} + SC_{km} + MC_{lm} + \\ TSM_{jkl} + TSC_{jkm} + TMC_{jlm} + SMC_{klm} + e_{ijklm}$$

where Y_{ijklm} is the dependent soil moisture availability of the i^{th} block, the j^{th} site, k^{th} S treatment, l^{th} MC treatment, m^{th} CWD treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of the i^{th} block nested in the j^{th} site ($i = 1,2,3,4$), T_j is the effect of the j^{th} site ($j = 1,2,3$), S_k is the effect of k^{th} S treatment ($k = 1,2$), M_l is the effect of l^{th} MC treatment ($l = 1,2$), C_m is the effect of the m^{th} CWD treatment ($m = 1,2$), and e_{ijklm} is the error random error component. Interactions of the single effects include up to three-way interactions, 4- and 5-way interactions are folded into the error term.

Summer, winter, frost heave, and total first year mortality were analyzed using analysis of variance (ANOVA). MC, S, CWD, species, and site were all considered as fixed effects. Block was a random effect. The following ANOVA model was used:

$$Y_{ijklno} = \mu + B_i(T_j) + T_j + P_k + S_l + C_n + M_o + TP_{jk} + TS_{jl} + TC_{jn} + TM_{jo} + PS_{kl} + PC_{kn} + \\ PM_{ko} + SC_{ln} + SM_{lo} + CM_{no} + TPS_{jkl} + TPC_{jkn} + TPM_{jko} + TSC_{jln} + TSM_{jlo} + TCM_{jno} + \\ PSC_{kln} + PSM_{klo} + PCM_{kno} + SCM_{lno} + e_{ijklno}$$

where Y_{ijklno} is the dependent mortality factor of the i^{th} block, within the j^{th} site, of the k^{th} species, in the l^{th} S treatment, n^{th} CWD treatment, o^{th} MC treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of block nested in site ($i = 1,2,3,4$), T_j is the effect of the j^{th} site ($j = 1,2,3$), P_k is the effect of the k^{th} species ($k = 1,2,3,4$), S_l is the effect of the l^{th} S treatment ($l = 1,2$), C_n is the effect of the n^{th} CWD treatment ($n = 1,2$), M_o is the effect of the o^{th} MC treatment ($o = 1,2$), and e_{ijklno} is the error random error component.

Interactions of the single effects include up to three-way interactions, 4- and 5-way interactions are folded into the error term.

All mortality traits were arcsine square root transformed to enhance normality. All effects were considered significant at the $p = 0.05$ level, though all p-values are presented for individual consideration. Assumptions of independence of data, normality of distribution, and normality of variance were met prior to assessing each statistical analysis (ANOVA). The general linear model from Systat Software Inc. (Chicago, Illinois) was used for analysis. If significant, site and species was post-hoc tested using Tukey mean separation test ($p = 0.05$). Significant interactions are referred to as either rank change interaction, or magnitude effect interaction. A rank change interaction occurs when one effect has a greater mean under one scenario and lower mean under another scenario. A magnitude effect would refer to when the effect mean is always greater than under both scenarios, but of different magnitudes.

Results

There was little or no difference in soil nutrient or texture between MC and NMC plots, so they were folded into the site only analysis. Additionally, soil bulk density showed no significant difference between sites or MC and NMC plots. Soil analysis in fall 2020 showed greater total N on site 1 compared to sites 2 and 3 (Table 2). Site 1 had a significantly lower Ca content and pH than sites 2 and 3. Two soil texture properties were significantly different: silt which was greatest on site 1 (43.8%) than site 2 and 3, and sand was greatest on site 3 (58.2%) than site 1 and 2.

Table 2. 2020 soil properties for three experimental sites on DND Base Gagetown

ID	Organic matter (%)	Total Nitrogen (%)	Carbon (%)	C:N Ratio	pH	Phosphorus (ppm)	Potassium (meq/100g)
Site 1	1.744±0.99a	0.219±0.05a	1.013±0.58a	4.350±1.59ab	4.43±0.16b	6.375±3.02a	0.110±0.03a
Site 2	0.871±0.37a	0.171±0.03b	0.509±0.21a	2.938±0.93b	4.63±0.15a	4.375±1.19a	0.113±0.03a
Site 3	1.303±0.54a	0.168±0.03b	0.758±0.31a	4.538±0.72a	4.61±0.08a	5.875±2.10a	0.104±0.02a
ID	Calcium (meq/100g)	Magnesium (ppm)	Clay (%)	Silt (%)	Sand (%)	Rocks (%)*	Average Depth (cm)
Site 1	0.381±0.15b	0.156±0.08a	15.81±3.41a	43.76±7.45a	40.44±10.69b	36.05±17.36a	31.93±12.18a
Site 2	1.044±0.32a	0.280±0.09a	13.51±3.01a	34.25±6.20b	52.20±9.04b	41.21±12.46a	11.64±7.27b
Site 3	1.198±0.72a	0.369±0.24a	12.93±2.69a	28.84±5.13b	58.21±7.66a	43.96±15.46a	14.94±9.78b

Note: Significant differences between sites are portrayed by letters "a", "b" or "c"

*Rocks(%) was taken before the sand, silt, clay (%), which are equal to 100%

Soil moisture content corresponded with the precipitation graph (Fig. 4A). When the greatest rainfall occurred (July 1st onwards) the average soil moisture content increased. Dry conditions from June 3rd to June 30th resulted in significantly lower soil moisture content for NS than S treatments. As the soil accumulated more rain, the effect of straw was not significant.

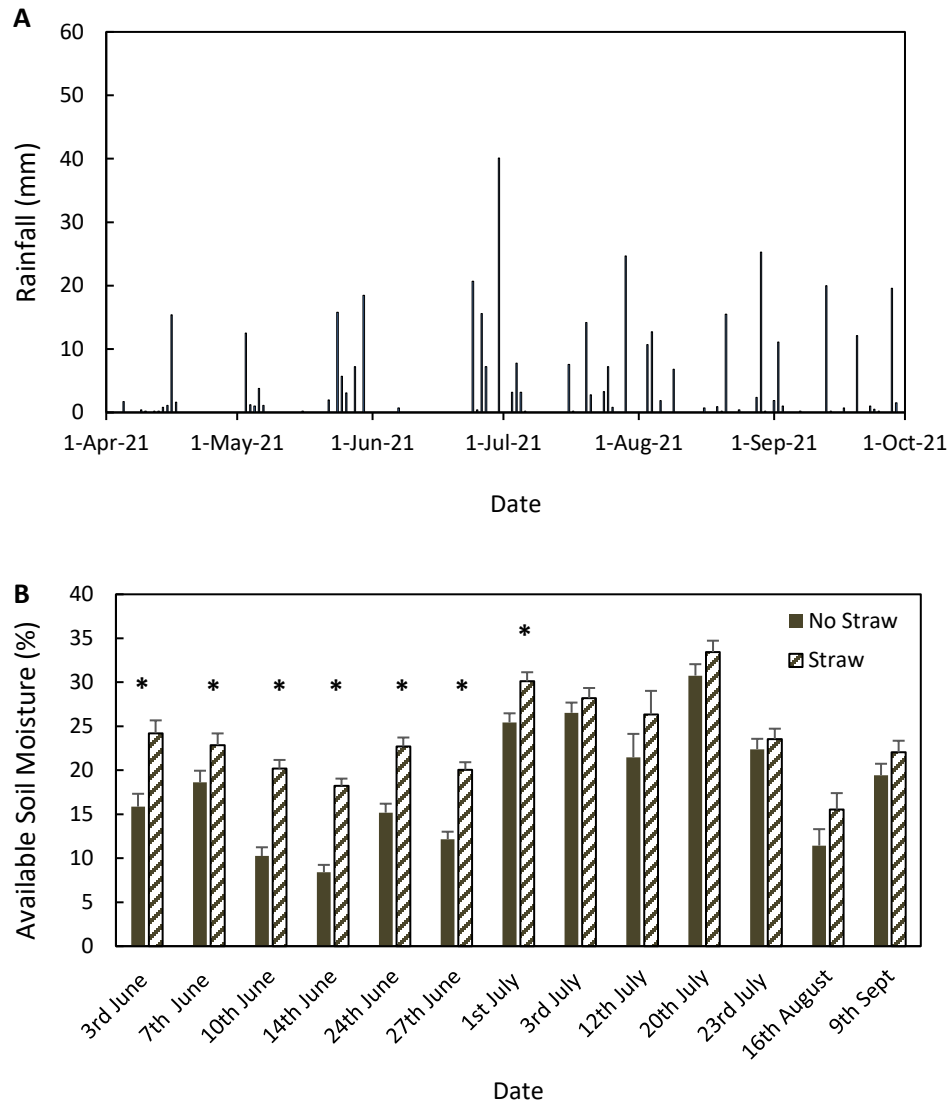


Figure 4. Soil moisture content (A) Rainfall (mm) sourced from Fredericton area from April 1st, 2022 - September 30th, 2022. (B) Soil moisture readings in 2021 showing differences between straw and no straw coverage on dates where field assessments were done. Dates marked with * are significantly different $P < 0.05$. Note x-axis dates range differ.

All summer mortality main effects excluding CWD were significant (Table 3). Straw was highly significant and accounts for the greatest source of variance (9.2%) in summer

mortality and appears in most other significant interactions which were magnitude effects.

Table 3. Site preparation treatments, species and site effects and interactions on summer 2021 mortality ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).

Summer 2021 Mortality				
Source of variation	df	MS	VC(%)	P value
MC	1	0.286	0.9	0.021
S	1	3.016	9.2	<0.001
CWD	1	0.001	0.0	0.908
SITE	2	0.588	3.6	<0.001
SPECIES	3	0.489	4.5	<0.001
BLOCK(SITE)	9	0.165	4.5	0.001
S*MC	1	0.161	0.5	0.084
CWD*MC	1	0.446	1.4	0.004
SITE*MC	2	0.330	2.0	0.002
SPECIES*MC	3	0.001	0.0	0.997
CWD*S	1	0.046	0.1	0.356
SPECIES*S	3	0.298	2.7	0.001
SITE*S	2	1.076	6.6	<0.001
SPECIES*CWD	3	0.050	0.5	0.421
SITE*CWD	2	0.082	0.5	0.219
SITE*SPECIES	6	0.084	1.5	0.154
CWD*S*MC	1	0.231	0.7	0.038
SPECIES*S*MC	3	0.031	0.3	0.626
SITE*S*MC	2	0.320	2.0	0.003
SPECIES*CWD*MC	3	0.092	0.8	0.162
SITE*CWD*MC	2	0.077	0.5	0.237
SITE*SPECIES*MC	6	0.034	0.6	0.701
SPECIES*CWD*S	3	0.009	0.1	0.923
SITE*CWD*S	2	0.072	0.4	0.261
SITE*SPECIES*S	6	0.244	4.5	<0.001
SITE*SPECIES*CWD	6	0.075	1.4	0.209
Error	308	0.053	50.2	
R ²				0.498

*arcsine square root transformed

The significant MC x S x Site ($P = 0.003$) interaction (Table 3) for summer mortality was a result of a single site rank change on only NS plots. Site 3 had the greatest summer mortality on NS, NMC treatments (25.8%), whereas site 3 had low summer mortality on NS, MC treatments plots (7.0%) compared to site 2 (21.0%) (Fig. 5A). The S x site x species interaction in summer mortality was largely due to a magnitude effect under NS. Site 2 NS had the greatest mortality particularly for SA mortality (45.3%) which is also seen in (Fig. 5B) whereas sites 2 and 3 summer mortality were somewhat equal for the other species.

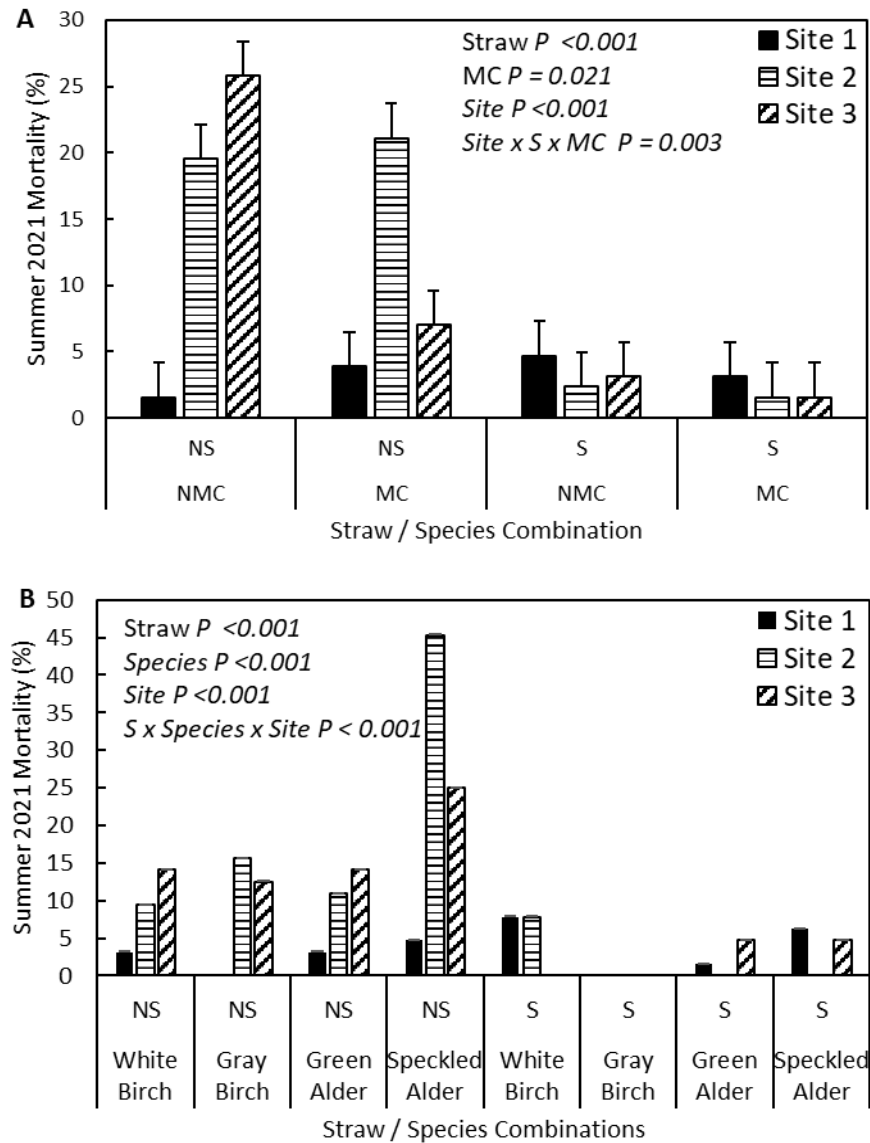


Figure 5. Summer 2021 mortality with (A) MC $\times$ S $\times$ Site interaction, (B) S $\times$ Site $\times$ Species interaction for species in DND base Gagetown. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$

The significant MC $\times$ S $\times$ CWD interaction in summer mortality was a result of a single rank change again under NS (Fig. 6A). Under the NS, CWD treatment, NMC plots had greater summer mortality than MC plots with 20.7% and 7.8%, respectively. Summer

mortality was reversed to a lesser degree under the NS, NCWD plots with 11 and 14%, respectively.

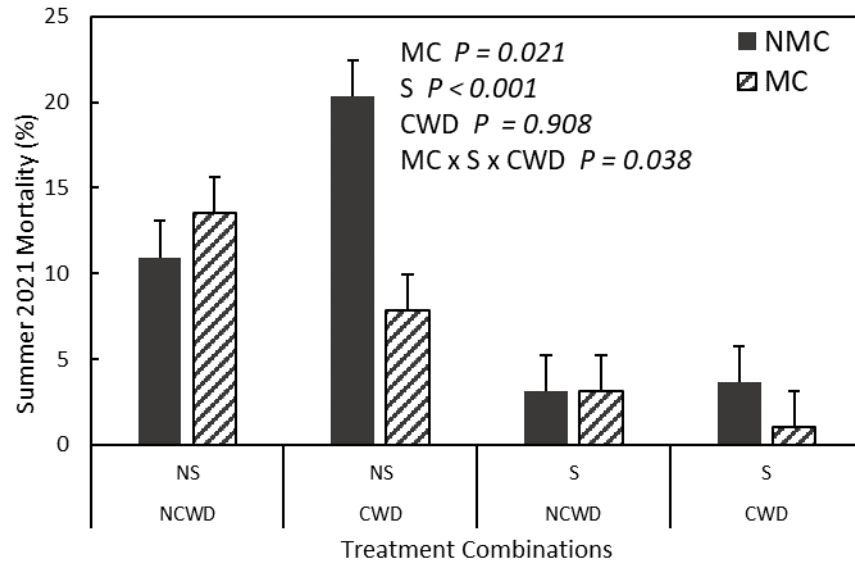


Figure 6. Summer 2021 mortality with MC x S x CWD interaction for species in DND Base Gagetown

Overall S and NS had 2.7% and 13.2% summer mortality, respectively. Site 1 mortality of 3.3% was significantly lower than sites 2 and 3 with 11.1% and 9.4%, respectively.

Winter mortality had the smallest mortality impact, resulting in the loss of only 36 seedlings, affecting only 1.9% of the total seedlings. Winter mortality had only one three-way interaction, site x S x CWD interaction (Table 4) and it was a small rank and largely a magnitude effect driven by S on site 2 (Fig. 7).

Table 4. Site preparation treatments, species and site effects and interactions on winter mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).

Winter Mortality				
Source of variation	df	MS	VC(%)	P value
MC	1	0.103	1.0	0.043
S	1	0.258	2.4	0.001
CWD	1	0.121	1.1	0.029
SITE	2	0.054	1.0	0.118
SPECIES	3	0.060	1.7	0.066
BLOCK(SITE)	9	0.020	1.7	0.632
S*MC	1	0.006	0.1	0.612
CWD*MC	1	0.006	0.1	0.612
SITE*MC	2	0.002	0.0	0.918
SPECIES*MC	3	0.058	1.6	0.076
CWD*S	1	0.346	3.3	<0.001
SPECIES*S	3	0.057	1.6	0.077
SITE*S	2	0.026	0.5	0.348
SPECIES*CWD	3	0.015	0.4	0.602
SITE*CWD	2	0.099	1.9	0.020
SITE*SPECIES	6	0.016	0.9	0.691
CWD*S*MC	1	0.026	0.2	0.311
SPECIES*S*MC	3	0.034	1.0	0.259
SITE*S*MC	2	0.009	0.2	0.709
SPECIES*CWD*MC	3	0.015	0.4	0.627
SITE*CWD*MC	2	0.000	0.0	1.000
SITE*SPECIES*MC	6	0.023	1.3	0.470
SPECIES*CWD*S	3	0.044	1.3	0.152
SITE*CWD*S	2	0.138	2.6	0.004
SITE*SPECIES*S	6	0.012	0.7	0.811
SITE*SPECIES*CWD	6	0.009	0.5	0.902
Error	308	0.025	72.5	
R ²				0.275

*arcsine square root transformed

S, NCWD on site 2 had greatest mortality with 12% winter mortality. (Fig. 7).

This was also driving the two significant two-way interactions: site x CWD and S x

CWD (Fig. 8A and B). Overall, S and NS resulted in winter mortality of 1.7% and 4%, respectively. Overall, CWD, NCWD had 1.6% and 3.6% winter mortality, respectively. MC, NMC had a winter mortality of 3.5% and 1.7%, respectively.

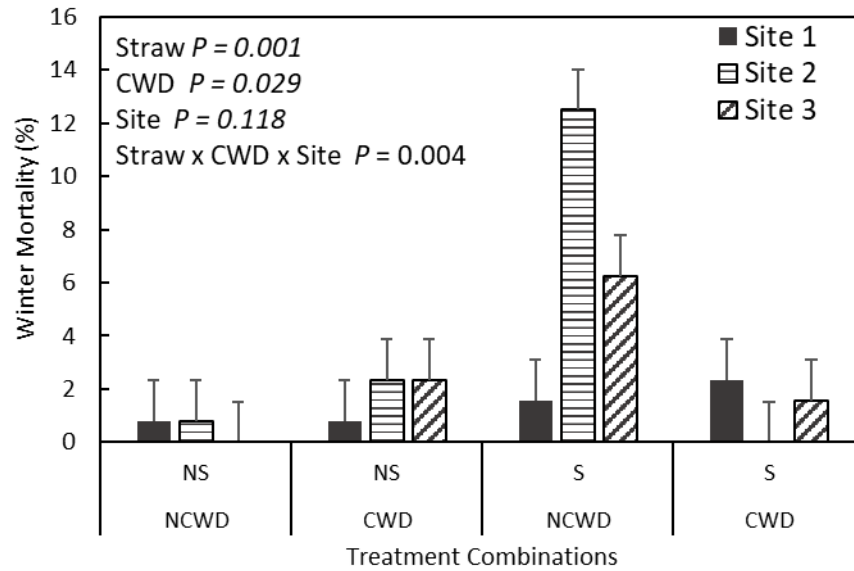


Figure 7. Winter mortality with Straw x CWD x Site interaction for species in DND base Gagetown

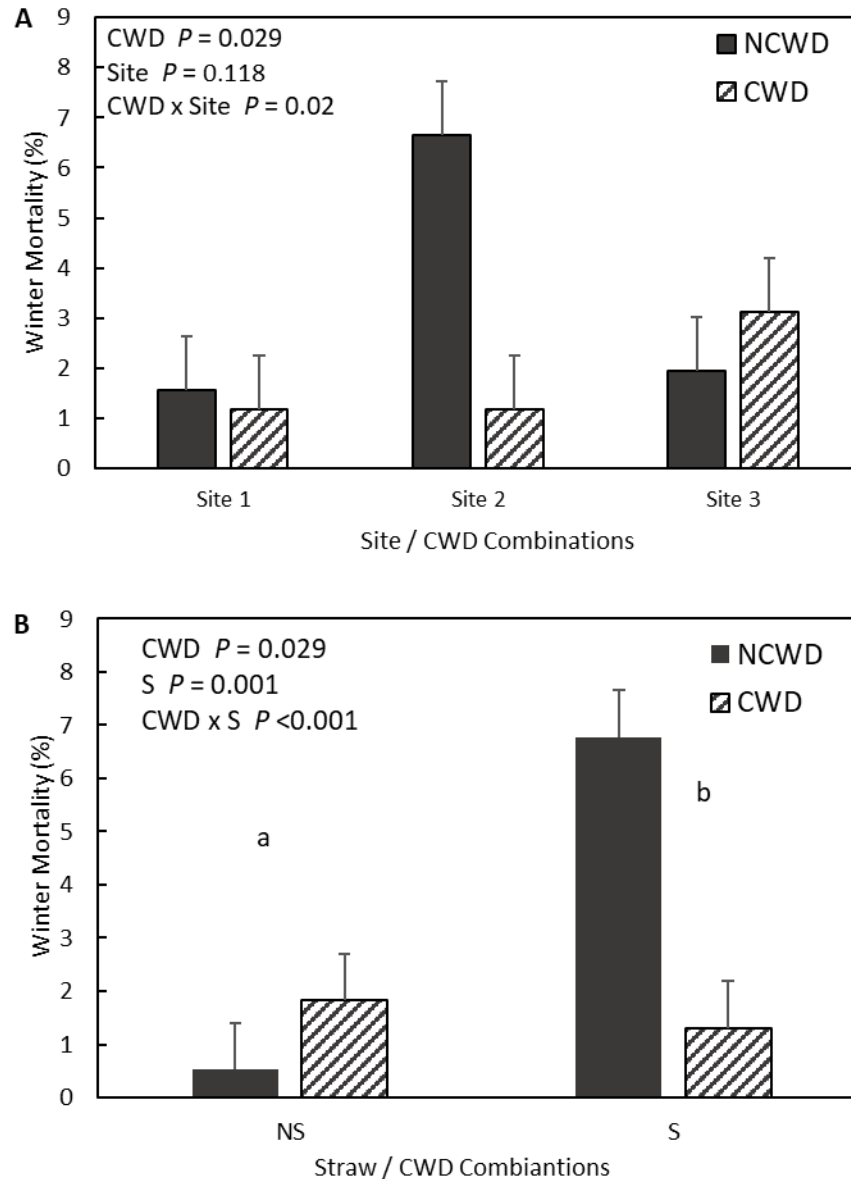


Figure 8. Winter mortality with (A) Site x CWD interaction, (B) Straw x CWD interaction, Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$.

There was only one frost heaved mortality three-way interaction (Table 5) and it was largely a magnitude effect and it was among the 3 site treatments and was driven by the

large frost heaved mortality under NS, NCWD with NMC, MC having 25 and 47% mortality, respectively (Fig 6).

Table 5. Site preparation treatments, species and site effects and interactions on frost heaved mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri- crushing (MC), Straw (S), Coarse woody debris (CWD).

Frost Heaved Mortality				
Source of variation	df	MS	VC(%)	P value
MC	1	0.483	0.9	0.010
S	1	10.110	19.0	<0.001
CWD	1	6.857	12.9	<0.001
SITE	2	0.451	1.7	0.002
SPECIES	3	0.226	1.3	0.026
BLOCK(SITE)	9	0.181	3.1	0.009
S*MC	1	0.777	1.5	0.001
CWD*MC	1	0.346	0.6	0.030
SITE*MC	2	0.155	0.6	0.119
SPECIES*MC	3	0.063	0.4	0.455
CWD*S	1	4.918	9.2	<0.001
SPECIES*S	3	0.110	0.6	0.211
SITE*S	2	0.227	0.9	0.045
SPECIES*CWD	3	0.189	1.1	0.052
SITE*CWD	2	0.072	0.3	0.372
SITE*SPECIES	6	0.060	0.7	0.546
CWD*S*MC	1	0.600	1.1	0.004
SPECIES*S*MC	3	0.015	0.1	0.887
SITE*S*MC	2	0.017	0.1	0.795
SPECIES*CWD*MC	3	0.020	0.1	0.838
SITE*CWD*MC	2	0.008	0.0	0.899
SITE*SPECIES*MC	6	0.075	0.8	0.406
SPECIES*CWD*S	3	0.101	0.6	0.244
SITE*CWD*S	2	0.024	0.1	0.721
SITE*SPECIES*S	6	0.032	0.4	0.850
SITE*SPECIES*CWD	6	0.024	0.3	0.921
Error	308	0.072	41.9	
R ²				0.581

*arcsine square root transformed

All other treatment combinations were 5% or less, with S, CWD with zero frost heaved mortality. The three two-way interactions: S x MC, CWD x MC and CWD x S were largely magnitude effects found in the three-way interaction figure (Fig. 9). The one other two-way interaction site x S was also a magnitude effect with site 2 and 3 having the largest magnitude with site 1 lesser (Fig 10).

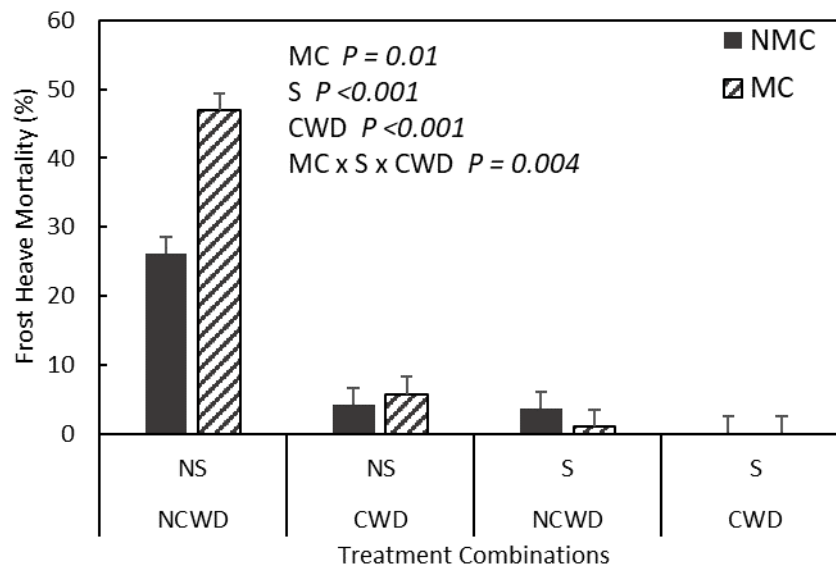


Figure 9. Frost heave mortality showing MC x S x CWD interaction for species in DND base Gagetown.

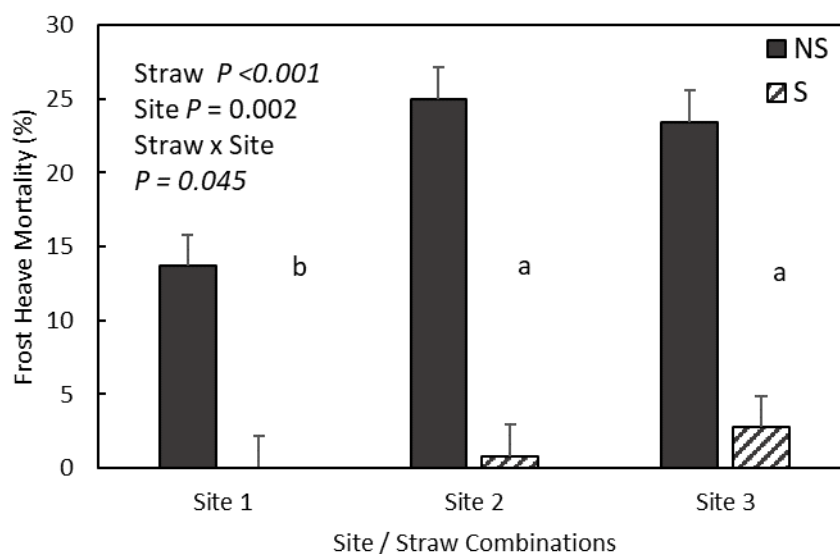


Figure 10. Frost heave mortality showing Site x S interaction. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$.

ANOVA for frost heaved mortality showed that all main effects were significant (Table 3). Straw accounts for the most variance in the model (19%) and CWD had the second largest variance (12.9%). Overall S vs. NS had 1.1% and 20.7% frost heaved mortality, CWD, NCWD had 2.5% and 19.4%, and MC, NMC had 13.4% and 8.5%, respectively. The species that was affected the most was SA with 14.8% mortality, then green alder at 11.7%, and both birches at 8.6%. Site was significant because of the reduced mortality on site 1 (6.8%) while sites 2 and 3 had increased mortalities of, 12.9% and 13.1%, respectively.

There was also only one total first-year mortality 3-way interaction (Table 6), and it was largely a magnitude effect, with some rank change and it was again among the 3 site treatments and was driven by the large frost heave mortality findings.

Table 6. Site preparation treatments, species and site effects and interactions on total first year mortality. ANOVA table includes degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print. Meri-crushing (MC), Straw (S), Coarse woody debris (CWD).

Total first year Mortality				
Source of variation	df	MS	VC(%)	P value
MC	1	0.193	0.2	0.202
S	1	17.204	19.1	<0.001
CWD	1	8.221	9.1	<0.001
SITE	2	2.317	5.1	<0.001
SPECIES	3	1.627	5.4	<0.001
BLOCK(SITE)	9	0.185	1.8	0.127
S*MC	1	0.194	0.2	0.201
CWD*MC	1	1.540	1.7	<0.001
SITE*MC	2	0.595	1.3	0.007
SPECIES*MC	3	0.009	0.0	0.974
CWD*S	1	1.889	2.1	<0.001
SPECIES*S	3	0.856	2.9	<0.001
SITE*S	2	1.697	3.8	<0.001
SPECIES*CWD	3	0.263	0.9	0.086
SITE*CWD	2	0.056	0.1	0.625
SITE*SPECIES	6	0.126	0.8	0.384
CWD*S*MC	1	1.284	1.4	0.001
SPECIES*S*MC	3	0.035	0.1	0.829
SITE*S*MC	2	0.131	0.3	0.332
SPECIES*CWD*MC	3	0.072	0.2	0.610
SITE*CWD*MC	2	0.132	0.3	0.329
SITE*SPECIES*MC	6	0.040	0.3	0.916
SPECIES*CWD*S	3	0.121	0.4	0.383
SITE*CWD*S	2	0.072	0.2	0.545
SITE*SPECIES*S	6	0.163	1.1	0.223
SITE*SPECIES*CWD	6	0.094	0.6	0.577
Error	307	0.118	40.4	
R ²				0.597

*arcsine square root transformed

Again, under NS, NCWD with NMC, MC having 39 and 60.9% mortality, respectively (Fig 11). The three-way interaction MC x S x CWD ($P < 0.001$) (Fig. 11) showed very similar trends to that discussed in the frost heaved model with MC alone having the greatest mortality (60.9%). Since spring 2022 mortality was the sum of the past three mortalities it followed similar trends. MC presence was largely negative by itself without other treatments, however once CWD or S was added, MC had a positive effect.

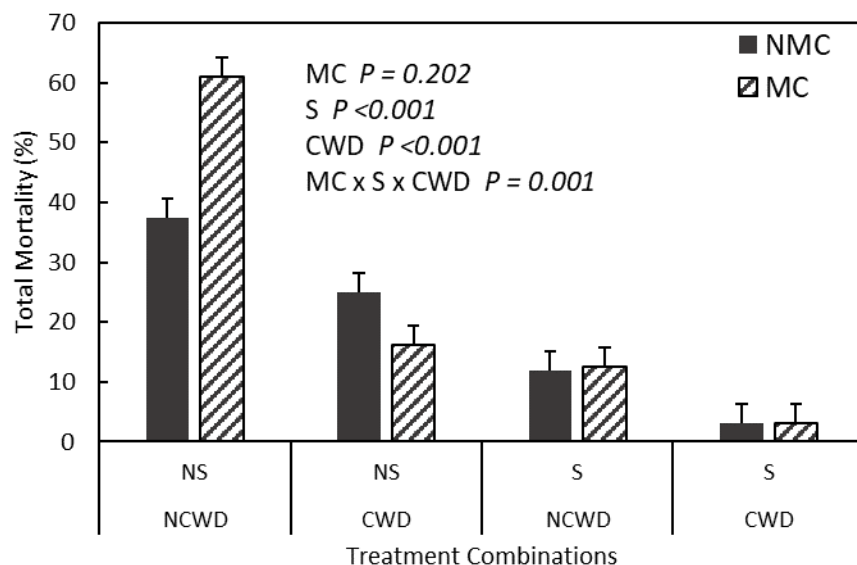


Figure 11. Total first year mortality showing MC x S x CWD interaction for species in DND base Gagetown.

The species x straw interaction ($P < 0.001$) (Fig. 12A) was a magnitude effect. When S was present, all species mortality stayed under 10% (Fig. 12A) but when S wasn't present, there was an average 21.3% increase in mortality for WB, GB, and GA with the greatest increase of 45.4% mortality in SA, which resulted in the greatest mortality through the year around 56.3% (Fig. 12A). Straw x site interaction ($P < 0.001$)

was also due to a magnitude effect. The lack of S on site 1 (16.8%) had a more muted effect when compared to sites 2 and 3 at 46.9% and 41%, respectively (Fig. 12B).

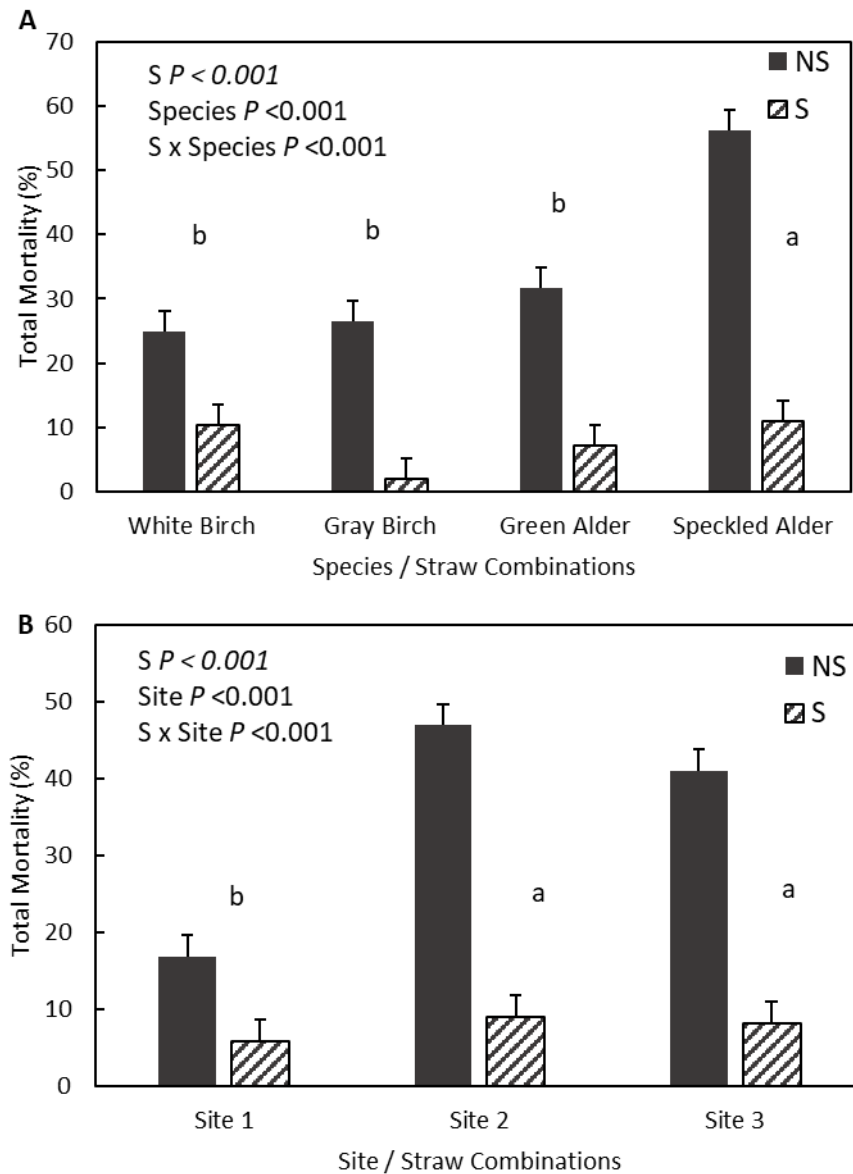


Figure 12. Total first year mortality showing (A) Species x Straw interaction, (B) Site x S interaction. Different letters in two-way interactions represent significant differences according to Tukey's mean separation test, $\alpha = 0.05$.

After the first full year, the overall survival of the seedlings was significantly affected by all main effects excluding MC (Table 3). However, MC was significantly present in two-way interactions with CWD ($P<0.001$) and site ($P=0.007$), also a three-way interaction with S and CWD ($P=0.001$). Like the other models, S had the highest variance component (19.1%) and is present in four of the six significant interactions. Overall, S and NS had 7.7% and 34.9% total mortality, respectively. CWD and NCWD had 11.8% and 30.7% total mortality. Sites 1,2 and 3 overall had 11.3%, 27.9%, and 24.6% total mortality, respectively, by spring 2022.

Total mortality was greatest in SA with 33.6% (Fig. 13A). WB, GB, and GA all had under 25% mortality with GA being the lowest at 20% mortality through the first year. Frost heaving was the largest contributor to mortality regardless of species with WB, GB, GA, and SA experiencing 8.6%, 8.6%, 11.7%, 14.8% mortality, across all sites. The effect of winter mortality was relatively minor with only 36 cases. 1.9% of all species were affected with most mortality occurring in SA with 4.4% of all SA dying (Fig. 13A). When broken down by treatments in Fig. 10B, the addition of S greatly reduces the high level of frost heaved mortality and the addition of CWD but to a lesser extent. The treatment of MC alone had the greatest mortality with 60.9% of all MC plots succumbing to 13.5% summer mortality and 46.9% frost heaving mortality. An additive effect can be seen where additional treatments reduced mortality. The treatment of MCSCWD had the lowest mortality rate with only 3.1% of the species dying within that plot type (Fig. 13B).

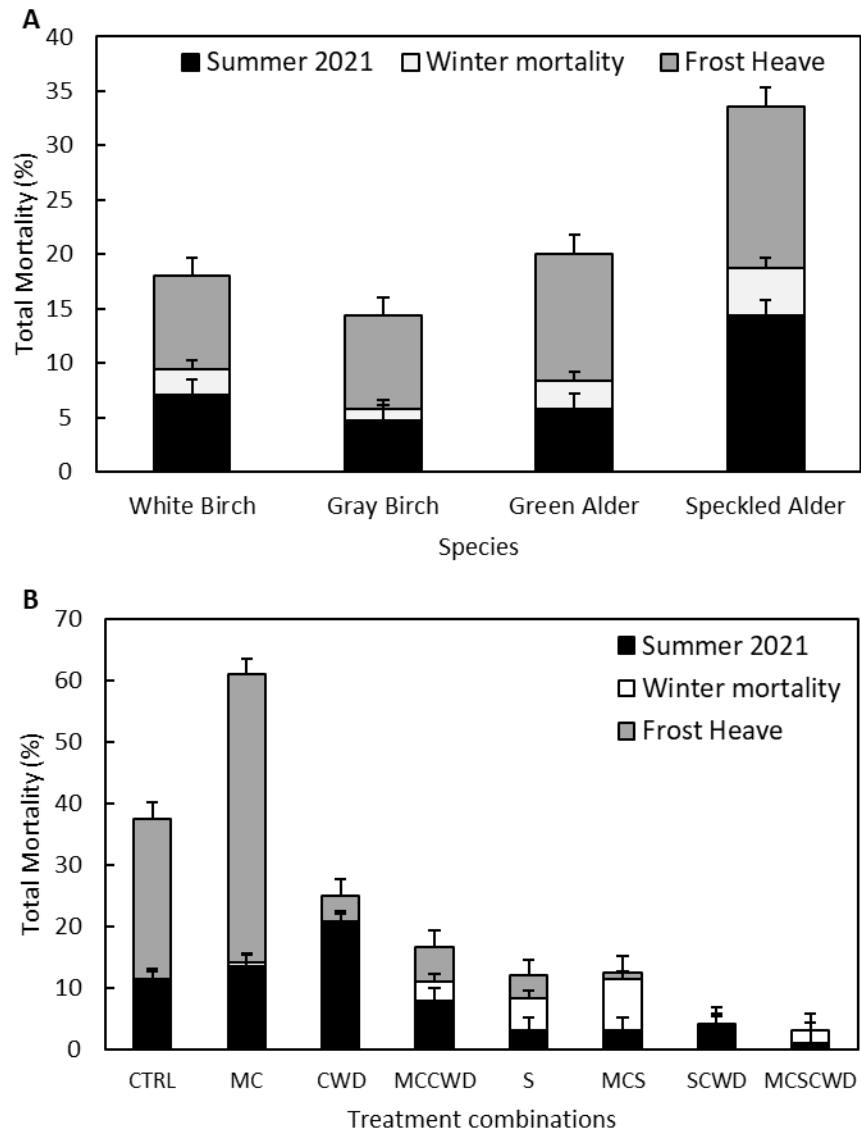


Figure 13. Total mortality classified by period of death. A) Species broken down by when they died. B) Treatment types and their associated mortality.

Discussion

Summer mortality

Straw alone had the largest summer mortality effect accounting for 9.2% of the overall variance resulting in an overall 10.5% reduction in summer mortality when S is present. In the case of SA and its interaction with S, summer mortality went from 25% mortality in NS plots to 3.6% in plots with S. Straw can reduce summer moisture evaporation (Zhu et al, 2010; Gan et al., 2013; Yang et al., 2020), increase soil water retention (Edwards et al., 2000), reduce erosion (Meyer et al., 1970; Gan et al., 2013), regulate surficial soil temperatures (Novak et al 2000), increase soil enzyme activity (Akhtar et al., 2018), and reduce weeds which may compete for above and below ground resources (Balwinder-Singh 2011). Straw also reduces solar radiation reaching the soil surface, lowering soil temperatures during early growth stages (Chen et al., 2005, Liu et al., 2014). All species were significantly better on site 1, than on either sites 2 or 3. Site 1 had deeper soil and hence had better soil moisture conditions compared to site 2 and 3, these conditions allowed all species to survive better regardless of the treatments. Straw effects differed depending on the site. Site 2 had a shallower soil, more visible bedrock, and was more open to the elements, and that is where S had the greatest impact.

The three-way site preparation treatment interaction that included NS, NMC and CWD had ~10% greater summer mortality than control plots. This result was somewhat unexpected, however other combinations with CWD decreased summer mortality (see below). CWD often create microsites and enhance future biodiversity to reclaimed sites (Pyper M, 2012). The addition of CWD decreases water loss and seed desiccation by

providing shelter from the elements (Jumpponen, 1999; Orman 2016). However, the presence of CWD is never homogenous since its physical properties and rate of decay differ both in time and among different forest communities (Yatskov, Harmon & Krankina 2003; Müller-Using & Bartsch 2009). While the immediate effects of CWD alone seem to have hindered the summer survival of the planted species, the evidence points towards a propensity for a more favourable environment once the CWD has begun decomposing and amassing organics within the plots (Jia-bing et al 2005). A theory as to why it may have heightened summer mortality in CWD plots is that total area of good planting spots is reduced with CWD as it takes up space on plots of limited size and available planting area. This issue was more important on site 2, which was already somewhat limited in available planting spots due to its shallow depth to bedrock.

As demonstrated above, MC interactions are dependent on other site preparation treatments. Treated with S or CWD there was very little summer mortality. MC by itself had 3% greater summer mortality than control plots. The benefits of ripping the soil with the MC treatment include improved aeration, water infiltration, root penetration, and erosion control (Richardson 1980). Loose aggregate also enhances moisture infiltration and retention but instead of controlling erosion, the churned earth was raised above the surrounding ground layer and probably suffered from increased rain and wind erosion. The MC plots without the implementation of S suffered too much water loss since the breaking of the aggregate created a substrate with lowers soil bulk density than NMC plots and increased the water infiltration rate. Our bulk density showed no significant difference, but this may be due to measuring in the fall of 2022, 2 years after MC treatment.

Species interactions with site for summer mortality was driven by the greater SA mortality on site 2. Overall, GB had the least amount of summer mortality (4.7%) with GA and WB at 5.7 and 7%, respectively, and SA mortality had the greatest at 14.3%. The difference in species quickly became evident as SA began to die off because they couldn't overcome the transplant shock on the harsh dry sites since SA are hydrophilic and are better adapted to mesic sites (Armstrong 1982; Brisson 2006). In addition, SA showed the greatest benefit from the S treatment and particularly on site 2 which experienced the greatest stress. GA prefers soil types ranging from sand to gravel and can regularly be found on upland glacial till (Furlow 1979). Although GB prefers moist, well-drained sites as other species, it can withstand harsh environments and can tolerate arid gravelly soils and has performed well in reclamation efforts on Pennsylvanian mine sites (Vogel 1981; DeHond 1989; Chapman 1990). WB has been used in the past to stabilize soil on former mine sites (Watson 1980; Perala 1990).

Winter mortality

After an extensive review of the literature, we could not find species or site preparation effects on winter mortality.

Interestingly, there were no species or species interactions for winter mortality. Though only 36 trees (1.9%) were affected, the treatments that saw the greatest winter mortality occurred in plots with S alone or S treatment interactions. Overall, treatments containing S had 4.0% winter mortality while treatments without had 1.2% mortality. The increased mortality with the presence of S appears to be largely due to a mold fungus that was observed on seedlings that died overwinter. There were significant but minor

interactions with S, but it appeared that CWD with S reduced winter mortality and that the site x CWD interaction was due to increased mortality on the more stressed site 2 without CWD. This was driving the three-way interaction found on the shallowest site 2, where S with NCWD had the greatest winter mortality at 12.5%. It is possible that CWD limited winter mortality since its sheltering properties (Pyper M, 2012) limited the elements which may have caused non fungal related mortality.

Frost heave mortality

Frost heaving occurs when ice forms within the soil surface layers and within wet soil, causing a volumetric expansion and lifting the seedlings from their original planting positions (Miller, 1980). The three-way site preparation (S x MC x CWD) interaction was driven by the NS NCWD combined treatment which had the greatest frost heaving mortality regardless of MC treatment. Overall, it was clear that there was a strong positive S treatment effect on frost heaving since S and NS had 1.2% and 20.7% frost heaving mortality, respectively. Mitigating frost heaving can be done by adding an insulating cover to the surface of the soil (Littlefield 1942; Goulet 1995; Chalker-Scott 2007). It has been reported that straw has an ability to insulate and maintain a higher temperature below ground in winter (Goulet 1995; Chalker-Scott 2007). Insulation covers such as straw, forest litter, or wooden laths are effective in reducing frost heave mortality (Bouyoucos 1928; MacKinney 1929; Littlefield 1942; MacGillvray 1973).

Site x S interaction showed that despite site differences in frost heaving, S always had a positive effect on mortality. In fact, the more severe the site, the greater the benefit S had in preventing frost heaving. It has been reported that frost heaving is dependent on

soil texture and depth to the water table (Kinosita 1989; Sheng 1994). These site factors along with the temperature and precipitation rates over the winter months severely affect the amount that a seedling can be lifted from its original planting position (Fahey 1979). An initial study by Beskow (1935) and then again demonstrated by Kinosita (1979) showed that the higher the ground water table, the greater the rate of frost heaving, and the opposite occurs with a lower ground water table. A full saturation of soil leads to a higher rate of frost heaving (Grant 1973; Russell 1978) and combined with the high ground water table, a maximum amount of frost heaving likely occurs in some areas of the sites, especially site 2 and 3 which has some of the shallowest soils in the experiment. Site 1 experienced the lowest frost heaving mortality (6.8%) likely due to the on average depth to bedrock of $31.93\text{cm} \pm 12.18\text{cm}$, whereas sites 2 and 3 had a 12.9% and 13.1% frost heaving mortality, respectively.

In addition, water permeability is another factor that determines the frost heaving susceptibility of a site. Permeability considers several factors including soil texture. Sandy soils have a larger pore space and therefore higher permeability, but the moisture suction will be lower. This lower moisture suction means that water cannot easily move to the freezing front and thus minimizes frost heaving. In contrast, clay has a fine-grained soil texture resulting in higher moisture suction but also a lower water permeability which hinders water movement to the freezing front mitigating frost heaving. Silty soils with intermediate permeability and moisture suction are also highly susceptible to frost heaving (Penner 1959).

CWD and its interactions had a positive effect on reducing frost heaving mortality. Overall, CWD and NCWD had a 2.5% and 19.4% frost heaving mortality,

respectively. The addition of CWD does insulate the ground by reducing direct environmental impacts; however, more importantly it creates a heavier overburden layer which also lowers the rate of frost heaving (Taber 1930; Goulet 1995). Over time, CWD will ameliorate the soil by trapping organic matter within the plots increasing the insulation of the soil from frost penetration, and the effects of frost heaving (MacKinney 1929; MacGillvray 1973). In addition, with each passing year the seedlings will have developed a more extensive root system that reduces the risk of frost heaving mortality.

The MC treatment increased frost heaving mortality from NMC at 8.5% to MC at 13.4%. In solely MC treated plots, frost heaving mortality was 47%, the greatest mortality of any treatment. The MC treatment created a slightly deeper soil profile than the NMC plots around them. The MC plots were easier to plant providing seedling root systems a better growth substrate, the new substrate had a higher susceptibility to heaving perhaps due to lower soil bulk density and created intermediate soil pore sizes which may have promoted frost heaving (Penner 1959).

The plant species effect was relatively small, accounting for 1.3% of the total variation and there were no significant species interactions for frost heaving mortality. Alders had slightly greater mortality than birches. A species that survives a period of frost heaving has a much higher chance at surviving to adulthood (Haasis 1923; Groeneveld 2002). The type of roots a plant puts out influences the survival of the species (Schramm 1958; Heidmann 1974). White birch and gray birch are both shallow rooting species depending on the soil depth (Pomerleau 1962, Chapman 1990) and GA and SA are also shallow rooting species (Hosie 1969; Farrar 1995). Schramm 1958 looked at tree seedlings being heaved out of the soil and concluded that the top 2-3 inches had the

largest effect, which was further confirmed by Heidmann in 1974 with their use of “Ontario” plugs being heaved out when planted flush with the soil surface. The alders particularly SA suffered the greatest frost heaving mortality with 14.8% and GA with 11.7% compared to birches at 8.6%

First full year mortality

Here we have documented and discussed the three causes of mortality on a severely degraded barren for 25 years landscape. Overall, frost heaving was the greatest factor in mortality during the first full year and the frost heaving mortality interactions and main effects were similarly found significant in the first full year mortality. From a species perspective, SA suffered the most mortality from all three causes of mortality probably for its hydrophilic requirements (Brisson 2006) were not met in the barren shallow soil landscape. The remaining three species survival were comparable. Growth will also be a determinant for how each species will be affected by site preparation treatments (Galea et al. 2023). As for site preparation factorial treatments, there was a clear demarcation between NS and S on overall first year mortality with S having very low mortality as well S interactions with other site preparation treatments on mortality. It's clear the combination of benefits that S provides such as moisture retention in the summer to prevent drought mortality (Tao et. al. 2015), and insulation in the winter to prevent frost heaved mortality (Chalker-Scott 2007) makes it the best single treatment with S having 12% mortality. The worst overall treatment, worse than control, for first full year mortality was MC alone at 60.9% which as discussed earlier was driven by frost heaving, accounting for most of this mortality (47%). Second worst overall mortality was

control (no site preparation treatments) with 37.5% overall mortality again driven mostly by frost heaving mortality. The third worst was CWD alone accounting for 25% mortality, this however was largely driven by summer mortality, but is expected to drastically reduce mortality and enhance the fertility of the plots in the future (Jia-bing et al 2005). In the literature there is a lack of information surrounding the combinations of the three treatments, however data from this experiment and Galea et al (2023, unpublished) regarding growth over two years provides insight on how the combinations effect the species. From these mortality causes and the overall full year mortality, there were additive effects or benefits to site preparation treatments such as S CWD and MC in that order, but also some negative site preparation effects such as MC alone. Next on the ranking list is MCCWD with 16.2% mortality. With the addition of CWD on MC plots, initially the first summer results saw a 4% increase in mortality but after the first full year there is a 27% reduction in mortality in plots containing both MC and CWD compared to just MC plots. The accumulation of organic matter in CWD over time should increase the moisture levels of the microsites and accelerate the decomposition of the CWD and other organic matter (Yatskov, Harmon & Krankina 2003; Müller-Using & Bartsch 2009). SMC had 12.5% mortality, still 0.5% higher than S alone, but considering the 60.9% mortality of MC alone, the apparent downsides of MC allowing for greater water infiltration (Richardson 1980) and creating a substrate more susceptible to frost heaving were balanced out by straws ability to retain moisture and insulate against frost heaving (Deters 1939; Littlefield 1942; Samra and Singh1998; Rokich, et al. 2002). MC has an additional benefit from a logistical view in that it made planting easier. The combination

of the three-site preparation and SCWD had the lowest first full year mortality both with 3.2% due to the additive effects of the three treatments.

Application

Many site restoration planting efforts fail in barren degraded areas due to the lack of soil, soil moisture, nutrients, and frost heaving. Barren sites are exposed to some of the harshest elements which include high temperatures, solar radiation and wind, extreme temperature changes and low soil moisture conditions. Site preparation treatments such as S, CWD and MC allow these sites to become more habitable for survival. The first year results found the implementation of all three treatments in combination reduced mortality to 3.1%. While the use of MC provides benefits such as improved aeration, water infiltration, root penetration, and ease of planting, the synergies with straw to reduce surface evaporation, erosion control, and increase soil moisture retention during critical times of the growing season substantially reduces mortality. In addition, the straw clearly acts as a temperature insulator to prevent frost heaving and resulting mortality. Straw plots in combination with CWD provides protection from severe elements but may be necessary on some sites to prevent straw from being blown or washed away by weather events. Early-successional species such as WB, GB, GA, and SA need site preparation treatments to establish and survive the first year on long-term barren lands. SA is a hydrophilic species and had greater mortality from summer drought and thus appears to need more moist sites. After one year, GB has proved itself to be the best at surviving the harsh site conditions; nevertheless, GA and WB had comparable survival under these harsh conditions.

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Chapter 2: Growth and biomass of four early-successional species on severely degraded sites using a factorial of three site preparation treatments.

Abstract

A land restoration experiment using three site preparation treatments, straw (S), Meri-Crusher (MC), and coarse woody debris (CWD) in a 2 x 2 x 2 factorial design using four early-successional species, white birch (WB, *Betula papyrifera* Marsh), gray birch (GB, *Betula populifolia* Marsh), green alder (GA, *Alnus viridis* Vill. ssp. *crispa* Ait) and speckled alder (SA, *Alnus incana* L. ssp. *rugose* Du Roi) on sites that were barren for 25-years. The two- and three-way interactions were very nearly all magnitude effects and not rank change. GB had the greatest overall first-year height growth followed by GA, SA, and WB, with 12.1, 9.7, 9.6 and 5.6 cm, respectively. Straw doubled while CWD and MC increased first-year height growth by 43 and 31%, respectively. Second year, GA now had the greatest height growth, followed by SA, GB, and WB, with 42.5, 30.5, 13.4 and 13.0 cm, respectively. Site preparation treatments further their height growth affect with S and CWD doubled second year height growth and MC approximately the same with an increase of 25%. Alders and birches had on average 3 and 1 stems, respectively and alders increased mean stem number under S and CWD. Overall stem dry mass, GA, SA, GB and WB had 58.4, 30.3, 5.4 and 4.0g, respectively. S tripled, CWD doubled and MC increased stem dry mass by 40%. For WB, site preparation combinations had an additive effect, whereas GB, GA, and SA had several combined site preparation treatments showing synergistic results, greater than the additive effects of single treatments. Under control (no site prep) 2nd year stem dry mass for WB, GB, GA and SA were 0.7, 1.4, 17.8 and 0.5g, respectively. Under the three, MCSCWD, treatments, WB, GB, GA and SA had 6.6, 12.3, 115.7 and 70.6g stem dry mass, respectively. SA is ecologically a lowland

species and hence the low 0.5g under control, however the result under the three combined treatments speak to the combined treatment effectiveness on these barren sites. There is very little literature on combined treatments results. GA seem to be the best adapted to the site having the greatest stem dry mass under control and was considerably magnified under site preparation treatments. In addition, alders form symbiotic relationships with N-fixing bacteria and although observed in some first-year roots did not fully express this advantage on these severely degraded sites until the second year by up to 13x the birches in stem dry mass production.

Introduction

Barren landscapes present great restoration challenges and if left alone lead to continued soil erosion and increased sedimentation in local waterways, negatively effecting aquatic environments (Patric 1976; Ryan 1991). Exposed areas with little vegetation provide no plant nor soil shelter from the elements which results in increased desiccation due to full exposure to the sun and heat. Drought is one of the principal factors limiting forest productivity on a worldwide basis (Abrams 1990; Trenberth et al. 2014, Fathi & Tari 2016). Increased shade from vegetation or otherwise provides greater moisture retention due to a lower surficial evaporation and allows for a greater survival and growth of seedlings (Amissah et al 2015; Asghar et al 2019; Galea et al. 2023). Successional restoration should start with planting of early-successional native species which have adaptations to allow sites to start natural successional processes (Polster 1989). Seedlings with no protection or cover will experience low moisture and nutrient availability, have restricted growth and, therefore, produce less biomass; however, biomass accumulation is crucial for enriching poor soils as it contributes to the soil organic matter.

Development of soils should be among the first priorities when reclaiming barren sites (Polster 1989). Soils in degraded areas are often compacted, lack water holding capacity and soil nutrients (Jochimsen 1996; Bradshaw 1997; Šourková 2005). Natural weathering and enlargement of rock fractures can be hastened by roots and their associated fungi (Frazier & Graham, 2000; Landeweert et al., 2001), and mycorrhizal hyphae can grow where roots can't fit (Bornyasz et al., 2005). Poor soil conditions limit what species can grow since, in addition to negative soil conditions, there is often a

shallow depth to bedrock that negatively affects plant growth (Rajakaruna & Boyd 2008). Reintroduction of original topsoil to barren sites is a promising method to ameliorate adverse environmental conditions; however, accessibility of topsoil is often restricted in severely disturbed sites and there is a very high likelihood of more erosion (Skrindo, 2005).

Early-successional trees are known for their ability to succeed in open, post-disturbance landscapes (Fox 1984; Swanson et al. 2011). Some early successional species are known for relatively fast growth despite existing in harsh environments and their tendencies to be bio-accumulators (Lanner 1983; Fox 1984; Monsen 2004). Returning nutrients to the soil and eventually ameliorating the coarse substrate into a forest supporting soil may be accelerated by using early-successional deciduous species, since it has been shown that nutrient content and organics within hardwood forests are often greater than conifer forests (Son et al. 2007; Ste-Marie et al. 2007). We examined four early-successional deciduous species; {white birch (WB, *Betula papyrifera* Marsh), gray birch (GB, *Betula populifolia* Marsh), green alder (GA, *Alnus viridis* Vill. ssp. *crispa* Ait) and speckled alder (SA, *Alnus incana* L. ssp. *rugose* Du Roi). All four species have some histories in restoration efforts due to their ability to withstand and reclaim harsh sites (Hosie 1969; Vogel 1981; Lanner 1983; Fox 1984; Blundon 1990; Monsen 2004). White birch prefers deep, well drained, rich soil, but can still compete in a wide range of soil types ranging from gravels to silts and organic bog to peat soils (Haeussler 1986). Gray birch grows best on a moist, well drained site, but is quite adaptable and can grow well on dry sandy or even gravelly soil (DeHond 1989; Chapman 1990). Green alders prefer moist sites but can tolerate dry sites with soil types ranging from gravelly to sandy and

will regularly be found on upland glacial till sites (Furlow 1979). Speckled alders prefer wet sites where it can compete best such as beside waterways, bogs, fens, but will also establish in mires with peaty soils (Armstrong 1982; Brisson 2006). In Minnesota, it was noted that speckled alder will grow in mesic to moist sites but was found more in moist sites (Bakuzis 1962).

In this study we used a three, site preparation factorial: 1) site crusher to create a loose aggregate using a Meri-Crusher (MC) (company and location), 2) straw (S) coverage, and 3) coarse woody debris (CWD) coverage. Site crushing involves mechanically ripping the top layer of aggregate to create a substrate which can be used to restore terrestrial ecosystems with little to no existing substrate available (Ashby 1997; Polster, 2009). Breaking in situ soil beds is better than replacing with soil (Lambermont & Lebon 1978) and benefits of ripping the soil include improved aeration, water infiltration, root penetration, and some control of erosion (Richardson 1980). Straw coverage can affect the processes occurring in the top layer of the soil such as reducing surface evaporation (Novak et al 2000), improve water infiltration (Adekalu et al 2007), increase moisture retention (Edwards et al 2000; Balwinder-Singh 2011; Rahma et al 2019), and can act as an insulator and regulate extreme temperatures in the winter to help prevent frost heave of planted seedlings (Liu et al 2014). Coarse woody debris can create protected microsites (Pyper M, 2012), has been shown to decrease water loss and seedling desiccation by providing shelter from the elements (Jumpponen, 1999). There is a preponderance towards larger CWD as smaller pieces like wood mulch can draw what little available nitrogen from the soil via different fungi to fuel decomposition (Wells and Boddy, 1990).

Our goal is to quantify the effects of three site preparation treatments: straw (S), Meri-Crusher (MC), and coarse woody debris (CWD); in a 2 x 2 x 2 factorial design resulting in 8 treatments on seedling growth of four early-successional species. Our objective was to quantify first- and second-year height growth, second-year stem number, and stem dry mass. We hypothesized that the presence of site preparation treatments will have a positive effect on growth. We also hypothesize that when site preparation treatments are used together their effects may be additive. In addition, we hypothesize that there will be genus and species differences in growth.

Methodology

Site preparation treatments

Three site preparation treatments: MC, S and CWD were used in a factorial design which resulted in eight site preparation treatments on three sites at CFB Gagetown, NB, (45.68108, -66.50179.). This was replicated by four blocks on each site resulting in 32 plots per site. The MC treatment was created using a John Deere 200D excavator equipped with a MJ hydraulic 1.4 ST Meri-Crusher (Voukatti, Finland). The MC plots produced a 3.2m by 3.2m square of torn aggregate. Straw square bails were used to cover approximately 18m² of area or roughly 2 experimental plots to a depth of 5cm. The CWD was sourced from DND Gagetown using primarily GB. All CWD was processed into ~3m length to match the MC plots. The CWD was placed in a north-south direction and had an average volume of 0.2033m³ ± 0.02m³ and was applied to 48 plots. The placement of CWD was done last to hold the straw if present in place.

Plant materials

Four species from bulked seedlots to better represent species (provenances, Table 1), WB, GB, GA, and SA, were grown during 2020 at the Atlantic Forestry Center (AFC), Fredericton, NB (45.93501, -66.65745) SA were grown in Scot and Stewart nurseries in St. Andrews, Nova Scotia (45.53292, -61.86888.). In January 2021 stems were cut to a height of roughly 10cm tall and put into boxes for frozen storage at - 4° C in AFC freezers. The seedlings were taken out 3-4 days prior to planting to thaw. Each experimental plot (32 plots x 3 sites = 96 plots) had four replicates of each species randomly planted in each plot May 7-8, 2021.

Table 7. Species and provenance seedling material used in the experiment.

Species	Source Year	Provenance	Country	Latitude (N)	Longitude (W)	Elevation (m)
<i>Betula papyrifera</i> white birch	1998	Wayerton, NB	CAN	47.21667	-65.93333	300
<i>Betula papyrifera</i> white birch	1998	Jewetts Creek, NB	CAN	45.83333	-66.98333	50
<i>Betula populifolia</i> gray birch	2008	Newmarket, NB	CAN	45.80501	-66.95634	149
<i>Betula populifolia</i> gray birch	2008	Newmarket, NB	CAN	45.83147	-66.97115	130
<i>Betula populifolia</i> gray birch	2008	Newmarket, NB	CAN	45.8076	-66.96825	141
<i>Betula populifolia</i> gray birch	2008	Newmarket, NB	CAN	45.83486	-66.96272	125
<i>Betula populifolia</i> gray birch	1999	Bai-du-Vin, NB	CAN	47.03333	-65.16666	5
<i>Alnus viridis ssp. crispa</i> green alder	2002	West Quaco, NB	CAN	45.33	-65.53	65
<i>Alnus viridis ssp. crispa</i> green alder	1999	Lower Prince William, NB	CAN	45.87	-67	20
<i>Alnus incana ssp. rugosa</i> speckled alder	1983	Enmore, PEI	CAN	46.58	-64.05	10
<i>Alnus incana ssp. rugosa</i> speckled alder	1983	Valleyfield, PEI	CAN	46.13	-62.72	45
<i>Alnus incana ssp. rugosa</i> speckled alder	1983	Shediac, NB	CAN	46.23	-64.6	15

Note: NB, New Brunswick; PEI, Prince Edward Island

Soil Properties

For each plot, five soil depth to bedrock measurements were made using an iron rod gently hammered into the soil in the spring of 2023. Soil samples were collected in October 2020 from 3 sites x 2 treatments MC, no MC (NMC) x 4 replicates for a total of 24 total samples. Soil analysis included percent sand, silt, clay, and organic matter; percent carbon (C), and nitrogen (N) using phosphorus (P) available potassium (K), calcium (Ca), magnesium (K), concentration, and pH by the Laboratory for Forest Soils and Environmental Quality at the University of New Brunswick, Canada. Soil bulk density measurements were made on 16 plots per site, 8 meri-crushed plots and 8 non-meri-crushed plots for a total of 48 samples, in the fall of 2022. Table 2 provides a soil property summary among sites. Soil moisture (%) was measured periodically using a ML3 ThetaProbe soil moisture sensor (Cambridge, England), by recording three readings per plot. In 2021, soil moisture readings were taken on 13 collection dates ranging from March 3rd to September 9th. In 2022 soil moisture readings were taken on three dates: June 22nd, July 12th, August 4th.

Plant Measurements

Initial heights (cm) were measured from the ground with a steel ruler on June 17th, 2021, and then again on November 2nd at the end of the season to determine first year growth. The last height measurement was made on the 6th of September 2022, which determined the second year's growth. The largest individual of each species in each plot was marked with a flag for harvesting for stem dry mass (stem *dm*) measurement in September 2022. The selected trees would later be removed approximately 3cm from

ground level by pruning sheers, stem numbers recorded and bagged and dried (65°C at equal or greater than 72 hrs) and weighed.

Statistical analysis

The experiment was established as a randomized block design. Initial soil properties were subjected to analyses of variance (ANOVA), site and MC were fixed effects, block was a random effect. The following ANOVA model was used:

$$Y_{ijk} = \mu + B_i(S_j) + S_j + M_k + SM_{jk} + e_{ijk}$$

where Y_{ijk} is the dependant soil property trait of the i^{th} block, j^{th} site, and the k^{th} MC treatment, and μ is the overall mean. $B_i(S_j)$ is the random effect of i^{th} block ($i = 1,2,3,4$) nested in site, S_j is the effect of the j^{th} site ($j = 1,2,3$), M_k is the effect of the k^{th} MC treatment ($k = 1,2$), SM_{jk} is the interaction effect between j^{th} site effect and k^{th} MC treatment effect, and e_{ijk} is the random error component.

Available soil moisture in 2021 were subjected to analyses of variance (ANOVA), site, S, MC, and CWD were fixed effects, block was a random effect. The following ANOVA model was used:

$$Y_{ijklm} = \mu + B_i(T_j) + T_j + S_k + M_l + C_m + TS_{jk} + TM_{jl} + TC_{jm} + SM_{kl} + SC_{km} + MC_{lm} + TSM_{jkl} + TSC_{jkm} + TMC_{jlm} + SMC_{klm} + e_{ijklm}$$

where Y_{ijklm} is the dependant soil moisture availability of the i^{th} block, the j^{th} site, k^{th} S treatment, l^{th} MC treatment, m^{th} CWD treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of the i^{th} block ($i = 1,2,3,4$) nested in the j^{th} site T_j is the effect of the j^{th} site

($j = 1,2,3$), S_k is the effect of k^{th} S treatment ($k = 1,2$), M_l is the effect of l^{th} MC treatment ($l = 1,2$), C_m is the effect of the m^{th} CWD treatment ($m = 1,2$), and e_{ijklm} is the random error component. Interactions of the single effects are included up to three-way interactions, 4- and 5-way interactions are folded into the error term.

First and second year growth (cm) stem count, and stem dm (g), were analyzed using analysis of variance (ANOVA). MC, S, CWD, species, and site were all considered as fixed effects. Block and replicates were random effects. The following ANOVA model was used:

$$Y_{ijklno} = \mu + B_i(T_j) + T_j + P_k + S_l + C_n + M_o + TP_{jk} + TS_{jl} + TC_{jn} + TM_{jo} + PS_{kl} + PC_{kn} + PM_{ko} + SC_{ln} + SM_{lo} + CM_{no} + TPS_{jkl} + TPC_{jkn} + TPM_{jko} + TSC_{jln} + TSM_{jlo} + TCM_{jno} + PSC_{kln} + PSM_{klo} + PCM_{kno} + SCM_{lno} + e_{ijklno}$$

where Y_{ijklun} is the dependant biomass trait of the i^{th} block, within the j^{th} site, of the k^{th} species, in the l^{th} S treatment, n^{th} CWD treatment, o^{th} MC treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of block ($i = 1,2,3,4$) nested in site, T_j is the effect of the j^{th} site ($j = 1,2,3$), P_k is the effect of the k^{th} species ($k = 1,2,3,4$), S_l is the effect of the l^{th} S treatment ($l = 1,2$), C_n is the effect of the n^{th} CWD treatment ($n = 1,2$), M_o is the effect of the o^{th} MC treatment ($o = 1,2$), and e_{ijklno} is the error random error component.

Interactions of the single effects are included up to three-way interactions, 4- and 5-way interactions are folded into the error term.

All effects were considered significant at the $p = 0.05$ level, though all p-values were presented for individual consideration. The data satisfied normality and equality of

variance assumptions. Stem count data were square root transformed to create a normal distribution for analysis. The general linear model from Systat Software Inc. (Chicago, Illinois) was used for analysis. If significant, site and species was post-hoc tested using Tukey mean separation test ($p = 0.05$). The variance components analysis was conducted using the sum of squares as outlined by Hicks (1982, pp. 55–57). Expected stem *dm* for single site preparation treatment were calculated using the individual treatment stem *dm* subtracting the base stem *dm* present in the control plots. Expected stem *dm* of site preparation treatment combinations for additive comparisons are from adding treatments and control stem *dm*. Significant interactions are referred to as either rank change interaction, or magnitude effect interaction. A rank change interaction occurs when one effect has a greater mean under one scenario and lower mean under another scenario. A magnitude effect would refer to when the effect mean is always greater than under both scenarios, but of different magnitudes.

Results

In Fall 2020 there were little to no differences in soil texture or nutrient contents between MC or NMC plots, so they were aggregated (Galea et al. 2020). In addition, soil bulk density was not significantly different between MC treatments or sites. In 2022, soil analysis showed that organic matter on site 1 was significantly greater compared to site 2 or 3 (Table 2). Site 1 total N was greater than site 2 and 3. Carbon was lowest in site 2 compared to sites 1 and 3. C:N ratio was highest in site 3, being more than double sites 1 and 2. pH differed between site 1 and 3 but not site 2. P was lowest in site 2 and equally

greater in sites 1 and 3. Site 1 had the highest clay content and conversely the lowest sand compared to sites 2 and 3. Silt was highest in site 1 and decreased in sites 2 and 3.

Average depth to bedrock for site 1 was greater than site 2 and 3. Rock content which was removed before analysis was on site 2 and 3 greater than site 1.

Table 8. 2022 soil properties for three experimental sites on DND Base Gagetown

ID	Organic matter (%)	Total Nitrogen (%)	Carbon (%)	C:N Ratio	pH	Phosphorus (ppm)	Potassium (meq/100g)
Site 1	1.27±0.91a	0.16±0.03a	4.33±2.15a	26.18±9.14b	4.83±0.11b	5.75±2.96a	0.14±0.08a
Site 2	0.61±0.33b	0.11±0.02b	3.21±1.61b	29.26±14.13b	4.85±0.13ab	3.94±1.92b	0.13±0.07a
Site 3	0.63±0.27b	0.08±0.01c	4.65±1.58a	60.54±19.55a	4.92±0.16a	5.78±2.27a	0.11±0.06a
ID	Calcium (meq/100g)	Magnesium (ppm)	Clay (%)	Silt (%)	Sand (%)	Rocks (%)*	Average Depth (cm)
Site 1	0.34±0.31b	0.18±0.11b	16.19±2.74a	42.38±6.27a	41.66±8.42b	31.75±15.59b	31.93±12.18a
Site 2	0.94±0.86a	0.35±0.23b	12.97±4.57b	34.22±8.28b	52.75±12.32a	39.88±15.99a	11.64±7.27b
Site 3	1.73±2.24a	0.66±0.85a	12.09±4.3b	28.88±7.94c	59.16±11.95a	50.06±19.01a	14.94±9.78b

Note: Significant differences between sites are portrayed by letters "a", "b" or "c"

*Rocks(%) was taken before the sand, silt, clay (%), which are equal to 100%

Soil Moisture

Soil moisture content during the first year corresponded with rainfall (Figure 1).

Average soil moisture content increased with the greater instances of rainfall from July 1st onwards. Soil moisture content was significantly greater for S than NS treatments during dry conditions such as June 2021. As the soil accumulated more rain, the effect of straw was not significant. The higher instances of rain fall during 2022 combined with

the reduced sampling saw that S had greater soil moisture content than NS on July 22nd ($p = 0.053$) (Fig. 2).

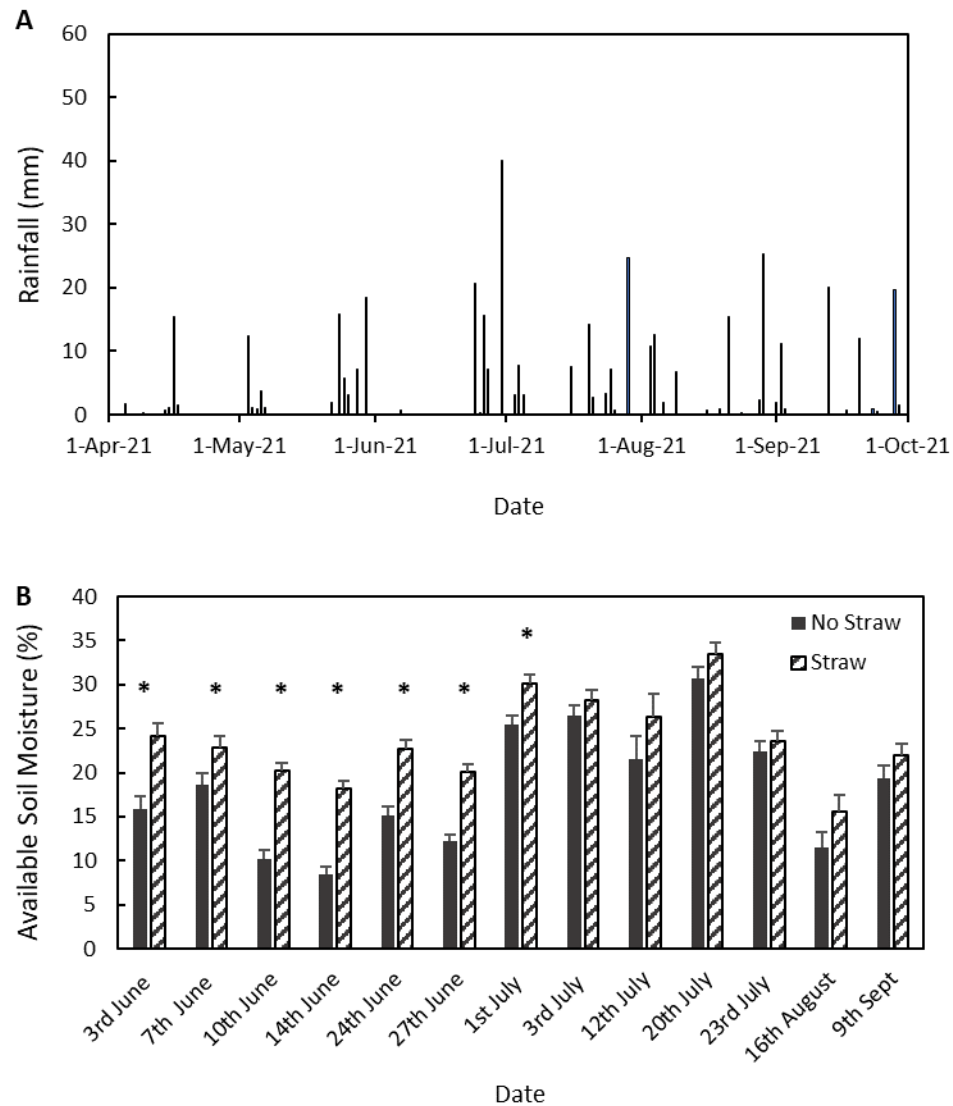


Figure 14.. Soil moisture content (A) Rainfall (mm) sourced from Fredericton area from April 1st, 2022 - September 30th, 2022. (B) Soil moisture readings in 2021 showing differences between straw and no straw coverage on dates where field assessments were done. Dates marked with * are significantly different $P < 0.05$. Note x-axis dates range differ.

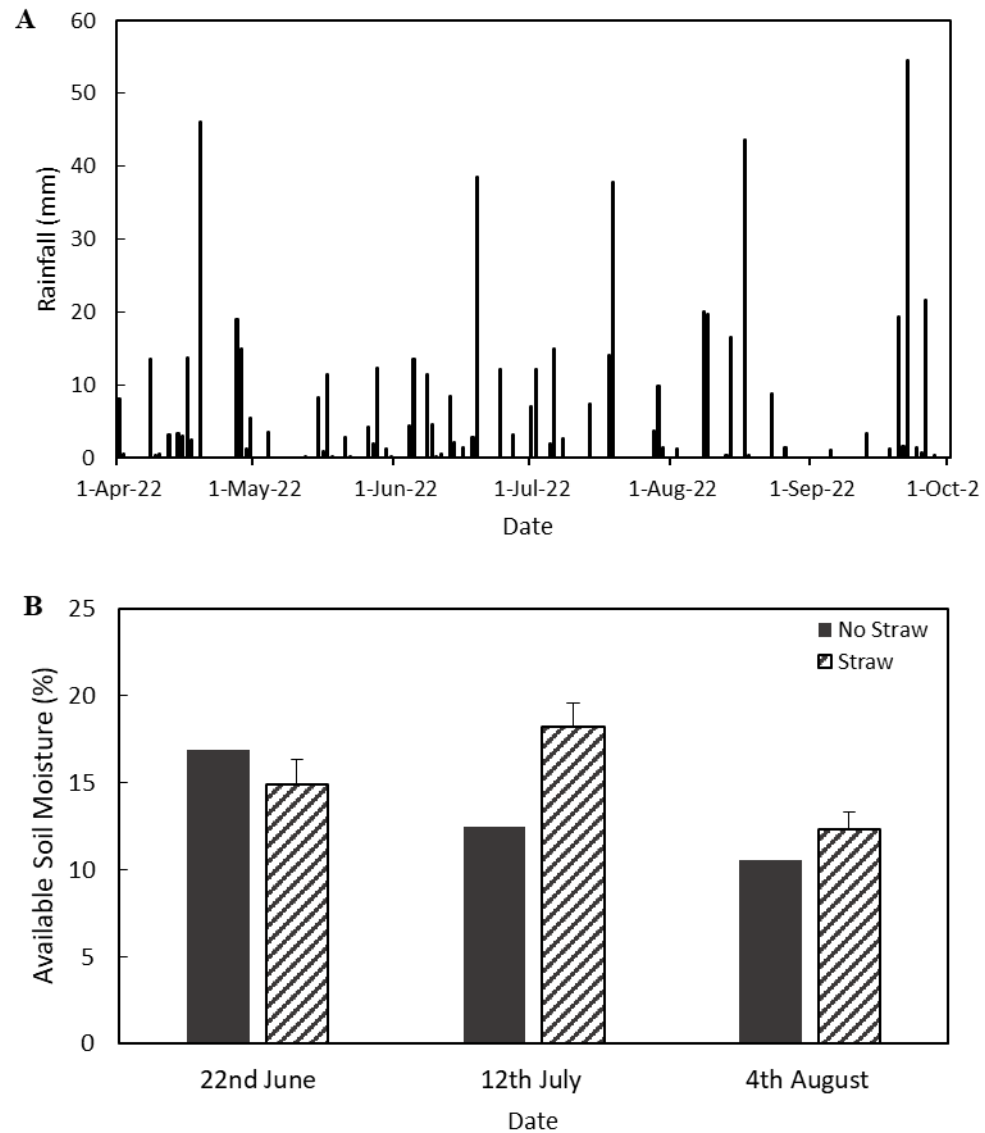


Figure 15. Soil moisture content. A) Rainfall (mm) sourced from Fredericton, NB. area from April 1st - Sept 30th. B) Soil moisture readings taken in 2022 showing differences between straw and no straw plots on dates when field assessments were done. Note: X-axis ranges differ.

First Year

First, first-year height growth (cm) was most influenced by S, species and CWD, accounting for 9.1%, 6% and 3% of total variance, respectively (Table 9). Second, it is important to note for ease of interpretation, first-year height growth two- and three-way interactions were all magnitude effects except for one small rank change inside the site x CWD x MC interaction.

Table 9. Site preparation treatments, species, and site effects and interactions on first year growth ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.

First Year Growth				
Source of Variation	df	MS	VC(%)	P value
MC	1	2229.036	1.8	<0.001
S	1	11329.324	9.1	<0.001
CWD	1	3766.011	3.0	<0.001
SITE	2	2312.886	3.7	<0.001
SPECIES	3	2616.067	6.3	<0.001
BLOCK(SITE)	9	461.287	3.3	<0.001
S*MC	1	124.613	0.1	0.151
CWD*MC	1	27.561	0.0	0.499
SITE*MC	2	840.471	1.3	<0.001
SPECIES*MC	3	37.453	0.1	0.602
CWD*S	1	0.012	0.0	0.989
SPECIES*S	3	504.543	1.2	<0.001
SITE*S	2	29.887	0.0	0.610
SPECIES*CWD	3	217.799	0.5	0.013
SITE*CWD	2	214.289	0.3	0.029
SITE*SPECIES	6	76.581	0.4	0.269
CWD*S*MC	1	11.183	0.0	0.667
SPECIES*S*MC	3	47.021	0.1	0.506
SITE*S*MC	2	151.289	0.2	0.082
SPECIES*CWD*MC	3	78.941	0.2	0.271
SITE*CWD*MC	2	195.077	0.3	0.040
SITE*SPECIES*MC	6	42.277	0.2	0.650
SPECIES*CWD*S	3	100.517	0.2	0.173
SITE*CWD*S	2	740.767	1.2	<0.001
SITE*SPECIES*S	6	143.817	0.7	0.037
SITE*SPECIES*CWD	6	63.679	0.3	0.388
Error	1347	60.386	65.2	
R2	0.59			

Site 1 always had greater height growth than sites 2 and 3 in all combinations except under CWD and MC, where site 3 had the greatest height. Third, the significant

two way and three-way interactions were best captured by presenting species x CWD x S interaction (Fig. 3A) and site x CWD x S (Fig. 16B). The species x S and species x CWD interactions are illustrated by S and CWD always had greater height growth for all species compared to NS and NCWD, respectively, but of differing magnitudes (Fig. 16A). Similarly, the site x S x CWD interaction (Fig. 16B) illustrated that S and CWD were always greater than NS and NCWD across all sites but of differing magnitudes. Given that the interactions were magnitude effects, for the main effect S overall resulted in a doubling of height growth from 6.4cm to 12.1cm, CWD increased height growth by 43% from 7.6cm to 10.9 cm and MC increased height growth 31% from 8cm to 10.5cm. GB had the greatest overall height growth followed by GA and SA and WB, with 12.1cm, 9.7cm, 9.6cm and 5.6 cm, respectively (Fig. 16A). Site 1 had the greatest height

growth followed by site 3 and site 2 with 11.5cm, 9.2cm and 7.1cm, respectively (Fig 16B).

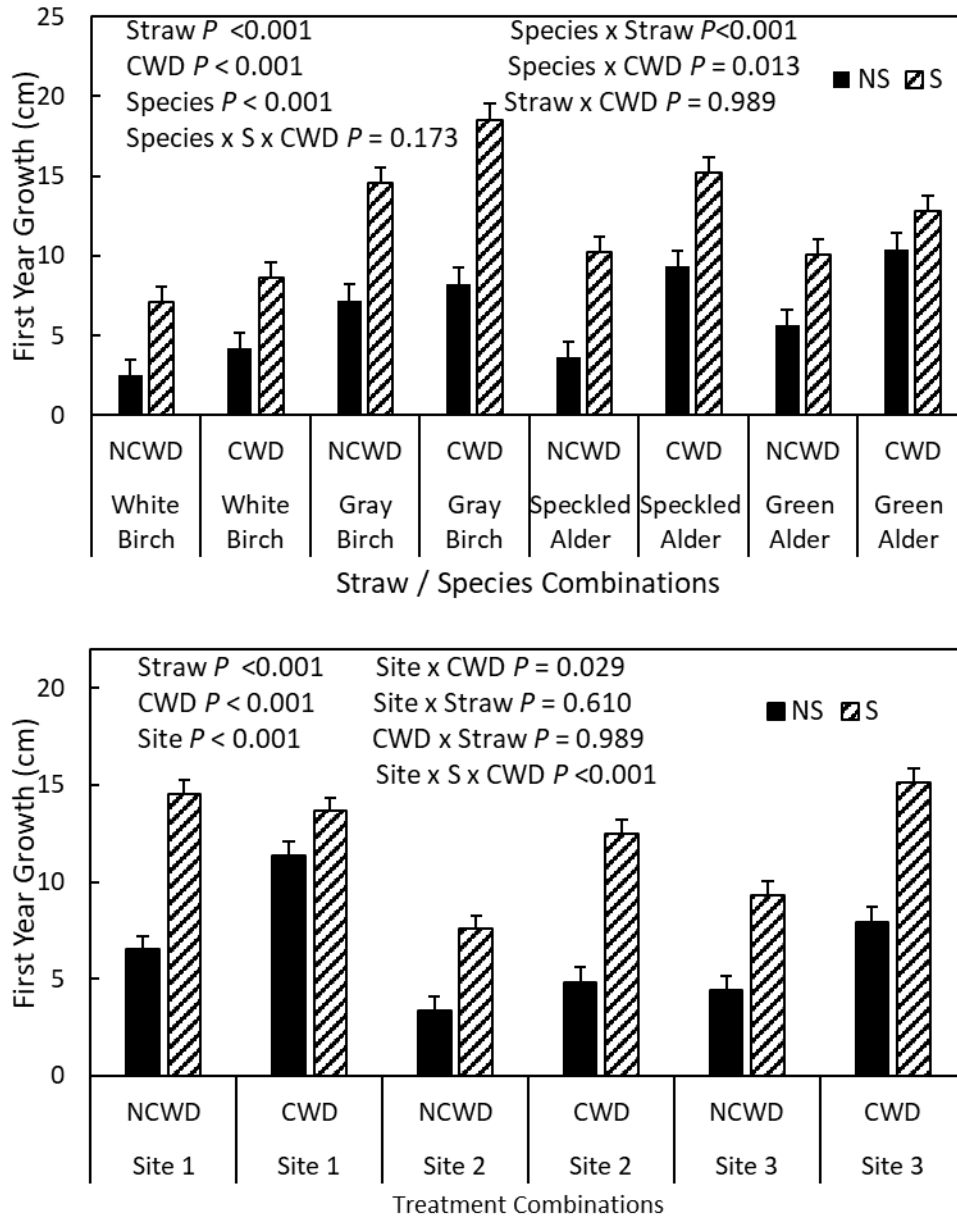


Figure 16. First year growth (cm) showing A) species x S x CWD interaction. B) Site x S x CWD interaction.

Second Year

First, second-year height growth (cm) was most influenced by the same three effects but in a different order and magnitude with species, S and CWD, accounting for 33.5%, 8.2% and 7.4% of the total variance, respectively (Table 10). Second, all second-year height growth two- and three-way interactions were all magnitude effects. Third, again significant two-way and three-way interactions were best captured by presenting species x CWD x S interaction (Fig. 17A) and site x CWD x S (Fig. 17B).

Table 10. Site preparation treatments, species, and site effects and interactions on second year growth ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.

Second Year Growth				
Source of Variation	df	MS	VC(%)	P value
MC	1	7523.429	1.4	<0.001
S	1	42715.569	8.2	<0.001
CWD	1	38554.355	7.4	<0.001
SITE	2	4746.407	1.8	<0.001
SPECIES	3	58212.778	33.5	<0.001
BLOCK(SITE)	9	439.142	0.8	0.012
S*MC	1	33.568	0.0	0.671
CWD*MC	1	477.750	0.1	0.109
SITE*MC	2	495.616	0.2	0.069
SPECIES*MC	3	582.258	0.3	0.025
CWD*S	1	39.746	0.0	0.643
SPECIES*S	3	1420.096	0.8	<0.001
SITE*S	2	345.167	0.1	0.156
SPECIES*CWD	3	3966.841	2.3	<0.001
SITE*CWD	2	620.287	0.2	0.036
SITE*SPECIES	6	453.808	0.5	0.023
CWD*S*MC	1	55.890	0.0	0.583
SPECIES*S*MC	3	504.243	0.3	0.043
SITE*S*MC	2	28.388	0.0	0.858
SPECIES*CWD*MC	3	36.562	0.0	0.898
SITE*CWD*MC	2	279.602	0.1	0.222
SITE*SPECIES*MC	6	292.118	0.3	0.151
SPECIES*CWD*S	3	939.252	0.5	0.002
SITE*CWD*S	2	583.284	0.2	0.043
SITE*SPECIES*S	6	183.842	0.2	0.490
SITE*SPECIES*CWD	6	31.091	0.0	0.985
Error	1140	185.361	40.5	
R ²	0.80			

Like first year height growth, the species x S and species x CWD interactions are illustrated by S and CWD always had greater height growth for all species compared to NS and NCWD, respectively, but of differing magnitudes (Fig. 17A). Similarly, the site x S x CWD interaction (Fig. 17B) illustrated that S and CWD were always greater than NS and NCWD across all sites but of differing magnitudes and that site 1 was greater than sites 2 and 3. Given that the interactions were all magnitude effects, for the main effect S overall resulted in a near doubling of height growth from 18.2 to 31.5 cm, CWD also increased height growth near doubling with 18.5 to 31.1 cm and MC increased height growth 25% from 22.1 to 27.6 cm. GA now had the greatest overall height growth followed by SA and GB and WB, with 42.5, 30.5, 13.4 and 13.0 cm, respectively (Fig. 17A). Similarly, site 1 had the greatest height growth followed by sites 3 and 2 with 28.5, 24.9 and 21.1 cm, respectively (Fig 17B).

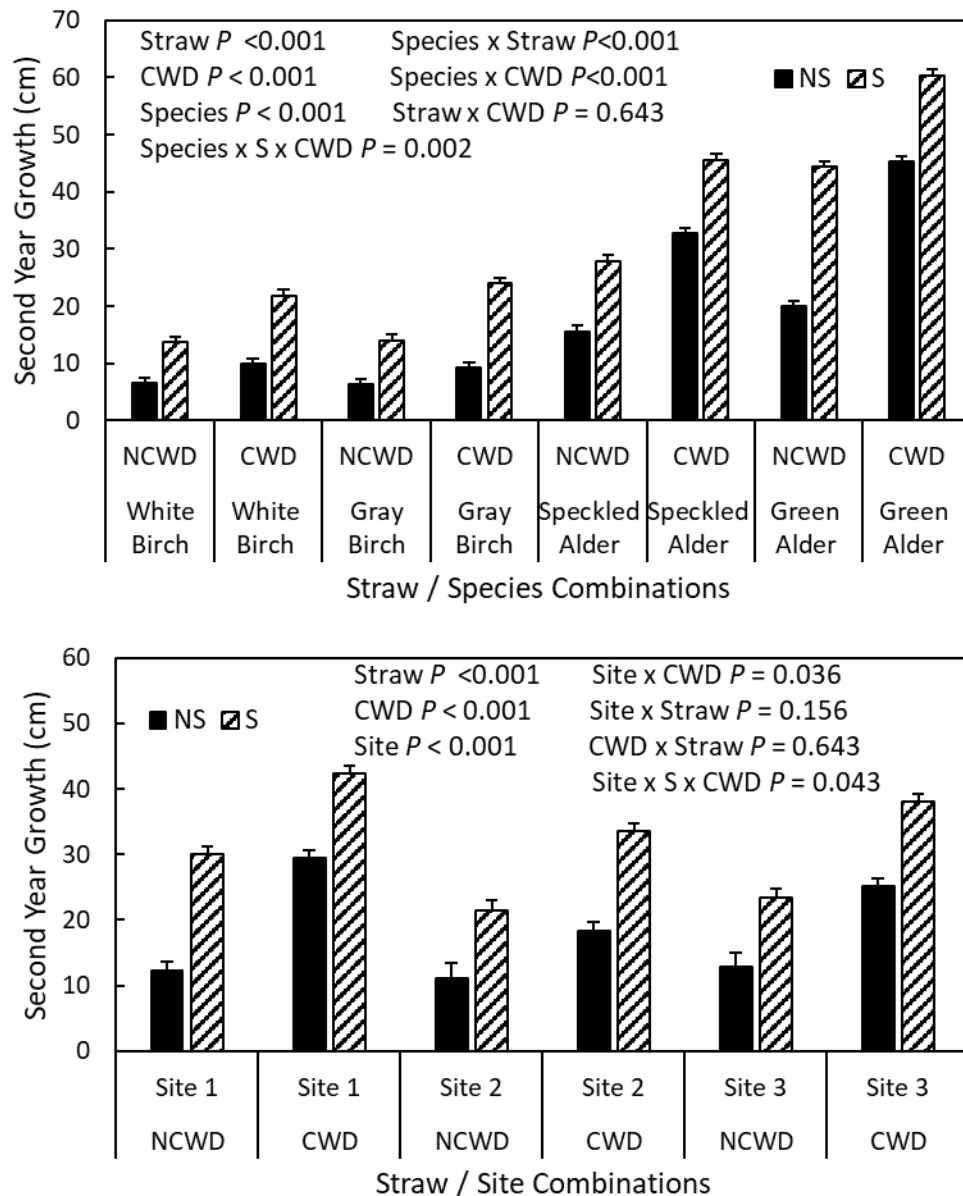


Figure 17. Second year growth (cm) showing A) species x S x CWD interaction. B) Site x S x CWD interaction.

A large difference in species and even genus was present and for the second growing season, species accounted for 33.5% of the total variance with CWD at 7.4% and S at 8.2% following as the next top effects. Site and MC did significantly influence the variance of the second-year growth with 1.8% and 1.4%.

Average stem count

For stem number, species accounted for 42% of the total variation (Table 11). Stem number for both birches were essentially one, while GA and SA mean stem numbers were 3.2 and 2.8 per plant (Fig. 18).

Table 11. Site preparation treatments, species, and site effects and interactions on average stem count ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.

Average Stem Count				
Source of Variation	df	MS	VC(%)	P value
MC	1	1.078	0.0	0.333
S	1	19.094	0.7	<0.001
CWD	1	12.409	0.5	0.001
SITE	2	0.571	0.0	0.608
SPECIES	3	365.217	42.0	<0.001
BLOCK(SITE)	9	1.184	0.4	0.413
S*MC	1	0.000	0.0	0.990
CWD*MC	1	11.625	0.4	0.002
SITE*MC	2	1.416	0.1	0.292
SPECIES*MC	3	0.210	0.0	0.908
CWD*S	1	6.506	0.2	0.018
SPECIES*S	3	10.181	1.2	<0.001
SITE*S	2	0.596	0.0	0.596
SPECIES*CWD	3	6.382	0.7	0.001
SITE*CWD	2	0.666	0.1	0.561
SITE*SPECIES	6	0.334	0.1	0.942
CWD*S*MC	1	1.285	0.0	0.291
SPECIES*S*MC	3	0.615	0.1	0.658
SITE*S*MC	2	5.712	0.4	0.007
SPECIES*CWD*MC	3	8.182	0.9	<0.001
SITE*CWD*MC	2	3.824	0.3	0.036
SITE*SPECIES*MC	6	1.118	0.3	0.442
SPECIES*CWD*S	3	5.314	0.6	0.003
SITE*CWD*S	2	2.841	0.2	0.085
SITE*SPECIES*CWD	6	0.504	0.1	0.854
SITE*SPECIES*S	6	0.904	0.2	0.620
Error	1140	1.149	50.2	
R ²	0.80			

The species x S was a magnitude effect, birches remained unchanged in S treatments; whereas GA and SA in NS to S increased mean stem number from 3.1 to 3.4 and 2.4 to 3.3, respectively. Again, other interactions were minor magnitude or rank change as seen in figure 5, where GA under CWD were basically equal between NS and S whereas the other alder species had greater stem numbers under S regardless of presence or absence of CWD.

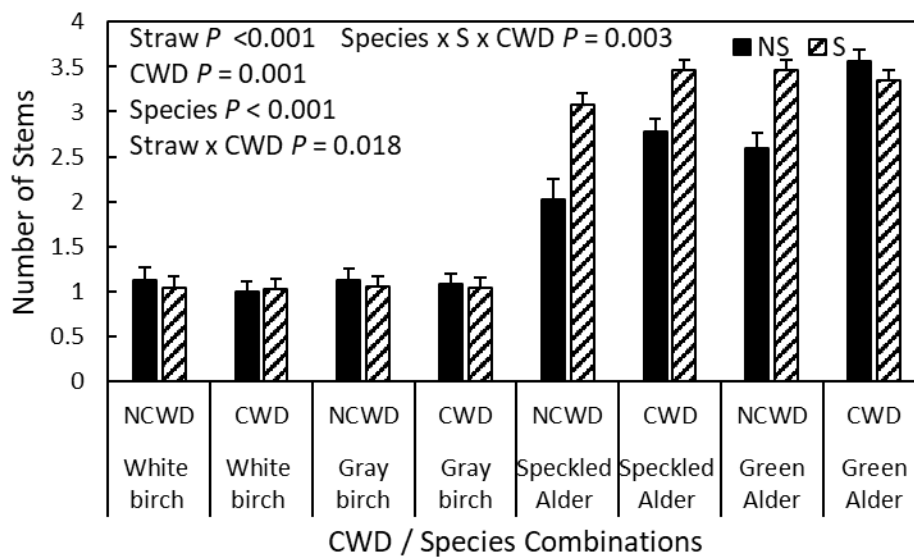


Figure 18. Number of stems showing a species x S x CWD interaction.

Stem dry mass

Mean stem *dm* was also heavily influenced by species accounting for 36.6% of variance (Table 6). There were other factors that were significant and accounted for substantial amount of variation such species x S (6.3%) and S itself (8.6%).

Table 12. Site preparation treatments, species, and site effects and interactions on stem dry mass ANOVA table including degrees of freedom (df), mean square values (MS), variance components (VC), and P values. P values < 0.05 are in bold print.

Stem Dry Mass				
Source of Variation	df	MS	VC(%)	P value
MC	1	6402.516	1.3	<0.001
S	1	41532.943	8.6	<0.001
CWD	1	22465.595	4.7	<0.001
SITE	2	2758.520	1.1	0.003
SPECIES	3	58811.420	36.6	<0.001
BLOCK(SITE)	9	1185.972	2.2	0.007
S*MC	1	1054.536	0.2	0.130
CWD*MC	1	76.506	0.0	0.683
SITE*MC	2	975.820	0.4	0.120
SPECIES*MC	3	1309.781	0.8	0.037
CWD*S	1	447.437	0.1	0.323
SPECIES*S	3	10179.717	6.3	<0.001
SITE*S	2	1278.509	0.5	0.063
SPECIES*CWD	3	7142.417	4.4	<0.001
SITE*CWD	2	50.165	0.0	0.896
SITE*SPECIES	6	780.715	1.0	0.119
CWD*S*MC	1	23.304	0.0	0.822
SPECIES*S*MC	3	600.204	0.4	0.270
SITE*S*MC	2	152.089	0.1	0.717
SPECIES*CWD*MC	3	84.651	0.1	0.906
SITE*CWD*MC	2	28.424	0.0	0.940
SITE*SPECIES*MC	6	1757.219	2.2	0.001
SPECIES*CWD*S	3	170.518	0.1	0.773
SITE*CWD*S	2	435.551	0.2	0.387
SITE*SPECIES*CWD	6	141.620	0.2	0.932
SITE*SPECIES*S	6	937.691	1.2	0.180
Error	288	457.215	27.3	
R ²	0.74			

First the only three-way interaction was a magnitude and one rank change: site x species x MC interaction. As seen in Figure 19B, MC always had equal or greater stem *dm* regardless of site or species except GA on site 1 where NMC had greater stem *dm* than MC. All two-way interaction were magnitude effects. For example, in figure 19A, the species x CWD and species x S, showed that for all species, CWD or S had greater stem *dm* than NCWD or NS, respectively. Thus, the main effects, species, as mentioned above, S, CWD, MC and site accounted for 36.6, 8.6, 1.3 and 1.1% of the total variation. Stem *dm* for GA, SA, GB, and WB were 58.4, 30.3, 5.4 and 4.0g, respectively. S on average tripled the stem dry mass from 13.3 to 35.6g. CWD on average doubled stem *dm* from 16.3 to 32.7g. MC on average increased stem *dm* from 20.1 to 28.8g. Sites 1, 2 and 3 had stem *dm* on average of 30.0, 21.2 and 22.2g, respectively.

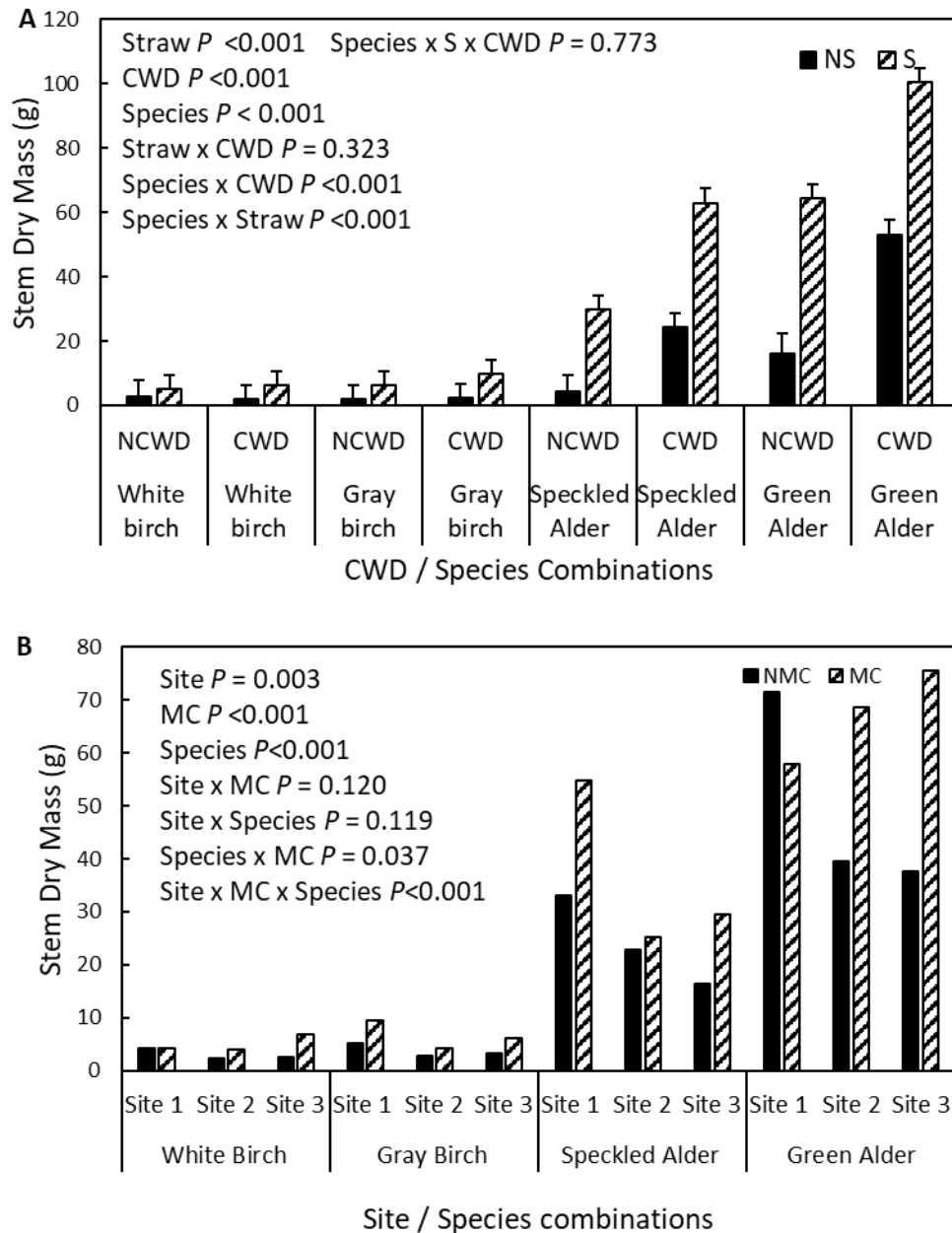


Figure 19. Stem dry mass ($\pm$ SE) showing A) Species x S x CWD interaction. B) Site x MC x Species interaction.

Assessing site preparation treatments and treatment combinations, WB and GB greatly benefitted from MCxSxCWD with 6.6 and 12.3g compared to the control with 0.7 and 1.4g, respectively (Fig. 20A, B). MCxSxCWD combined treatment compared to

control resulted in a 9.4, 8.7-fold increase in stem *dm* productivity for WB and GB, respectively. CWD alone was the least effective in increasing stem *dm* for both WB and GB with only a 0.9 and 0.5g increase over control, respectively. S as an individual treatment outperformed or came within the margins of MCxCWD plots. In the combined site preparation treatments, WB realized (empirical) reached what would be additive effects of the site preparation treatments. For GB, realized exceeded additive effects (synergistic effect) in all but one combination MCxCWD which met additive expected.

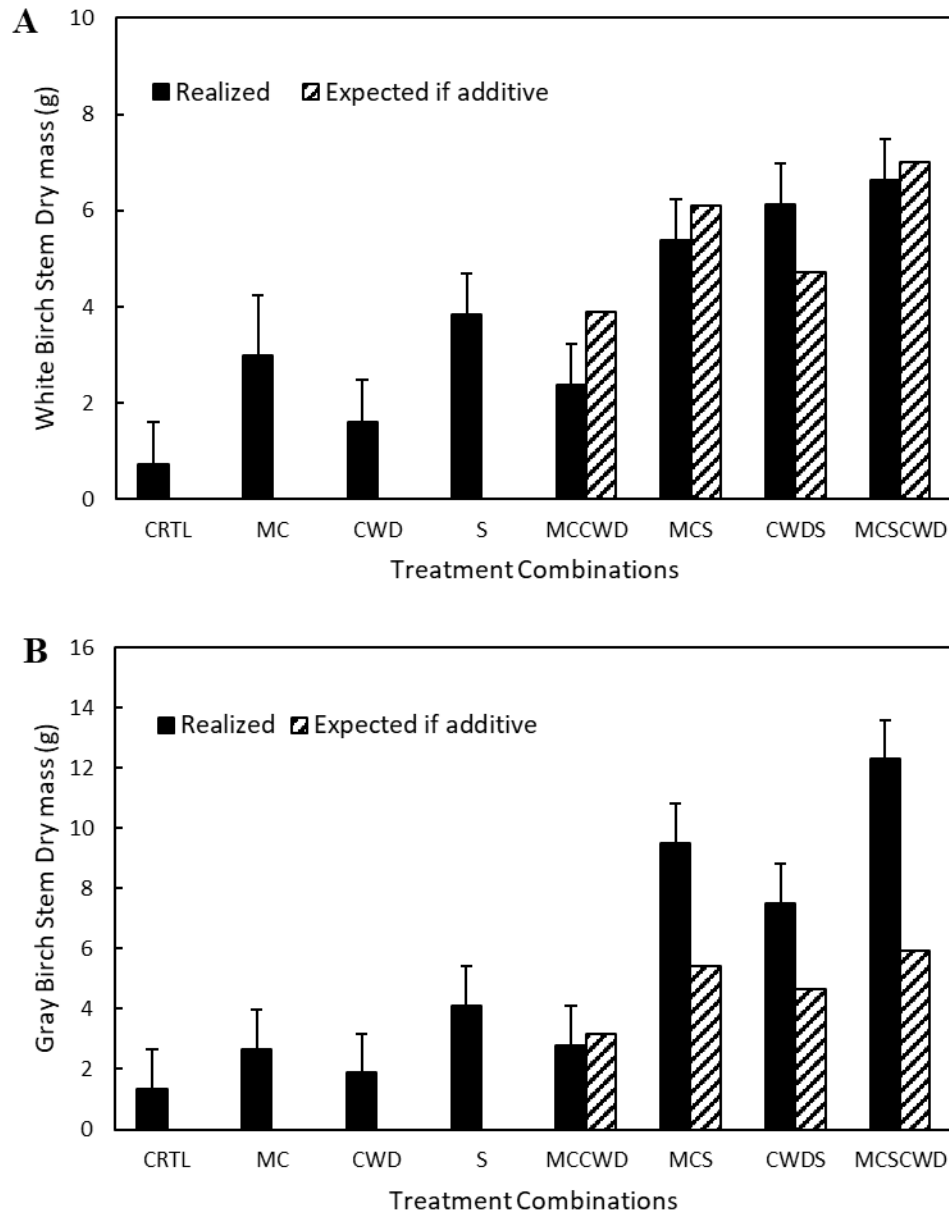


Figure 20. Stem dry mass ($\pm$ SE) for each treatment combination including an expected line assuming single treatment effects were additive for A) white birch B) gray birch. A and B have differing Y-axis

Assessing site preparation treatments and treatment combinations, GA and SA also greatly benefitted from MCxSxCWD in slightly different ways. SA control was a

very small 0.5g compared to GA 17.8g (Fig 21A, B). Under the MCxSxCWD combination GA and SA were 115.7 and 70.6g, compared to control, that was a 6.5- and 140-fold increase in stem *dm* productivity, respectively. Both species had greatly benefited from MCxSxCWD in that realized site preparation treatments met additive expectations and exceeded additive (synergistic) expectations. For GA synergistic results were found in MCxS and MCxSxCWD. For SA synergistic results were found in CWDxS and MCxSxCWD.

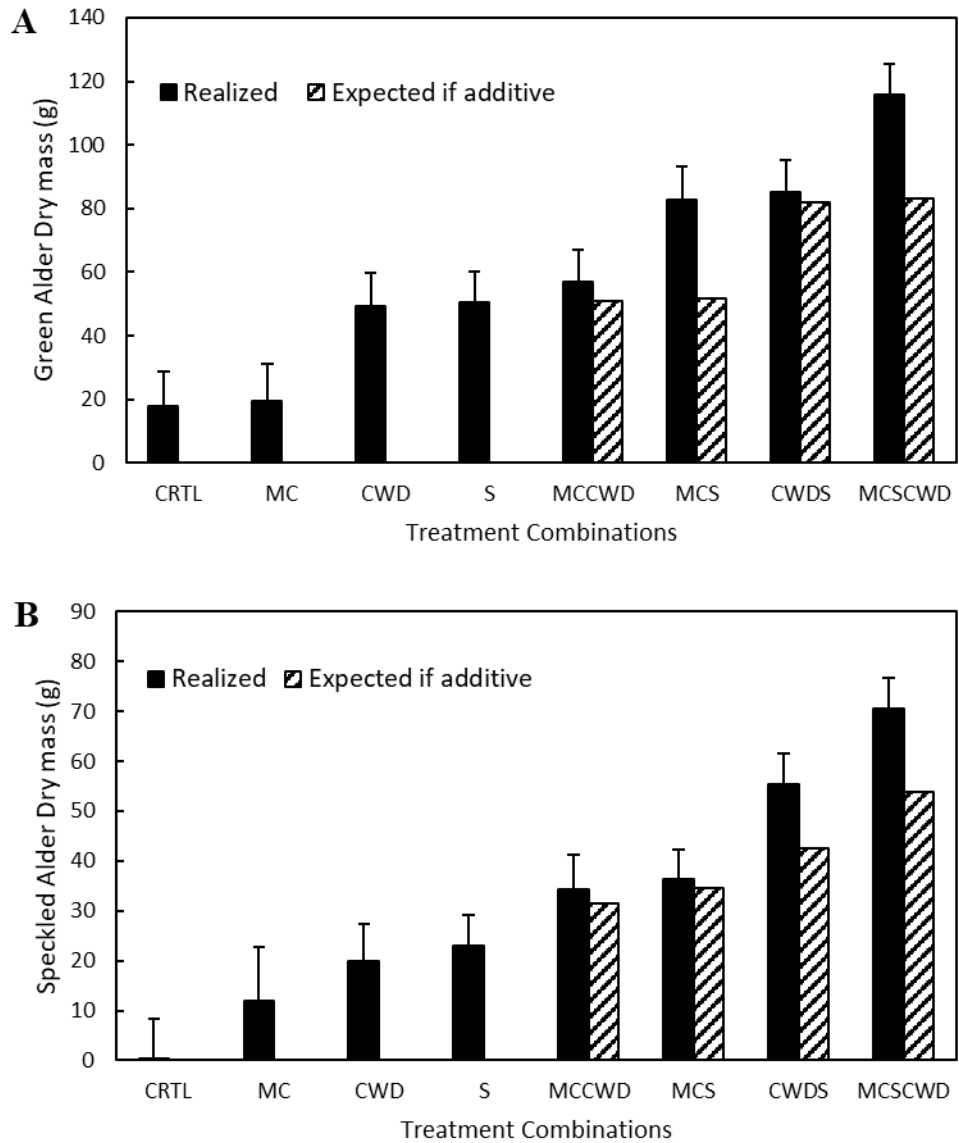


Figure 21. Stem dry mass ($\pm$ SE) for each treatment combination including an expected line assuming single treatment effects were additive for A) green alder B) speckled alder. A and B have differing Y-axis

Discussion

2021 Growing Season

First-year growth was most influenced by the effect of S, accounting for 9.1% of total variance and resulted in a doubling of height growth. During the first year, significant 2- and 3-way growth interactions between treatments, species, and site were nearly all magnitude effects with only one rank change occurring in site x CWD x MC (Table 9), this allows us to consider the main treatments since their addition always increased growth for all factors. Species accounted for the second highest variance at 6.3% and showed GB with the greatest overall height (12.1cm) while WB was the lowest (5.6cm). Both GA and SA grew relatively similarly around 9.7cm and 9.6cm. WB probably did not grow as much due to its preference for a more nutrient rich site (Leak 1978).

Straw had the largest effect on growth due to its ability to reduce summer moisture evaporation (Novak et al 2000), increase soil water storage (Balwinder-Singh 2011), and regulate surficial temperatures (Liu et al., 2014). S allowed for SA, a hydrophilic species (Brisson 2006), to overcome the drought conditions of these sites as SA had half the summer mortality (Galea 2023, unpublished). CWD also decreases water loss by shading and reducing seedling desiccation as it provides shelter (Jumpponen, 1999; Orman 2016). Seedlings growing with the CWD treatment had an average increase of growth by 2.1cm for WB and GB, and a 4.5cm increase for GA and SA. It appeared that SA and GA benefitted more from the sheltering properties of CWD (Pyper M 2012).

Straw and CWD combined, while providing somewhat the same soil moisture retaining effect, and possibly reducing one or both effects together, provided the greatest increases to growth when compared to control, and in fact was additive in the first year. After extensive literature review, there is little published knowledge of this combined effect on growth, and in fact any combinations of these treatment types. Growth of species on site 1 doubled with S and CWD present and species grown on site 2 and 3 were tripled. Site 1 had deeper soil and thus better inherent moisture retaining properties than sites 2 or 3, which benefitted more from the site preparation treatments. MC was minorly successful creating improved aeration, water infiltration, and root penetration, (Richardson 1980) unless paired with either of the other two treatments, and thus overall, first-year MC alone had by far the worst, 60% mortality greater than control at 38% (Galea 2023).

2022 Growing Season

Height Growth

Second-year growth was influenced by similar effects as the first year, particularly species. Species became the greatest source of variation, accounting for 33.5%, while S and CWD accounted for 8.2 and 7.4% of the total variation, respectively (Table 10). Site effect was not as important in the second year with 1.8% of the total variance and was only involved in small magnitude interactions. All two- and three-way interactions were magnitude effects. The change from GB having the greatest height to being dwarfed by

GA and SA is most probably explained by the ability of GA and SA to fix atmospheric nitrogen through a symbiotic relationship with the bacteria *Frankia alni* (Ekblad 1995; Fessenden 1979). This difference in growth could not be realized in the first growing year since resources were being diverted to roots *Frankia alni* was establishing, however, once established in the second year it was able to fully benefit alder's growth. The increase in foliar N levels as found by Brisebois et al. 2023 allowed for much larger growth compared to birches as there was very little nitrogen in the soil (mean soil N = 0.12%). According to Ekblad 1995, the N fixation by *Alnus* doesn't assist nearby other species in uptake of N, however since the leaves are where majority of nitrogen gets allocated to, once fallen on the ground can provide some nitrogen through decomposition. Straw's effect on second year growth was like the first years, increasing moisture retention (Tao et. al. 2015) and regulating surficial temperature (Goulet 1995; Chalker-Scott 2007). CWD's effect changed compared to the first year, with it being more effective in increasing growth doubling it from 18.5cm in NCWD plots to 31.1cm in CWD plots (Figure 14). CWD plots trapped fallen organic matter from surrounding area and creates a moisture retaining micro-site favourable for growth (Jia-bing et al 2005). Site differences didn't change with site 1 still providing the best growing conditions with more soil depth to bedrock and slightly better soil nutrients than sites 2 and 3 (Table 8).

Stem Count

Species was the only main factor for differences in stem count with it accounting for a large 42% of the total variation. Only the species x S interaction ($P < 0.001$) was over 1% of the total variance in the model. Both WB and GB can exist with multiple stems

and are unknown to grow more from the base if not coppiced (Hutnik et al 1965; Hosie 1969; Webb 1988). SA and GA are both known to have the ability to have multiple stems as they are shrub species (Hosie 1969; Farrar 1995). In fact, coppiced after one year growth in a greenhouse experiment examining the same species under a 2x2 factorial of CO₂ x soil moisture stress treatments, alders and birches produced on average 7.9 and 3.8 stems per plants, respectively (Brisebois et al. 2023b). As might be expected, overall well-watered and drought resulted 6.7 and 5.1 stems per plant an obvious reduction under soil moisture stress, and ambient and elevated CO₂ resulted in a significant 5.7 and 6.1 stems per plant, an atmospheric fertilizing effect (Brisebois et al. 2023b).

Stem Dry Mass

Stem dry mass production followed similar second year height trends and was primarily affected by species which accounted for 36.6% of total variance (Table 12). However, the magnitudes were much greater with stem *dm* 58.4, 30.3, 5.1, 4.0g for GA, SA, GB, and WB, respectively. The largest difference between GA and WB represented almost 15x larger stem *dm* after two years on these impoverished sites. All significant interactions but one was magnitude effects and the addition of S, CWD, or MC yielding greater stem *dm* than if they were not present. While combinations of S, CWD, and MC and how they influence stem *dm* is largely not present in the literature, individual effects can be teased out and help explain the results. Straw's ability to increase moisture (Rokich et al 2002) while reducing surface evaporation (Novak et al 2000) and temperature (Lui et al 2014) allowed it to create a more suitable environment for plant growth. CWD as mentioned in the second-year growth section, changed from being

largely a shelter providing element (Jumpponen, 1999; Pyper M, 2012) to also moisture retaining microenvironment after capturing surrounding organics (Jia-bing et al 2005). Straw tripled while CWD doubled stem *dm* after two years likely because of the moisture retaining qualities. Both GA and SA took the increased moisture content and were able to utilize it the most with their ability to generate their own nitrogen through their symbiosis with N fixing bacteria (Schwencke 1998). GB and WB both tripled and doubled of stem *dm* with the addition of S and CWD, but they didn't come close to the stem *dm* of either alder. For WB regardless of the increased moisture in S or CWD, the lack of available nutrients, which it generally requires for adequate growth, stunted its growth compared to GB (Ingestad& Lund 1979; Leak 1978). While S and CWD by themselves and in combination with other treatments made the best growing conditions, MC increased stem *dm* by 40% across all species.

WB was the only species to demonstrate only an additive effect from the treatment types in combination, implying that perhaps the lack of N for a more N demanding birch can't be made up for by increasing the moisture regime alone. GA, SA, and GB all or most had synergistic effects from the site preparation treatments, that is greater than the addition of the single effects. Again, after an extensive literature review, there were none to be found for treatment combination. It was surprising to see the synergistic effect as two of the treatments S and CWD which provided similar benefits of soil water retention. Perhaps the site is so depleted in soil water holding capacity, as it has been largely barren for the last 25 years, thus resulted in at least additive results. However, additive, and synergistic effects from site preparation treatments are again novel result as little is found in the literature. In fact, the best site preparation treatment for growth for all species was

MC×S×CWD. Mortality showed largely additive effects except for MC alone which had the greatest mortality at 60%, but in combination with S or CWD greatly reduced mortality (Galea et al. 2023, unpublished). Furthermore, the best treatment for lowest mortality with only 3.1% was the MCxSxCWD; for reference in the control plots WB, GB, GA, and SA were 0.7, 1.4, 17.8 and 0.5g, respectively. Under MCxSxCWD WB, GB, GA and SA saw a 9.4x, 8.7x, 6.5x and 140x increase in stem *dm* to 6.6, 12.3, 115.7 and 70.6g, respectively. It should be noted that the 0.5g for SA under control, are from sites that may be considered “off site” for SA which had the greatest summer drought and frost heaved mortality. At the same time, it demonstrated how effective the site preparation combination was in that it was rather effective for a species like SA.

Application

Using S, CWD, and MC together yielded the greatest values for growth and biomass particularly in the second year. The application of S alone is the simplest treatment and provides the greatest moisture retention and drought prevention capabilities, but does require, as logistics, a skid steerer and straw chopper. MC does require access for large, tracked machinery that can support the MC head, and CWD need 20–30-year-old early successional species cut and forwarded. CWD can provide sufficient drought prevention and shelter from the elements and after it has accumulated organic matter within the microsite. CWD may also prove harder to plant in, and if the site is shallow and lacking MC treatments, then CWD may limit “good” planting spots. For the long term, CWD and

S together provided excellent environments for early successional species to grow since they regularly prefer mostly full light which may be limited by drought conditions. Not every treatment need be used and should be assessed to find the best prescription for each site. CWD appear to be second best in open sites that require sheltering from wind and rain erosion.

GA was the overall best performing species for capturing barren sites due to its inherent nitrogen fixing ability and drought tolerance. SA can also fixate nitrogen however, its preference for a moist site holds it back in areas without the S or CWD treatment. GB grew better than WB as WB appear to need more nutrients, particularly N limitation in the soil. Biomass production, and therefore eventual soil amelioration via organic decomposition, would also be accelerated using GA. The focus of this land restoration is to prevent further soil erosion and promote soil creation, therefore the full combined three treatments MCSCWD produced the best results, reduced erosion, in combination with GA or SA, generated the greatest biomass to capture barren sites and create more desirable environment to restart forest succession.

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Conclusion

Our initial analysis revealed that S resulted in an average mortality reduction of 27%, while CWD reduced mortality by 19%. Conversely, MC led to a marginal increase in mortality of approximately 4%. The most noteworthy survival rates were observed in plots where all three treatments were combined, resulting in a mortality rate of 3.1%, a 34.4% reduction compared to the control plots. When MC was administered alone, it demonstrated substantial negative effects, yielding a first-year mortality of 60.9% (Figure 8). However, when paired with either S or CWD, the mortality rates were significantly reduced to 12.5% and 16.5%, respectively. This decrease in mortality in MC plots when combined with S or CWD underscores the significant water loss observed in MC plots and the necessity for complementary treatments to mitigate this challenge. Straw by itself increased moisture availability in plots by roughly 10%, and its ability to be spread so easily across large areas makes it a perfect candidate for larger reclamation projects.

Given hydrophilic nature of SA (Brisson, 2006), in the drought-prone conditions of the study sites, it experienced the highest mortality rate at 33.6%. The effective moisture retaining properties of S and CWD (Jumpponen, 1999; Balwinder-Singh, 2011) significantly reduced SA mortality, thereby indicating the potential viability of these treatments for other hydrophilic species facing similar conditions.

The second chapter highlights the significant influence of species-specific attributes and sheds light on the remarkable capacity of alders to fixate nitrogen (N) in N-depleted soils (Schwencke 1998), as evidenced by their substantial stem dry mass accumulation (58.4g)(Figure 18). SA demonstrated substantial growth, resulting in an increased stem dry mass of 30.3g, and up to 70.6g in the MCSCWD plot, while

exhibiting minimal growth (0.5g) in control plots. The low stem dry mass in control plots can be attributed to the alarmingly low survival rates of SA after two years. In contrast to the previous chapter where MC exhibited negative effects on survival without the assistance of S or CWD, chapter 2 revealed that MC benefits the initial and subsequent growing seasons, albeit to a lesser extent than S or CWD. The enhanced root development facilitated by MC contributed to the establishment of more substantial foundations (Lantagne & Burger, 1983; Alcázar et al., 2002).

Overall, these findings offer valuable novel insights into the combined effects of the three site preparation treatments on early successional plant species. They underscore the potential for enhanced reforestation efforts in denuded areas, particularly for species that are vulnerable to water stress. Moving forward, future research could address the existing variability gaps within degraded sites. Previous reclamation efforts employed grasses to mitigate erosion, with the hope that they would follow forest succession in the future. However, these grassland areas proved excessively competitive. Additional studies on the site preparation plots should be done regarding different species combinations as to diversify the planting efforts in the restoration projects. Conducting experiments to identify species capable of thriving in such challenging and competitive environments could provide crucial insights toward solving the intricate puzzle of rehabilitating DND Base Galetown. Research by Brisebois et al. (2023, unpublished), investigated the response of the same four early successional species to elevated drought and CO₂ levels, and is anticipated to yield valuable perspectives on the adaptability of these species under varying climatic scenarios.

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Glossary

Coarse substrate: Refers to a substrate or material with larger particles or components.

Coarse woody debris (CWD): Dead or decaying wood material, including logs, branches, or stumps, present on the forest floor.

Denuded: Land or ecosystems that have been stripped of vegetation or topsoil, leaving them exposed and vulnerable to erosion or degradation.

Desiccate: To become extremely dry or dehydrated.

Early successional species: Plant species that are adapted to thrive in open, disturbed, or early stages of ecological succession.

Erosion: The process of wearing away or removal of soil or rock by natural agents such as wind, water, or ice.

Frost heave: The upward displacement or lifting of soil or plants caused by the expansion of frozen water within the soil.

Reclamation: The process of restoring or rehabilitating degraded or damaged land, typically with the goal of returning it to a functional and productive state.

Sedimentation: The deposition of eroded soil or sediment in water bodies, leading to increased sediment accumulation.

Topsoil: The uppermost layer of soil, rich in organic matter and nutrients, where plants typically grow.

Water table: The underground level at which the soil or rock is saturated with water.

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