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Ecological Restoration in Eastern Canada Using Four Early-Successional Species on Severely Degraded Sites Using a Factorial of Site-Preparation Treatments: Growth and Biomass over Two Years

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Abstract: Barren sites that lack soil are exposed to some of the harshest elements, which include high temperatures, solar radiation, wind, extreme temperature changes, and low soil moisture and nutrient conditions. An ecological restoration experiment was conducted using three site-preparation treatments, straw (S), Meri-Crusher (MC), and coarse woody debris (CWD), in a site-/no site-preparation 2 × 2 × 2 factorial on sites that had been barren for 25 years. In addition, four early successional deciduous species, white birch (WB, *Betula papyrifera* Marshall), gray birch (GB, *Betula populifolia* Marshall), green alder (GA, *Alnus viridis* Vill. subsp. *crispa* Ait), and speckled alder (SA, *Alnus incana* L. subsp. *rugosa* Du Roi), were examined. The two- and three-way interactions were almost all magnitude effects and not rank changes. Gray birch 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 first-year growth, while CWD and MC increased first-year height growth by 43 and 31%, respectively. Straw's ability to retain moisture in the dry summer provided the greatest benefit. In the second year, GA had the greatest height growth, followed by SA, GB, and WB, with 42.5, 30.5, 13.4, and 13.0 cm, respectively. Alders form symbiotic relationships with N-fixing bacteria and, although this was observed in some first-year roots, they did not fully express this advantage at these severely degraded sites until the second year, which allowed them to surpass birches in growth. Site-preparation treatments furthered their height growth affect, with S, and CWD doubling second-year height growth and MC, with an increase of 25%. Alders and birches had, on average, three and one stems, respectively, and the mean stem number of alders increased under S and CWD. After two years, overall stem dry mass had very large genus and species differences with GA, SA, GB, and WB, with 58.4, 30.3, 5.4, and 4.0 g, respectively. The N-fixing ability of alders under these conditions resulted in a 13-fold stem dry mass production increase compared with birches. Straw 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, which were greater than the additive effects of single treatments. Under the control (no site prep.), second-year stem dry masses for WB, GB, GA, and SA were 0.7, 1.4, 17.8, and 0.5 g, respectively. Under the three combined treatments, MC × S × CWD, WB, GB, GA, and SA had 6.6, 12.3, 115.7, and 70.6 g stem dry masses, respectively. SA is ecologically a lowland species, hence the low 0.5 g under the control; however, the result under the three combined treatments demonstrates their combined effectiveness on these barren sites. Green alder seems to be the best adapted to the sites, having the greatest stem dry mass under control, although that was considerably magnified under the site-preparation treatments. This study using combinations of treatments with these early successional species introduces a novel research concept, and similar studies in the literature are currently lacking, creating an opportunity for future exploration.

Keywords: ecological restoration; birches; alders; site-preparation; growth; biomass

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1. Introduction

Barren landscapes present great restoration challenges and, if left alone, lead to continued soil erosion and increased sedimentation in local waterways, negatively affecting aquatic environments [1,2]. Exposed areas with little soil and vegetation provide no plant shelter from the elements, which results in increased desiccation due to full exposure to the sun, heat, and wind. Drought is one of the principal factors limiting forest productivity on a worldwide basis [3–5]. Increased shade from vegetation or otherwise provides greater moisture retention due to a lower surficial evaporation and allows for greater survival and growth of seedlings [6–8]. Ecological restoration should start with the growing and later planting of early-successional native species with adaptations, to allow sites to start natural successional processes [9]. Seedlings with no protection or cover will result in low soil moisture and nutrient availability, have restricted growth, and, therefore, produce low biomass, though biomass accumulation is crucial for enriching poor soil, as it contributes to the organic matter in soils.

Development of soils should be among the first priorities when restoring barren sites, which can be aided by using site-preparation treatments [9]. Soils in degraded areas are often compacted, lacking water-holding capacity and soil nutrients [10–12]. Natural weathering and the enlargement of rock fractures can be hastened by roots and their associated fungi [13,14], and mycorrhizal hyphae can grow where roots cannot fit [15]. Poor soil conditions limit what species can grow since, in addition to negative soil conditions, there is often a shallow depth to bedrock that can also negatively affect plant growth [16]. The reintroduction of original topsoil to barren sites can offer a promising method to ameliorate adverse environmental conditions; however, accessibility to topsoil is often restricted in severely disturbed sites, and there is a very high likelihood of more erosion [17].

Early-successional trees are known for their ability to succeed in open, post-disturbance landscapes [18,19]. Some early-successional species are known for relatively fast growth despite existing in harsh environments, and they are also known for their tendencies to be bio-accumulators [18,20,21]. Returning nutrients to the soil and eventually ameliorating the coarse substrate into a forest may be accelerated by using early-successional deciduous species since it has been shown that nutrient contents and organics within hardwood forests are often greater than those in conifer forests [22,23]. We examined four early-successional deciduous species: white birch (WB, *Betula papyrifera* Marshall), gray birch (GB, *Betula populifolia* Marshall), green alder (GA, *Alnus viridis* Vill. subsp. *crispa* Ait), and speckled alder (SA, *Alnus incana* L. subsp. *rugosa* Du Roi). All four species have some history in restoration efforts due to their ability to withstand and restore harsh sites [18–21,24–26]. 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 [27]. Gray birch grows best on moist, well-drained sites, but is quite adaptable and can grow well on dry sandy or even gravelly soil [28,29]. Green alder prefers 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 [30]. Speckled alder prefers wet sites where it can compete best beside waterways, bogs, and fens, but will also establish in mires with peaty soils [31,32]. In Minnesota, it was noted that SA will grow in mesic to moist sites, but it was found more in moist sites [33].

In this study, we examined a factorial of three site-preparation treatments: (1) application of a site crusher (Meri-Crusher, MC, Voukatti, Finland) to create a loose aggregate, (2) straw (S) coverage, and (3) coarse woody debris (CWD) coverage. Please note that the prefix "N" on the site-preparation treatment indicates no such treatment. Site crushing involves mechanically ripping up the top layer of aggregate to create a substrate that can be used to restore terrestrial ecosystems with little to no existing substrate available [34,35]. Breaking in situ soil beds is better than replacing them with soil [36], and the benefits of ripping up the soil include improved aeration, water infiltration, and root penetration [37]. Straw coverage can affect the processes occurring in the top layer of the soil, such as reducing surface evaporation [38], improving water infiltration [39], increasing moisture retention [40–42], and acting as an insulator and regulating extreme temperatures in the winter to help prevent frost heave of planted seedlings [8,43]. Coarse woody debris can create protected microsites [44], and it has been shown to decrease water loss and seedling desiccation by providing shelter from the elements [45]. There is a preponderance of using larger CWD since smaller pieces like wood mulch can draw what little available nitrogen there is from the soil via different fungi to fuel decomposition [46].

Our goal was to quantify the effects of a site-/no site-preparation factorial—S, NS; MC, NMC; and CWD, NCWD in a 2 × 2 × 2 factorial, resulting in 8 treatments including a control—with four early-successional deciduous species on seedling growth. 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 would have a positive effect on growth. We also hypothesized that when site-preparation treatments were used together, their effects would be additive. In addition, we hypothesized that there would be genus and species effects on growth.

2. Material and Methods

2.1. Site-Preparation Treatments

Three separate sites were selected at CFB Gagetown, NB, (45.68108, −66.50179). A randomized site-preparation design with a site-, no site-preparation factorial—of S, NS; MC, NMC; and CWD, NCWD in a 2 × 2 × 2 factorial—resulted in eight treatments including a control. Please note that a prefix of "N" on the site-preparation treatment indicates no such treatment. The eight-treatment factorial comprised (1) NS × NMC × NCWD, the control, (2) S × NMC × NCWD, (3) NS × MC × NCWD, (4) NS × NMC × CWD, (5) S × MC × NCWD, (6) S × NMC × CWD, (7) NS × MC × CWD, and (8) S × MC × CWD. The eight treatments were replicated (blocked) four times per site. This equated to 32 plots per site, on three sites, leading to a total of 96 plots in the experiment. The MC treatment was created using a John Deere 200D excavator (Moline, IL, USA) equipped with an MJ hydraulic 1.4 ST Meri-Crusher (Voukatti, Finland). The MC plots produced a 3.2 × 3.2 m square of torn aggregate. Square straw bales were used to cover approximately 18 m^2 of area or roughly two experimental plots to a depth of 5 cm. The CWD was sourced from DND Gagetown using primarily GB. All CWD was processed into ~3 m length to match the MC plots. The CWD was placed in a north–south direction, had an average volume of 0.2033 $m^3 \pm 0.02$ m^3, and was applied to 48 plots. The placement of CWD was carried out last to hold the straw, if present, in place.

2.2. Plant Materials

Four species from bulked seedlots selected to represent the chosen species (provenances, Table 1), WB, GB, and GA, were grown during 2020 at the Atlantic Forestry Center (AFC) greenhouses, Fredericton, NB (45.93501, −66.65745). Speckled alders were grown during 2020 at Scot and Stewart nurseries in St. Andrews, Nova Scotia (45.53292, −61.86888). The seedlings grew in trays with root container volumes of 110 mL. In January 2021, one-year-old seedlings were cut to a height of roughly 10 cm to reduce the shoot-to-root ratio for these harsh sites and had a shoot-to-root ratio of 1:1 by dry mass. The seedlings were packed into boxes for frozen storage at −4 °C in AFC freezers. The seedlings were taken out 3–4 days prior to planting to thaw. On 7–8 May 2021, 4 individual replicates per species were randomly planted per plot, with 32 plots per site, thus 128 individual species per site, and thus 384 individuals per species across the three sites. The seedlings were planted with narrow planting shovels at 0.5 × 0.5 m spacing. The experiment contained 1536 total planted seedlings across the three sites.

Table 1. Species and provenance of seedling materials used in the experiments.

Species		Source Year	Provenance	Country	Latitude (N)	Longitude (W)	Elevation (m)
Betula papyrifera	White birch	1998	Wayeton, NB	CAN	47.21667	−65.93333	300
Betula papyrifera	White birch	1998	Jewetts Creek, NB	CAN	45.83333	−66.98333	50
Betula populifolia	Gray birch	2008	Newmarket, NB	CAN	45.80501	−66.95634	149
Betula populifolia	Gray birch	2008	Newmarket, NB	CAN	45.83147	−66.97115	130
Betula populifolia	Gray birch	2008	Newmarket, NB	CAN	45.8076	−66.96825	141
Betula populifolia	Gray birch	2008	Newmarket, NB	CAN	45.83486	−66.96272	125
Betula populifolia	Gray birch	1999	Bai-du-vin, NB	CAN	47.03333	−65.16666	5
Alnus viridis subsp. *crispa*	Green alder	2002	West Quaco, NB	CAN	45.33	−65.53	65
Alnus viridis subsp. *crispa*	Green alder	1999	Lower Prince William, NB	CAN	45.87	−67	20
Alnus incana subsp. *rugosa*	Speckled alder	1983	Enmore, PEI	CAN	46.58	−64.05	10
Alnus incana subsp. *rugosa*	Speckled alder	1983	Vallyfield, PEI	CAN	46.13	−62.72	45
Alnus incana subsp. *rugosa*	Speckled alder	1983	Shediac, NB	CAN	46.23	−64.6	15

2.3. Soil Properties

For every plot (96), five soil depth-to-bedrock measurements were taken using an iron rod gently hammered into the soil in the spring of 2023. For soil nutrient analysis, a single sample was taken from each plot in the experiment, equaling 96 samples. These samples had a minimum requirement amount of 80 g (without coarse fragments), were oven-dried and sieved (2 mm) for the soil fertility and texture analysis, and more was taken to secure the replicate. The soil was placed into a plastic bag. The soil analysis was conducted according to McKeague (1978) [47] as follows: available P—#TP-CSS-MSSA 4.41 (sodium bicarbonate extraction), exchangeable cations, K, Ca, and Mg—#TP-CSS-MSSA 4.5, FCMM 15 (ammonium acetate extraction), pH—#TP-CSS-MSSA3.13 (pH in 1:1 water), texture—#TP-CSSMSSA 2.12 (hydrometer method), organic matter, N, C, and S—#TP-LFIM (total C by LECO induction furnace) by the Laboratory for Forest Soils and Environmental Quality at the University of New Brunswick, Canada. We converted P from ppm to P meq/100 g using the following equation:

$$\text{P meq/100 g} = (\text{Pppm} \times \text{DF})/\text{PMw} \tag{1}$$

where Pppm is the concentration of P in ppm, and DF = the dilution factor (20) for the prepared test solutions. PMw is the molecular weight of P in g/eq. Although a P molecule can take many forms, we used the P atomic equivalent weight of 30.974 g/eq for P molecular weight. Note some use 4P or a molecular weight of 124 g/eq. Table 2 provides a soil property summary among sites. Soil moisture (%) was measured periodically using an ML3 ThetaProbe soil moisture sensor (Cambridge, UK), by recording three readings per plot. In 2021, soil moisture readings were taken on 13 collection dates ranging from 3 March to 9 September. In 2022, soil moisture readings were taken on three dates: 22 June, 12 July, and 4 August.

Table 2. 2022 soil properties for three experimental sites. Sites with different letters are significantly different at $p = 0.050$, ($n = 96$).

ID	Organic Matter (%)	Total Nitrogen (%)	Carbon (%)	C:N Ratio	pH	Phosphorus (meq/100 g)	Potassium (meq/100 g)
Site 1	1.27 ± 0.91 a	0.16 ± 0.03 a	4.33 ± 2.15 a	26.18 ± 9.14 b	4.83 ± 0.11 b	3.71 ± 1.91 a	0.14 ± 0.08 a
Site 2	0.61 ± 0.33 b	0.11 ± 0.02 b	3.21 ± 1.61 b	29.26 ± 14.13 b	4.85 ± 0.13 ab	2.54 ± 1.24 b	0.13 ± 0.07 a
Site 3	0.63 ± 0.27 b	0.08 ± 0.01 c	4.65 ± 1.58 a	60.54 ± 19.55 a	4.92 ± 0.16 a	3.73 ± 1.47 a	0.11 ± 0.06 a
ID	**Calcium (meq/100 g)**	**Magnesium (ppm)**	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Rocks (%)**	**Average Depth (cm)**
Site 1	0.34 ± 0.31 b	0.18 ± 0.11 b	16.19 ± 2.74 a	42.38 ± 6.27 a	41.66 ± 8.42 b	31.75 ± 15.59 b	31.93 ± 12.18 a
Site 2	0.94 ± 0.86 a	0.35 ± 0.23 b	12.97 ± 4.57 b	34.22 ± 8.28 b	52.75 ± 12.32 a	39.88 ± 15.99 a	11.64 ± 7.27 b
Site 3	1.73 ± 2.24 a	0.66 ± 0.85 a	12.09 ± 4.3 b	28.88 ± 7.94 c	59.16 ± 11.95 a	50.06 ± 19.01 a	14.94 ± 9.78 b

The soil bulk density measurements were carried out on 16 plots per site, 8 Meri-Crusher plots and 8 no Meri-Crusher plots, for a total of 48 samples, in the fall of 2022. Soil bulk density (BD) was tested by digging a hole around 5 cm deep × 10 cm long × 10 cm wide. This varied across the sites depending on the depth to bedrock and presence of rocks;

however, an average of 547.5 cm^3 was achieved. After the hole was dug, a thin layer of plastic was laid down to cover the sides and that was then filled with a measured amount of water till it was flush with the surface, allowing us to determine the initial hole volume (Vh). The samples were then dried in ovens at 65 °C for 72 h and weighed for total weight (t). Rocks (r) greater than 2 mm were sieved out, weighed, and subtracted from t to gain the finer particle weight (F). Rocks were then added to a graduated cylinder to obtain their volume (via displacement (Vr)). Vr was then subtracted from Vh to calculate the rootable volume (Vn). F was divided by Vn to derive BD.

$$\text{Step 1: F = t} - \text{r, Step 2: Vn = Vh} - \text{Vr, Step 3: BD = F/Vn} \quad (2)$$

2.4. Plant Measurements

The initial heights (cm) were measured on all plants (n = 1536) from the ground with a steel ruler on 17 June 2021, and then again on 2 November 2021 (1536—dead plants, n = 1417). The next height measurement was taken on 6 September 2022, which determined the second year's growth (n = 1210). 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. This resulted in sampling 4 seedlings (one per species) per plot for a total of 384 samples. The selected trees would later be removed roughly 3 cm from ground level using pruning shears; then, stem numbers were recorded, the stems bagged and dried (65 °C for 72 h or more), and stem dm determined.

2.5. 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, and block was a random effect. The following ANOVA model was used:

$$Y_{ijk} = \mu + B_i(S_j) + S_j + M_k + SM_{jk} + e_{ijk} \quad (3)$$

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

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

$$Y_{ijklm} = \mu + B_i(T_j) + T_j + S_k + M_l + C_m + TS_{jk} + TM_{jl} + TC_{jm} + SM_{kl} + SC_{km} + MC_{lm} + TSM_{jkl} + TSC_{jkm} + TMC_{jlm} + SMC_{klm} + e_{ijklm} \quad (4)$$

where Y_{ijklm} is the dependent soil moisture availability of the ith block, the jth site, the kth S treatment, the lth MC treatment, and the mth CWD treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of the ith block (i = 1, 2, 3, 4) nested within the jth site, T_j is the effect of the jth site (j = 1, 2, 3), S_k is the effect of kth S treatment (k = 1, 2), M_l is the effect of lth MC treatment (l = 1, 2), C_m is the effect of the mth 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, while 4- and 5-way interactions are folded into the error term.

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

$$Y_{ijklno} = \mu + B_i(T_j) + T_j + P_k + S_l + C_n + M_o + TP_{jk} + TS_{jl} + TC_{jn} + TM_{jo} + PS_{kl} + PC_{kn} + PM_{ko} + SC_{ln} + SM_{lo} + CM_{no} + TPS_{jkl} + TPC_{jkn} + TPM_{jko} + TSC_{jln} + TSM_{jlo} + TCM_{jno} + PSC_{kln} + PSM_{klo} + PCM_{kno} + SCM_{lno} + e_{ijklno} \quad (5)$$

where Y_{ijklun} is the dependent biomass trait of the ith block, within the jth site, of the kth species, of the lth S treatment, of the nth CWD treatment, of the oth MC treatment, and μ is the overall mean. $B_i(T_j)$ is the random effect of block (i = 1, 2, 3, 4) nested within site, T_j is the effect of the jth site (j = 1, 2, 3), P_k is the effect of the kth species (k = 1, 2, 3, 4), S_l is the effect of the lth S treatment (l = 1, 2), C_n is the effect of the nth CWD treatment (n = 1, 2), M_o is the effect of the oth MC treatment (o = 1, 2), and e_{ijklno} is the random error component. Interactions of the single effects are included up to three-way interactions, while 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 are 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. (San Jose, CA, USA) was used for analysis. If significant, site and species were post hoc tested using the Tukey mean separation test (p = 0.05). The variance component analysis was conducted using the sum of squares as outlined by Hicks [48]. Expected stem dm for single site-preparation treatments was calculated using the individual treatment stem dm and subtracting the base stem dm present in the control plots. Expected stem dm values of site-preparation treatment combinations for additive comparisons were produced 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 refers to when the effect mean is always greater than under both scenarios but with different magnitudes.

3. Results

In fall 2020, there was little to no difference in soil texture or nutrient content between MC and NMC plots, and as such, they were aggregated together [8]. In addition, soil bulk density was not significantly different between MC and NMC plots. In 2022, the soil analysis showed that organic matter at site 1 was significantly greater compared to sites 2 or 3 (Table 2). Site 1 total N was greater than sites 2 and 3. Carbon was lowest at site 2 compared to sites 1 and 3. The C:N ratio was highest at site 3, being more than double sites 1 and 2. pH differed between sites 1 and 3 but not site 2. P was lowest at site 2 and equally greater at sites 1 and 3. Site 1 had the greatest clay content and conversely the lowest sand compared to sites 2 and 3. Silt was greatest at site 1 and decreased at sites 2 and 3. The average depth to bedrock for site 1 was greater than sites 2 and 3. Note, the rock content was removed before analysis and was greater at sites 2 and 3 than at site 1.

3.1. Soil Moisture

The soil moisture content during the first year corresponded with rainfall (Figure 1). The average soil moisture content increased with the greater rainfall from 1 July onwards. The soil moisture content was significantly greater for S than NS treatments during dry conditions such as June 2021. As the soil took on more rain, the effect of S was not significant. The higher rainfall during 2022 combined with the reduced sampling meant that S had a greater soil moisture content than NS on 22 July (p = 0.053) (Figure 2).

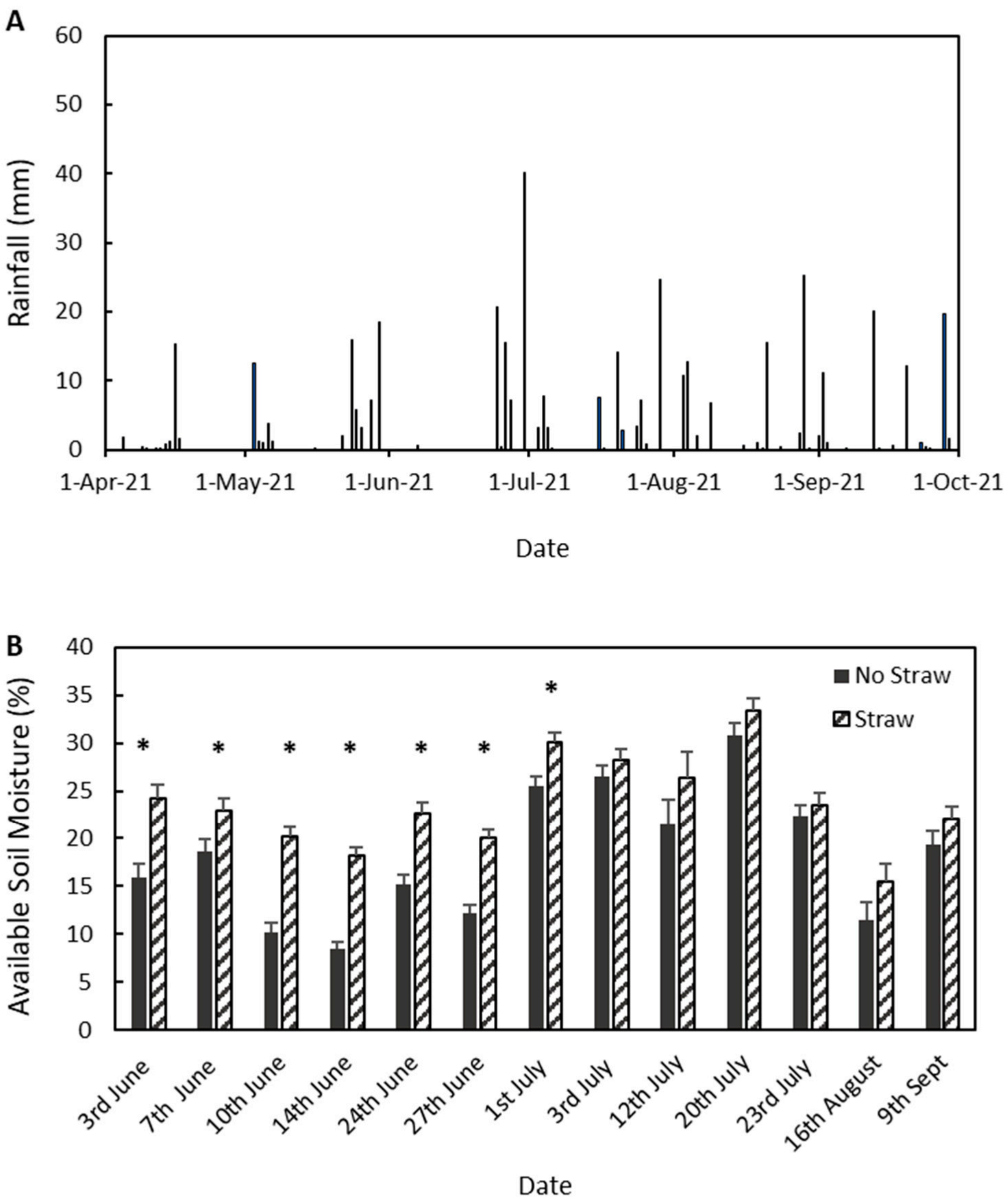

Figure 1. (**A**) Rainfall (mm) sourced from nearby Fredericton, New Brunswick (45.9636° N, 66.6431° W) from 1 April 2021 to 30 September 2021. (**B**) Soil moisture readings in 2021 showing differences between straw and no straw coverage on dates when field assessments were performed. Dates marked with * are significantly different at $p < 0.05$. Note that the x-axis date ranges differ.

3.2. First-Year Height Growth

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 3). Second, it is important to note for ease of interpretation that first-year height growth two- and three-way interactions were all magnitude effects except for one small rank change in the site × CWD × MC interaction.

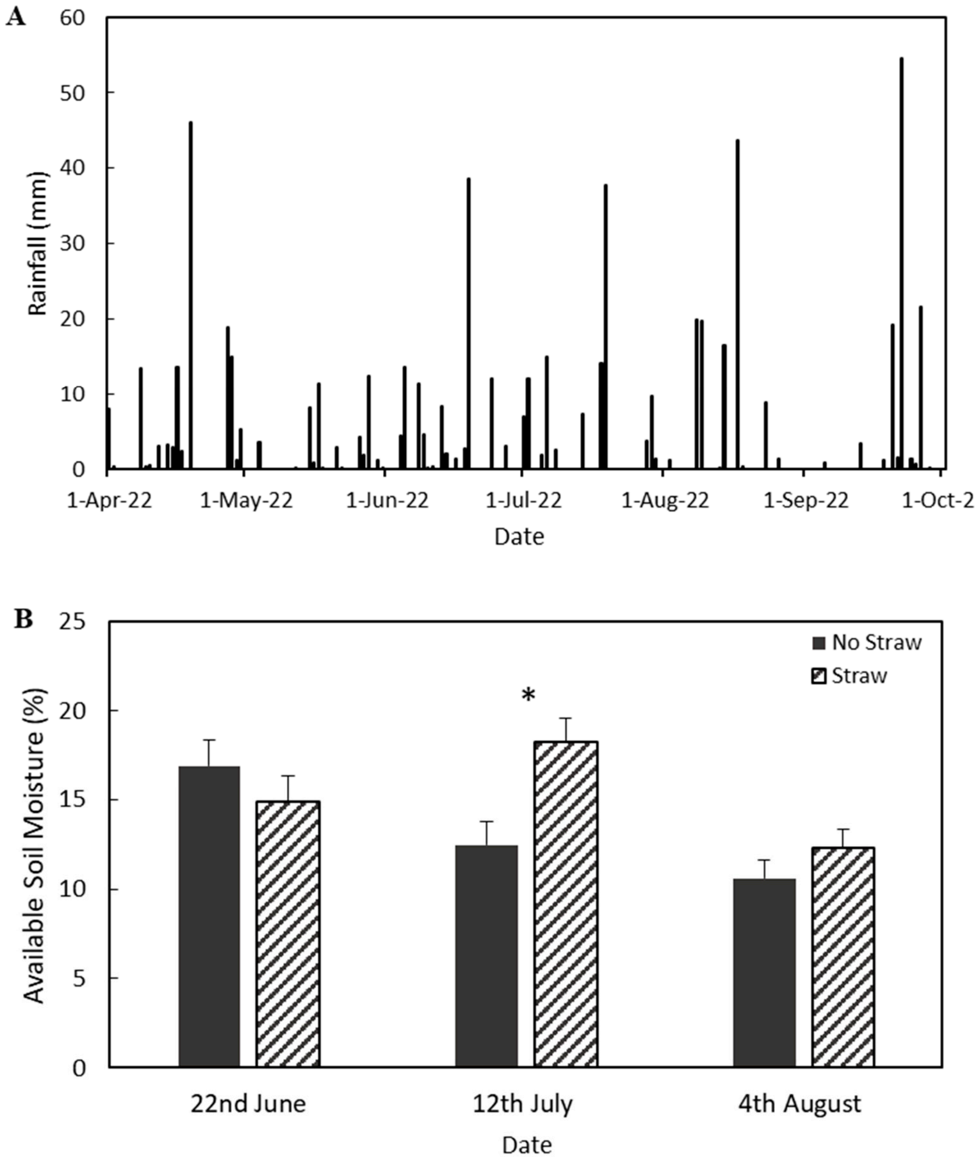

Figure 2. (**A**) Rainfall (mm) sourced from nearby Fredericton, NB (45.9636° N, 66.6431° W) from 1 April to 30 September 2022. (**B**) Soil moisture readings taken in 2022 showing differences between straw and no straw plots on dates when field assessments were performed. Dates marked with * are significantly different at $p < 0.05$. Note that the x-axis ranges differ.

Site 1 had greater first-year 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- and three-way interactions were best captured by the species × CWD × S interaction (Figure 3A) and site × CWD × S interaction (Figure 3B). The species × S and species × CWD interactions are illustrated by S and CWD, which always had greater height growth for all species compared to NS and NCWD, respectively, but of differing magnitudes (Figure 3A). Similarly, the site × S × CWD interaction (Figure 3B) 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 6.4 cm to 12.1 cm, CWD increased height growth by 43% from 7.6 cm to 10.9 cm, and MC increased height growth by 31% from 8 cm to 10.5 cm. Gray birch had the greatest overall height growth followed by GA, SA, and WB, with 12.1 cm, 9.7 cm, 9.6 cm, and 5.6 cm, respectively (Figure 3A). In addition, site 1 had the greatest height growth followed by sites 3 and 2 with 11.5 cm, 9.2 cm, and 7.1 cm, respectively (Figure 3B).

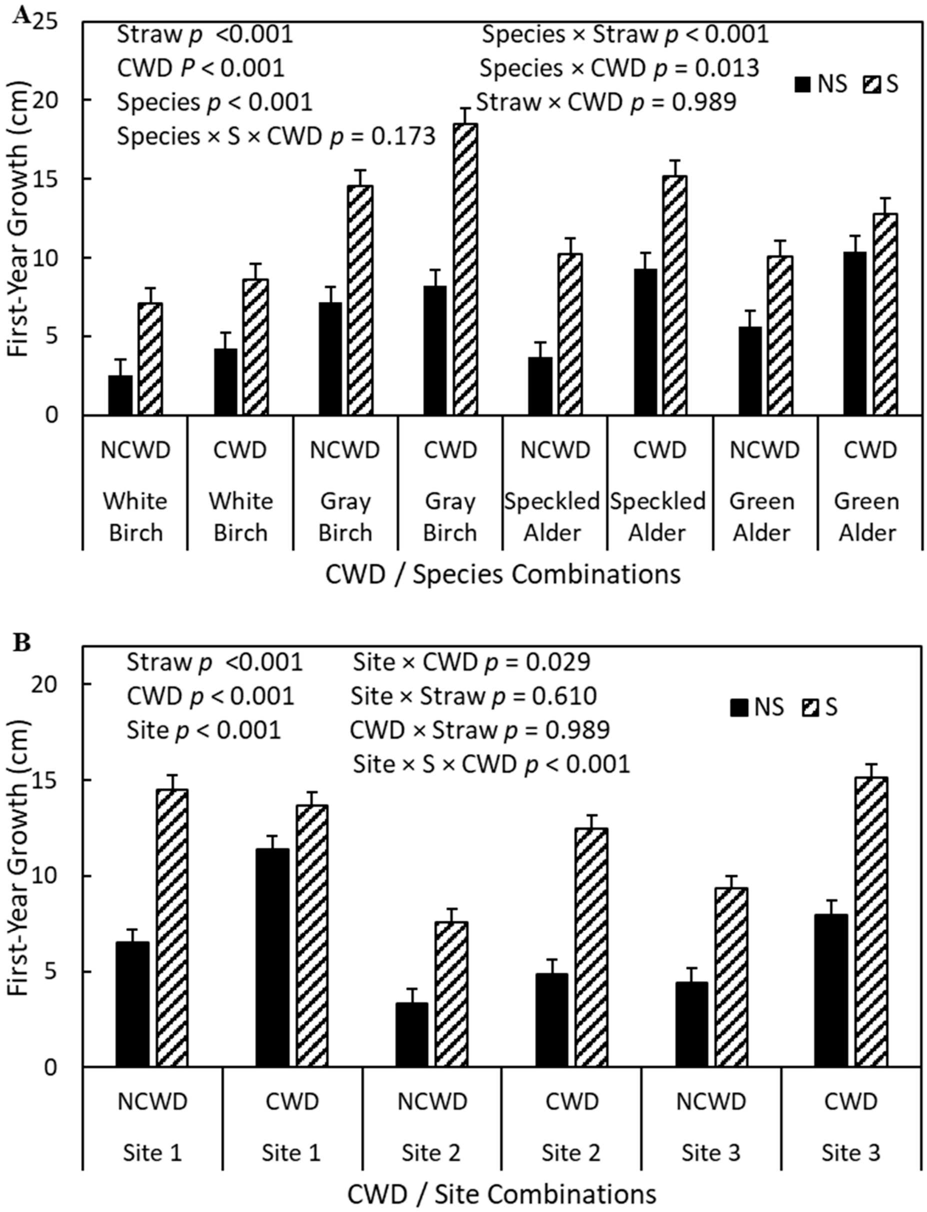

Figure 3. First-year growth (cm) (mean ± SE) showing (**A**) species × S × CWD interaction; (**B**) site × S × CWD interaction. NS: no straw, S: straw, NCWD: no coarse woody debris, CWD: coarse woody debris (n = 1417).

Table 3. Impacts of 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. Source of variation abbreviations are Meri-Crusher (MC), straw (S), and coarse woody debris (CWD).

First-Year Growth				
Source of Variation	**df**	**MS**	**VC (%)**	***p*-Value**
MC	1	2229.036	1.8	**<0.001**
S	1	11,329.324	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

Table 3. *Cont.*

First-Year Growth				
Source of Variation	**df**	**MS**	**VC (%)**	***p*-Value**
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	
R^2	0.59			

3.3. Second-Year Height Growth

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 4). Site and MC significantly influenced the variance of the second-year growth with 1.8% and 1.4%, respectively. Second, second-year height growth two- and three-way interactions were all magnitude effects. Third, again, significant two- and three-way interactions were best captured by the species × CWD × S interaction (Figure 4A) and site × CWD × S interaction (Figure 4B).

Table 4. Impacts of 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. Source of variation abbreviations are Meri-Crusher (MC), straw (S), and coarse woody debris (CWD).

Second-Year Growth				
Source of Variation	**df**	**MS**	**VC (%)**	***p*-Value**
MC	1	7523.429	1.4	**<0.001**
S	1	42,715.569	8.2	**<0.001**
CWD	1	38,554.355	7.4	**<0.001**
SITE	2	4746.407	1.8	**<0.001**
SPECIES	3	58,212.778	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			

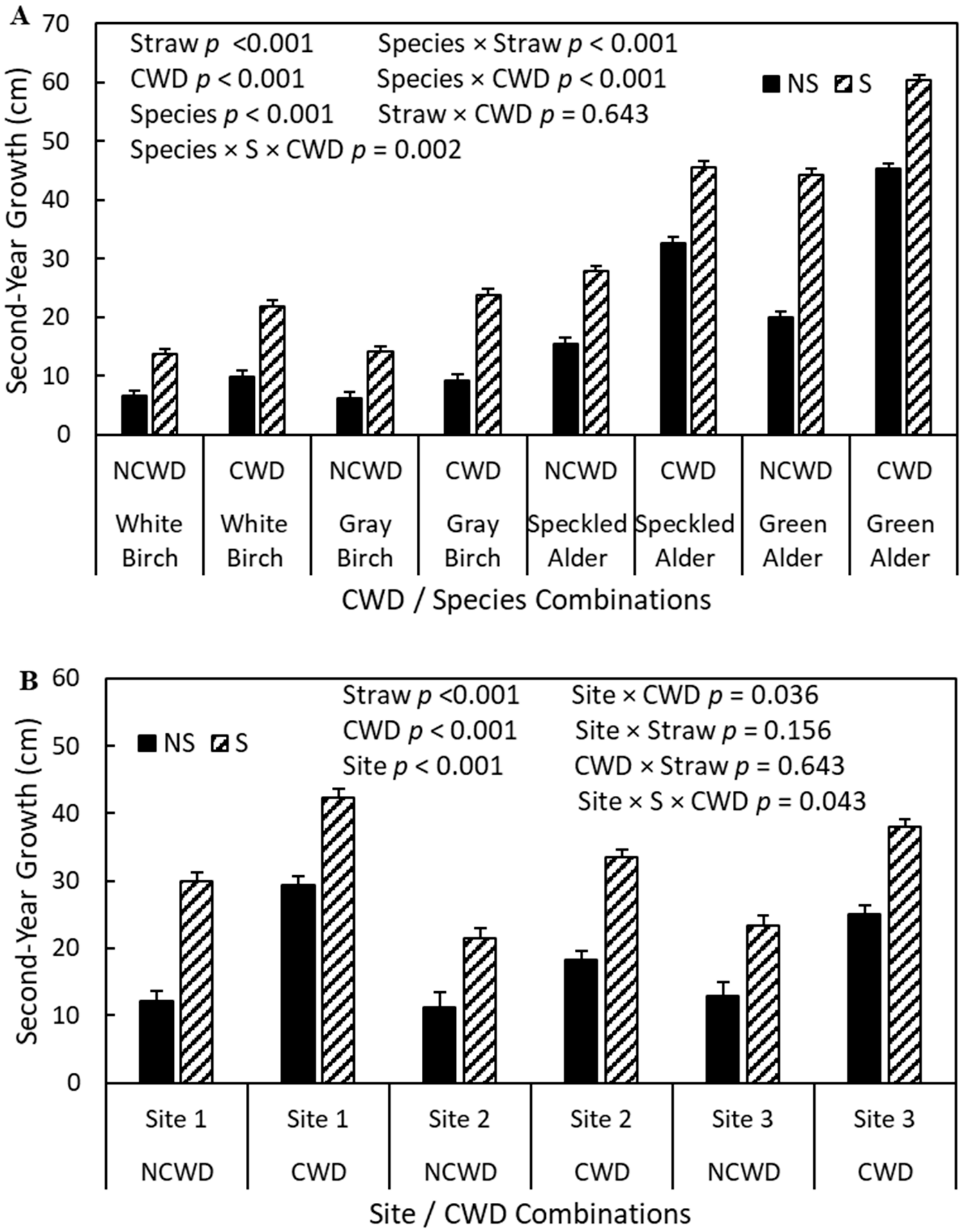

Figure 4. Second-year growth (cm) (mean ± SE) showing (**A**) species × S × CWD interaction; (**B**) site × S × CWD interaction. NS: no straw, S: straw, NCWD: no coarse woody debris, CWD: coarse woody debris (n = 1210).

Like first-year height growth, the species × S and species × CWD interactions illustrated that S and CWD always had greater second-year height growth for all species compared to NS and NCWD, respectively, but of differing magnitudes (Figure 4A). Similarly, the site × S × CWD interaction (Figure 4B) illustrated that S and CWD always had greater second-year height growth than NS and NCWD across all sites, but of differing magnitudes. Given that the interactions were all magnitude effects, the main effect of S versus NS overall resulted in a near-doubling of height growth from 18.2 to 31.5 cm, CWD versus NCWD also increased height growth (near-doubling it) from 18.5 to 31.1 cm, and MC versus NMC increased height growth by 25% from 22.1 to 27.6 cm. Green alder now had the greatest overall height growth followed by SA, GB, and WB, with 42.5, 30.5, 13.4, and 13.0 cm, respectively (Figure 4A). Similarly, site 1 had the greatest height growth followed by sites 3 and 2 with 28.5, 24.9, and 21.1 cm, respectively (Figure 4B).

3.4. Second-Year Stem Number

For stem number, species accounted for a very large 42% of the total variation (Table 5). The stem numbers for both birches were essentially one, while the GA and SA mean stem numbers were 3.2 and 2.8 per plant (Figure 5).

Table 5. Impacts of site-preparation treatments, species, and site effects and interactions on stem number. 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. Source of variation abbreviations are Meri-Crusher (MC), straw (S), and coarse woody debris (CWD).

		Stem Number *		
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	<0.001	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			

* Square root transformed.

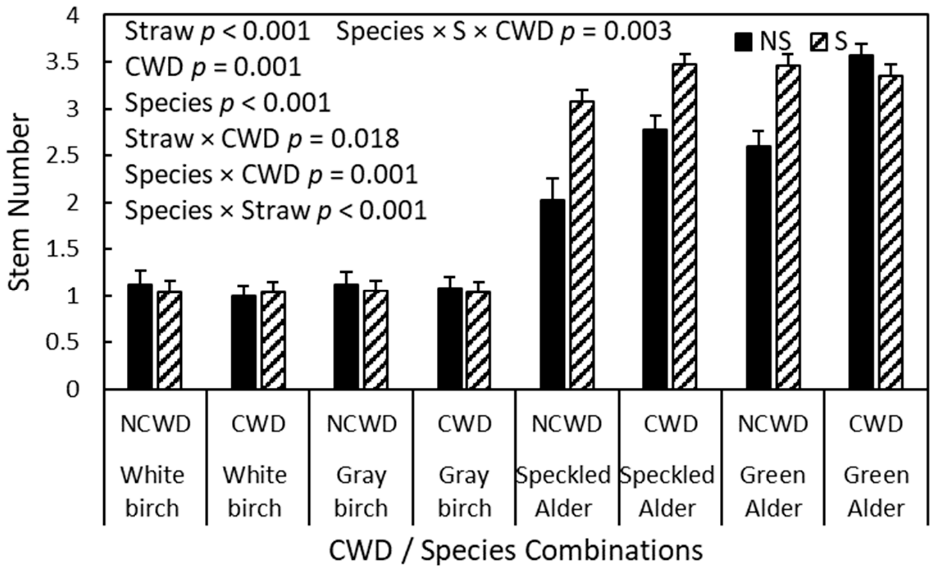

Figure 5. Stem number (mean ± SE) showing a species × S × CWD interaction. NS: no straw, S: straw, NCWD: no coarse woody debris, CWD: coarse woody debris (n = 1210).

Species × S interaction was a magnitude effect, and birch remained unchanged in the NS and S treatments, whereas GA and SA in NS and S increased in mean stem number from 3.1 to 3.4 and 2.4 to 3.3, respectively. Again, other interactions were of minor magnitudes or rank changes, as shown in Figure 5, where GA under CWD were basically equal in NS and S, whereas the other alder species had greater stem numbers under S regardless of the presence or absence of CWD.

3.5. Second-Year Stem Dry Mass

Mean stem dm was also heavily influenced by species, accounting for 36.6% of variance (Table 6). Additionally, there were other factors that were significant and accounted for substantial amounts of variation, such as species × S (6.3%) and S itself (8.6%).

Table 6. Impacts of 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. Source of variation abbreviations are Meri-Crusher (MC), straw (S), and coarse woody debris (CWD).

		Stem Dry Mass		
Source of Variation	**df**	**MS**	**VC (%)**	***p*-Value**
MC	1	6402.516	1.3	**<0.001**
S	1	41,532.943	8.6	**<0.001**
CWD	1	22,465.595	4.7	**<0.001**
SITE	2	2758.520	1.1	**0.003**
SPECIES	3	58,811.420	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	10,179.717	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			

The only significant three-way interaction for stem dm was a magnitude, with one small rank change for the site × species × MC interaction. As can be seen in Figure 6B, MC always had an equal or greater stem dm regardless of the site or species, except for GA at site 1, where NMC had a greater stem dm than MC. All two-way interactions were magnitude effects. For example, in Figure 6A, species × CWD and species × S interactions show that for all species, CWD or S had greater stem dm than NCWD or NS, respectively. Thus, in terms of the main effects, species, S, CWD, MC, and site accounted for 36.6, 8.6, 1.3, and 1.1% of the total variation (Table 6). Stem dm values for GA, SA, GB, and WB were 58.4, 30.3, 5.4, and 4.0 g, respectively. Straw versus NS on average tripled the stem dm from

13.3 to 35.6 g. Coarse woody debris versus NCWD on average doubled the stem dm from 16.3 to 32.7 g. Meri-Crusher versus NMC on average increased the stem dm from 20.1 to 28.8 g or by 43%. Sites 1, 2, and 3 had stem dm values that averaged 30.0, 21.2, and 22.2 g, respectively.

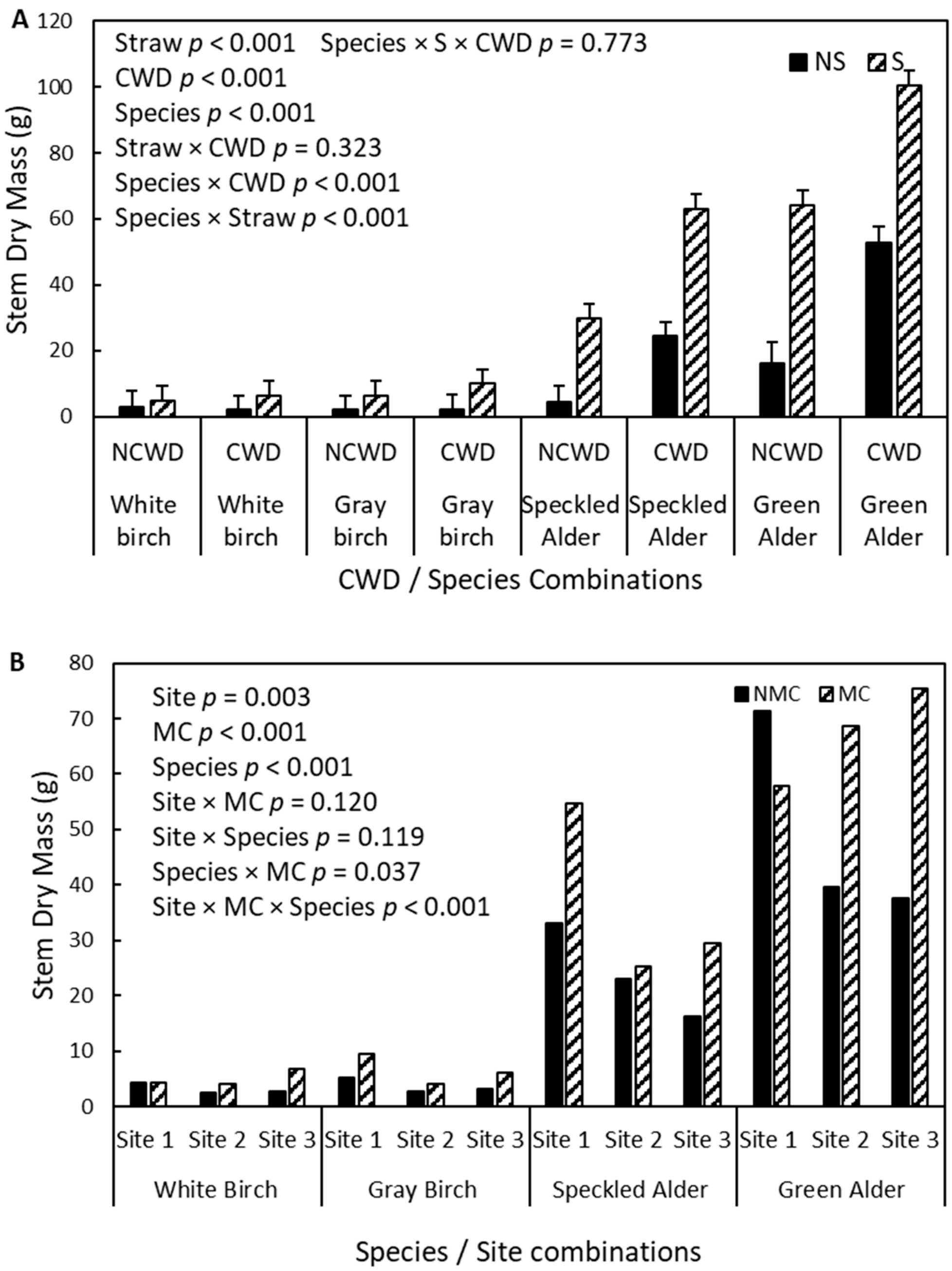

Figure 6. Stem dry mass (mean ± SE) showing (**A**) species × S × CWD interaction; (**B**) site × MC × species interaction. NS: no straw, S: straw, NCWD: no coarse woody debris, CWD: coarse woody debris, NMC: no Meri-Crusher, MC: Meri-Crusher (n = 358).

When assessing individual treatments and treatment combinations for both WB and GB, the control treatment stem dm values were 0.7 and 1.4 g, respectively, whereas, for the MC × S × CWD combination, they were 6.6 and 12.3 g, respectively (Figure 7A,B). The MC × S × CWD combination, when compared to the control, resulted in a 9.4- and 8.7-fold increase in stem dm productivity for WB and GB, respectively. Coarse woody debris alone was the least effective in increasing stem dm for both WB and GB with only a 0.9 and 0.5 g increase over the control, respectively. Straw as an individual treatment outperformed or came within the margins of MC × CWD plots. In assessing the site-preparation treatments, for WB, the realized stem dm met additive effects expectations. For GB, the realized stem dm met or exceeded additive effects expectations and thus resulted in site-preparation synergistic effects in all but one combination, MC × CWD.

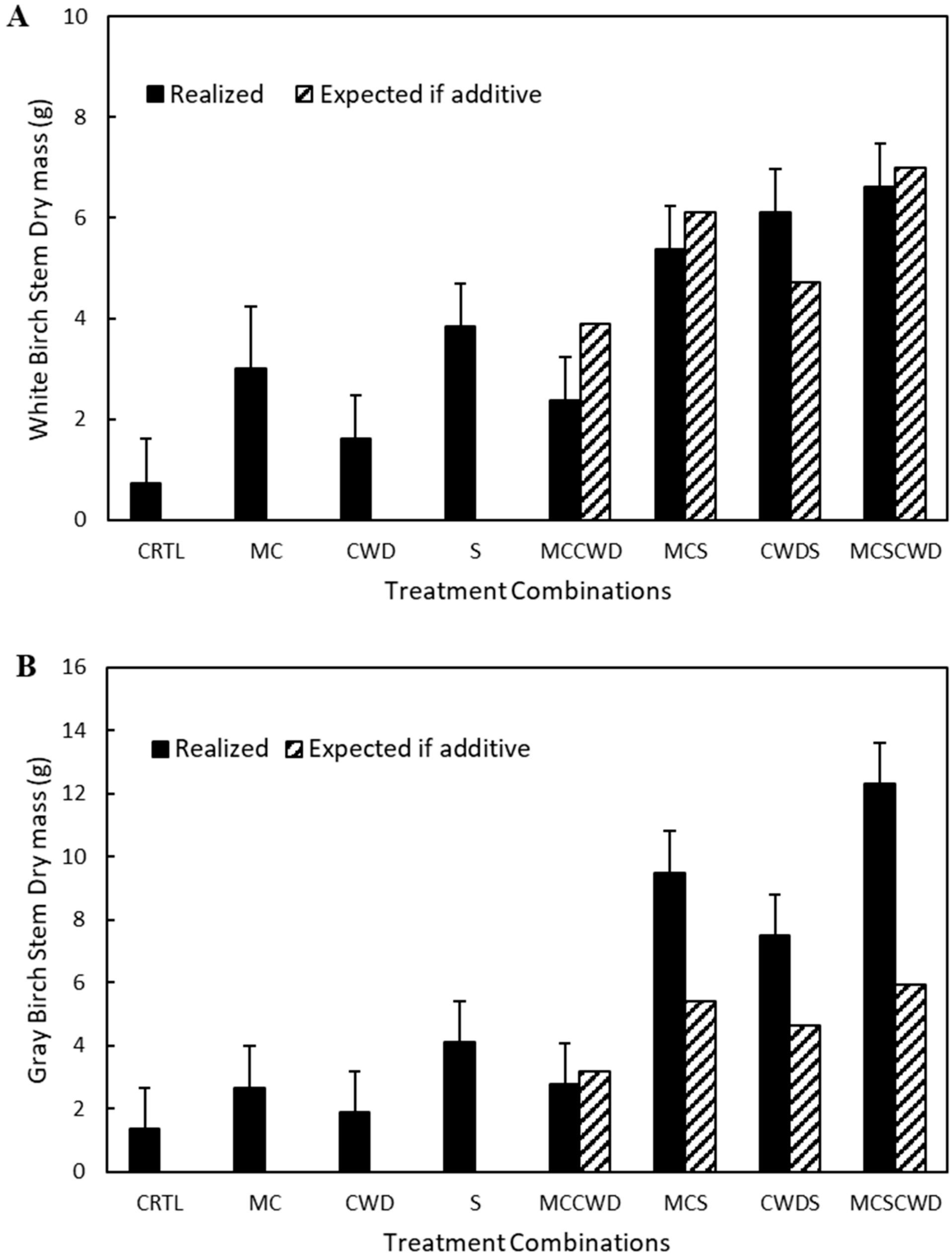

Figure 7. Stem dry mass (mean ± SE) for each treatment combination including an expected line assuming single-treatment effects were additive for (**A**) white birch and (**B**) gray birch. Note that (**A**,**B**) have differing Y-axis scales. CRTL: control, no treatments, MC: Meri-Crusher, CWD: coarse woody debris, MCCWD: Meri-Crusher + coarse woody debris, S: straw, MCS: Meri-Crusher + straw, SCWD: straw + coarse woody debris, MCSCWD: Meri-Crusher + straw + coarse woody debris (n = 358).

When assessing individual site-preparation treatments and treatment combinations, GA and SA also greatly benefitted in slightly different ways. The stem dm for SA in the control was a very small 0.5 g, compared to GA with 17.8 g (Figure 8A,B). Under the MC × S × CWD combination, GA and SA were 115.7 and 70.6 g, respectively. Compared to control, that was a 6.5- and 140-fold increase in stem dm productivity for GA and SA, respectively. Both species had greatly benefited from the site-preparation combinations in that the realized site-preparation treatments met or exceeded additive effects expectations and thus resulted in site-preparation synergistic effects. For GA, synergistic results were found in the MC × S and MC × S × CWD combinations, and for SA, in the CWD × S and MC × S × CWD combinations.

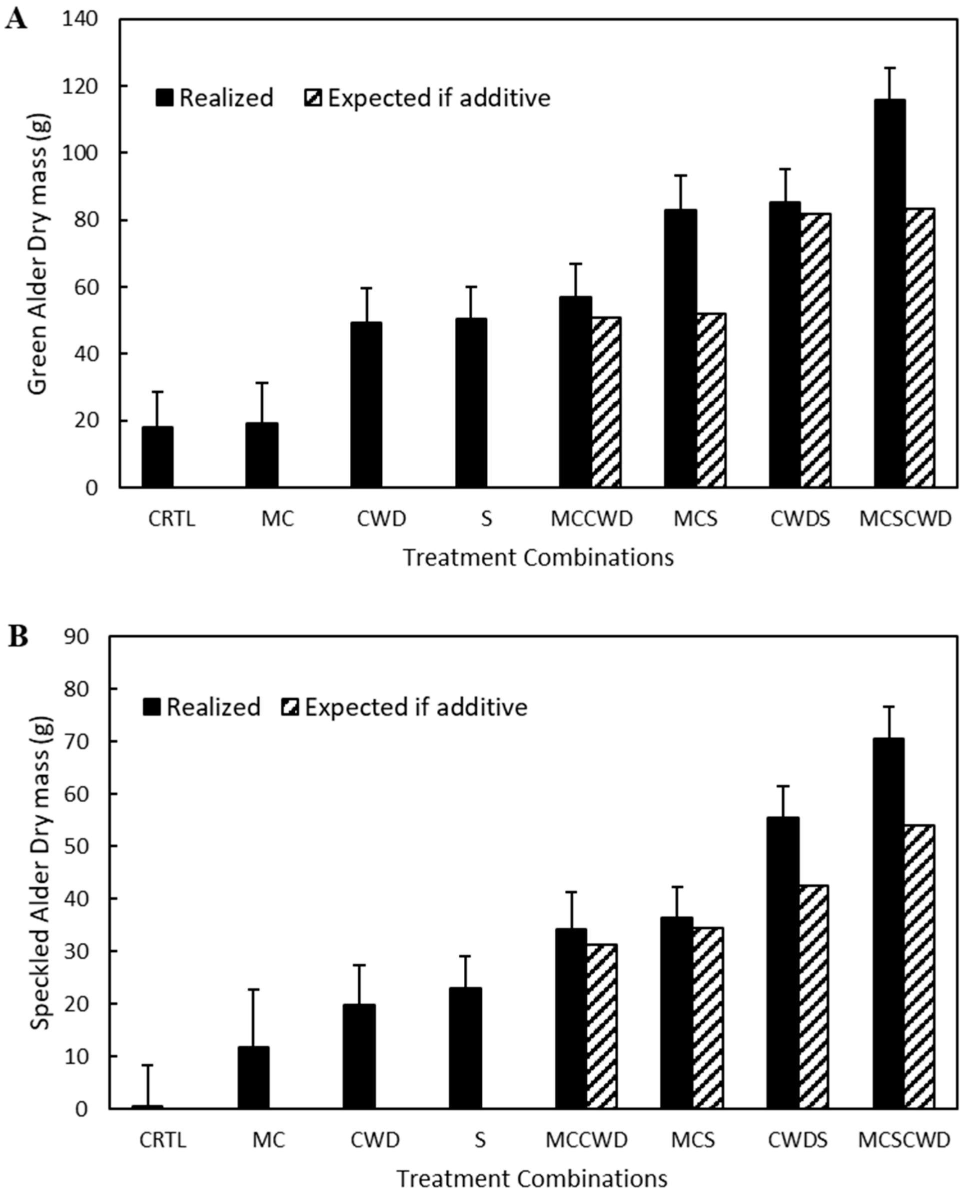

Figure 8. Stem dry mass (mean ± SE) for each treatment combination including an expected line assuming single-treatment effects were additive for (**A**) green alder and (**B**) speckled alder. Note that (**A**,**B**) have differing Y-axis scales. CRTL: control, no treatments, MC: Meri-Crusher, CWD: coarse woody debris, MCCWD: Meri-Crusher + coarse woody debris, S: straw, MCS: Meri-Crusher + straw, SCWD: straw + coarse woody debris, MCSCWD: Meri-Crusher + straw + coarse woody debris (n = 358).

4. Discussion

4.1. First-Year Height Growth

First-year height growth was most influenced by the effect of S, accounting for 9.1% of total variance, which resulted in a doubling of height growth. During the first year, significant two- and three-way growth interactions between treatments, species, and sites were almost all magnitude effects with only one slight rank change occurring in site × CWD × MC (Table 3); this allows us to consider the main treatments since their addition always increased growth for all factors. Straw had the largest effect on growth due to its ability to reduce summer moisture evaporation [38], increase soil water storage [41], and regulate surficial temperatures [43]. Straw allowed for SA, a hydrophilic species [32], to overcome the drought conditions of these sites since SA had half the summer related mortality [8]. Coarse woody debris has also been shown to decrease water loss by shading and reducing seedling desiccation as it provides shelter [45,49]. Seedlings grown with the CWD treatment had an average growth increase of 2.1 cm for WB and GB and a 4.5 cm increase for GA and SA. Speckled alder and GA benefitted more from the sheltering properties of CWD [44].

Straw and CWD combined, while previously understood as providing largely the same soil-moisture-retaining effect and possibly reducing one or two effects together, provided the greatest growth increase when compared to the control, and in fact, stood as an additive combination in the first year. After an extensive literature review, we can surmise that published knowledge is lacking on this combined effect on growth, and, in fact, any combinations of these site-preparation treatments. Site 1 growth doubled with S and CWD present, and site 2 and 3 growth was tripled. Site 1 had deeper soil and thus better inherent moisture-retaining properties than sites 2 or 3, meaning it benefitted more from the site-preparation treatments. The Meri-Crusher treatment had some success in creating improved aeration, water infiltration, and root penetration [37]; however, unless paired with either of the other two treatments, first-year MC alone had by far the worst (60%) mortality, greater than even that of the control at 38% [8].

4.2. Second-Year Height Growth

Second-year height growth was influenced by similar factors as the first-year growth. However, species turned into the greatest source of variation, accounting for 33.5% of the total variation, while S and CWD accounted for 8.2% and 7.4% of the total variation, respectively (Table 4). The site effect was not as important in the second-year, accounting for 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 first-year height growth to being dwarfed by GA and SA is probably best explained by the ability of GA and SA to fix atmospheric nitrogen through a symbiotic relationship with the bacteria *Frankia alni* Woronin [50,51]. The difference in genera growth was not realized in the first-year height growth, as it appears resources were being diverted to roots for *Frankia alni* establishment in nodules. However, once established, it fully benefited alder's second-year growth. The increase in alder foliar N concentrations, as found by [52], allowed for far greater growth compared to birch as there was very little soil N (mean soil N = 0.12%). According to Ekblad [50], the N fixation by *Alnus* does not assist other nearby species in the uptake of N since the leaves are where the majority of N is allocated; during the fall, most foliar N is reallocated back into the stem and roots but there is residual N in senesced leaves. Once they have fallen to the ground, these can provide some N through decomposition [50]. Straw's effect on second-year growth was like the first year in that it increased soil moisture retention [53] and regulated surficial temperature [54,55]. The second-year height growth CWD effect changed compared to the first-year growth, with it being more effective in increasing growth, doubling it from 18.5 cm in NCWD plots to 31.1 cm in CWD plots (Figure 4). Coarse woody debris plots also appeared to effectively trap fallen organic matter from the surrounding area and, in doing so, created a moisture-retaining microsite favorable for growth [56]. Site differences did not change, with site 1 still providing the best growing conditions, with greater soil-depth-to-bedrock and slightly better soil nutrients than sites 2 and 3 (Table 2).

4.3. Second-Year Stem Number

Species was the only main factor for stem number differences, with it accounting for a large 42% of the total variation (Table 5). Only the species × S interaction ($p < 0.001$)

accounted for over 1% of the total variance in the model. Both WB and GB can exist with multiple stems but are not always known to grow more than one or two from the base if not coppiced [57]. Speckled alder and GA are both known to have the ability to have multiple stems since they are shrub species [58]. In fact, when coppiced after one year of growth in a greenhouse experiment examining the same species under a 2 × 2 factorial of CO_2 × soil moisture stress treatments, the alders and birches produced on average 7.9 and 3.8 stems per plant, respectively [59]. As might be expected, well-watered and drought resulted 6.7 and 5.1 stems per plant, respectively, an obvious response to soil moisture stress. The ambient and elevated CO_2 treatments resulted in a significant increase in stem number from 5.7 and 6.1 stems per plant, respectively, in a response to atmospheric CO_2 fertilization [59].

4.4. Second-Year Stem Dry Mass

Stem dry mass production followed second-year height trends and was primarily affected by species, which accounted for 36.6% of total variance (Table 6). However, the magnitudes were much greater, with stem dm values of 58.4, 30.3, 5.1, and 4.0 g for GA, SA, GB, and WB, respectively. The largest difference between GA and WB was an almost 15-fold larger stem dm after two years on these impoverished and degraded sites. All significant interactions, but one, were magnitude effects, and the addition of S, CWD, and MC yielded greater stem dm values than if they were not present. While explorations of combinations of S, CWD, and MC and findings on how they influence stem dm are lacking in the literature, individual effects can be teased out and may help explain the results. Straw's ability to increase soil moisture [60] while reducing surface evaporation [38] and moderating soil temperature [43] allowed it to create a more suitable environment for plant growth. Coarse woody debris, as mentioned in the second-year growth section, changed from largely a shelter treatment [44,45] but also a moisture-retaining microenvironment after capturing surrounding organics [56]. Straw tripled stem dm while CWD doubled stem dm after two years likely because of their moisture-retaining and sheltering qualities. Both GA and SA took the increased soil moisture content and were able to utilize it the most with their ability to generate their own N through their symbiosis with N-fixing bacteria [61]. Gray birch and WB both tripled and doubled stem dm with the addition of S and CWD, but had far less stem dm than both alders. For WB, regardless of the increased soil moisture with S or CWD, the lack of available nutrients stunted its growth compared to GB [62,63]. While S and CWD by themselves and in combination with other treatments produced the best growing conditions, MC also increased stem dm on average by 40% across all species.

White birch was the only species to demonstrate only additive site-preparation treatment effects, which is impressive, implying that perhaps the lack of N for a more N-demanding birch cannot be made up for by increasing the soil moisture alone. Green alder, SA, and GB, in all or most site-preparation interactions, had synergistic effects that were greater than the addition of the single effects. Again, after an extensive scientific literature review, we found site-preparation treatment combination information to be lacking. It was surprising to see the synergistic effect as two of the treatments, S and CWD, are thought to provide similar benefits of soil moisture retention. Perhaps the site is so depleted in its soil moisture-holding capacity, as it has been largely barren for the last 25 years, that this resulted in at least additive results. 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 was very much reduced in combination with S or CWD [8]. Furthermore, the best treatment for lowest mortality, with only 3.1%, was MC × S × CWD. For reference, in the control plots, WB, GB, GA, and SA were 0.7, 1.4, 17.8, and 0.5 g, respectively. Under MC × S × CWD, WB, GB, GA, and SA saw a 9.4-, 8.7-, 6.5-, and 140-fold increase in stem dm to 6.6, 12.3, 115.7, and 70.6 g, respectively. It should be noted that the 0.5 g for SA under the control was from sites that may be considered "off site" for SA, which had the greatest summer drought and frost-heaved mortality. At the same time, this demonstrates how effective the site-preparation combination was in that it was rather effective for a species like SA.

5. 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 and provides the greatest moisture retention and drought prevention capabilities, but does require logistics, a skid steerer, and straw chopper. Furthermore, the Meri-Crusher requires access to large, tracked machinery that can support the MC head, and CWD requires a source for 20–30-year-old trees cut and forwarded. Coarse woody debris can provide sufficient drought prevention and shelter from the elements, and more so after it traps and accumulates more organic matter within the microsite. However, coarse woody debris may also prove harder to plant in, and if the site is shallow and lacking MC treatments, then CWD may limit "good" planting spots. In terms of long-term success, CWD and S together provided excellent environments for early-successional species to grow, since they prefer mostly full light, but may be limited by drought conditions on degraded sites. Not all three site-preparation treatments need be used, and an assessment should be carried out to find the best prescription for each planned restoration site. Coarse woody debris appears to be second best in open sites that require shelter from sun, wind, and rain erosion. Naturally, each restoration project will have different levels of degradation and require specific species and treatment prescriptions to help best restore sites. The species and treatments used in this experiment were selected based on the site challenges and to quantify survival and growth on these sites (forming the hypotheses of the experiment), to expand restoration activities. These treatments and their combinations are feasibly applicable to other ecosystems, but that decision should be made considering regional native early-successional species that are part of the ecosystem. Overall, GA was the best-performing species for capturing barren sites due to its inherent nitrogen-fixing ability and drought tolerance. Speckled alder can also fixate nitrogen; however, its preference for a moist site holds it back in areas without the S or CWD treatment. Gray birch grew better than WB since WB appeared to need more available soil nutrients. Biomass production, and, therefore, eventual soil amelioration via organic decomposition, would also be accelerated when using GA. The focus of this ecological restoration is to prevent further soil erosion and promote soil creation; in those regards, the full combination of the three treatments (MC $\times$ S $\times$ CWD) produced the best results, reduced erosion, and with GA or SA, generated the greatest biomass to capture barren sites and create more desirable environment in which to start forest succession. Further potential research includes examining other early-successional species, quantifying the coppice response, and exploring future mortality and growth.

Author Contributions: J.E.M. designed the experiment, co-analyzed the data, and co-authored the manuscript. D.G. managed the experiment, co-analyzed the data, and co-authored the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. Patric, J.H. Soil Erosion in the Eastern Forest. *J. For.* **1976**, *74*, 671–677.
2. Ryan, S.E.; Grant, G.E. Downstream Effects of Timber Harvesting on Channel Morphology in Elk River Basin, Oregon. *J. Environ. Qual.* **1991**, *20*, 60. [CrossRef]
3. Abrams, M.D. Adaptations and responses to drought in Quercus species of North America. *Tree Physiol.* **1990**, *7*, 227–238. [CrossRef] [PubMed]
4. Trenberth, K.; Dai, A.; van der Schrier, G.; Jones, P.D.; Barichivich, J.; Briffa, K.R.; Sheffield, J. Global warming and changes in drought. *Nat. Clim. Chang.* **2014**, *4*, 17–22. [CrossRef]
5. Fathi, A.; Tari, D.B. Effect of Drought Stress and its Mechanism in Plants. *Int. J. Life Sci.* **2016**, *10*, 1–6. [CrossRef]
6. Amissah, L.; Mohren, G.M.J.; Kyereh, B.; Poorter, L. The Effects of Drought and Shade on the Performance, Morphology and Physiology of Ghanaian Tree Species. *PLoS ONE* **2015**, *10*, e0121004. [CrossRef]
7. Asghar, M.A.; Du, J.; Jiang, H.; Li, Y.; Sun, X.; Shang, J.; Liu, J.; Liu, W.; Imran, S.; Iqbal, N.; et al. Shade pretreatment enhanced drought resistance of soybean. *Environ. Exp. Bot.* **2020**, *171*, 103952. [CrossRef]
8. Galea, D.; Major, J.E. First-Year Mortality of Four Early-Successional Species on Severely Degraded Sites in Eastern Canada as Influenced by a Factorial of Site Preparation Treatments. *Forests* **2024**, *15*, 143. [CrossRef]
9. Polster, D.F. Successional reclamation in Western Canada: New light on an old subject. In Proceedings of the Canadian Land Reclamation Association and American Society for Surface Mining and Reclamation Conference, Calgary, AB, Canada, 27–31 August 1989.
10. Jochimsen, M.E.A. Reclamation of colliery mine spoil founded on natural succession. *Water Air Soil Pollut.* **1996**, *91*, 99–108. [CrossRef]
11. Bradshaw, A. Restoration of mined lands—Using natural processes. *Ecol. Eng.* **1997**, *8*, 255–269. [CrossRef]
12. Šourková, M.; Frouz, J.; Fettweis, U.; Bens, O.; Hüttl, R.F.; Šantrůčková, H. Soil development and properties of microbial biomass succession in reclaimed post mining sites near Sokolov (Czech Republic) and near Cottbus (Germany). *Geoderma* **2005**, *129*, 73–80. [CrossRef]
13. Frazier, C.S.; Graham, R.C. Pedogenic Transformation of Fractured Granitic Bedrock, Southern California. *Soil Sci. Soc. Am. J.* **2000**, *64*, 2057. [CrossRef]
14. Landeweert, R.; Hoffland, E.; Finlay, R.D.; Kuyper, T.W.; van Breemen, N. Linking plants to rocks: Ectomycorrhizal fungi mobilize nutrients from minerals. *Trends Ecol. Evol.* **2001**, *16*, 248–254. [CrossRef]
15. Bornyasz, M.A.; Graham, R.C.; Allen, M.F. Ectomycorrhizae in a soil-weathered granitic bedrock regolith: Linking matrix resources to plants. *Geoderma* **2005**, *126*, 141–160. [CrossRef]
16. Rajakaruna, N.; Boyd, R.S. Edaphic Factor. In *Encyclopedia of Ecology*; Jorgensen, S.E., Fath, B., Eds.; Elsevier: Amsterdam, The Netherlands, 2008; Volume 2, pp. 1201–1207.
17. Skrindo, A.B. Natural Revegetation from Indigenous Soil. Ph.D. Thesis, Norwegian University of Life Sciences, Ås, Norway, 2005.
18. Fox, J.E.D. Rehabilitation of Mined Lands, Review Artick. Forest Abstract. *Commonw. For. Bur.* **1984**, *9*, 565–600.
19. Swanson, M.E.; Franklin, J.F.; Beschta, R.L.; Crisafulli, C.M.; Dellasala, D.A.; Hutto, R.L.; Lindenmayer, D.B.; Swanson, F.J. The forgotten stage of forest succession: Early-successional ecosystems on forest sites. *Front. Ecol. Environ.* **2011**, *9*, 117–125. [CrossRef]
20. Lanner, R.M. *Trees of the Great Basin: A Natural History*; University of Nevada Press: Reno, NV, USA, 1983; 215p.
21. Monsen, S.B.; Stevens, R.; Shaw, N.L. *Restoring Western Ranges and Wildlands*; Gen. Tech. Rep. RMRS-GTR-136-vol-2; Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2004; pp. 597–699.
22. Son, Y.; Lee, Y.Y.; Lee, C.Y.; Yi, M.J. Nitrogen fixation, soil nitrogen availability, and biomass in pure and mixed plantations of alder and pine in central Korea. *J. Plant Nutr.* **2007**, *30*, 1841–1853. [CrossRef]
23. Ste-Marie, C.; Pare, D.; Gagnon, D. The contrasting effects of aspen and jack pine on soil nutritional properties depend on parent material. *Ecosystems* **2007**, *10*, 1299–1310. [CrossRef]
24. Hosie, R.C. *Native Trees of Canada*, 7th ed.; Canadian Forestry Service, Department of Fisheries and Forestry: Ottawa, ON, Canada, 1969.
25. Vogel, W.G. *A Guide for Revegetating Coal Mine Soils in the Eastern United States*; Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Broomall, PA, USA, 1981; Volume 68, 190p.
26. Blundon, D.J.; Dale, M.R.T. Dinitrogen fixation (Acetylene reduction) in primary succession near Mount Robson, British Columbia, Canada. *Arct. Alp. Res.* **1990**, *22*, 255–263. [CrossRef]
27. Haeussler, S.; Coates, D. Autecological characteristics of selected species that compete with conifers in British Columbia: A literature review. *Land Manag. Rep.* **1986**, *33*, 180.
28. DeHond, P.E.; Campbell, C.S. Multivariate analyses of hybridization between *Betula cordifolia* and *B. populifolia* (*Betulaceae*). *Can. J. Bot.* **1989**, *67*, 2252–2260. [CrossRef]
29. Chapman, W.K.; Bessette, A.E. *Trees and Shrubs of the Adirondacks*; North Country Books: Utica, NY, USA, 1990; 131p.
30. Furlow, J.J. The systematics of the American species of Alnus (Betulaceae) Part 1. *Rhodora* **1979**, *81*, 1–121.
31. Armstrong, R.C.; Heston, K. Control of woody invasion of a kettle bog. *Restor. Manag. Notes* **1982**, *1*, 18.
32. Brisson, J.; Cogliastro, A.; Robert, M. Controlling speckled alder (*Alnus incana* ssp. *rugosa*) invasion in a wetland reserve of southern Quebec. *Nat. Areas J.* **2006**, *26*, 78–83. [CrossRef]

33. Bakuzis, E.V.; Hansen, H.L. Ecographs of shrubs and other undergrowth species of Minnesota forest communities. *Minn. For. Notes* **1962**, *117*, 1–2.
34. Ashby, W.C. Soil Ripping and Herbicides Enhance Tree and Shrub Restoration on Stripmines. *Restor. Ecol.* **1997**, *5*, 169–177. [CrossRef]
35. Polster, D.F. Natural Processes: The Application of Natural Systems for the Reclamation of Drastically Disturbed Sites. In Proceedings of the B.C. Technical and Research Committee on Reclamation, BC Mine Reclamation Symposium, Cranbrook, BC, Canada, 14–17 September 2009.
36. Lambermont, J.; Lebon, G. Erosion of Cohesive Soils. *J. Hydraul. Res.* **1978**, *16*, 27–44. [CrossRef]
37. Richardson, B.Z.; Pratt, M.M. *Environmental Effects of Surface Mining of Minerals Other Than Coal: Annotated Bibliography and Summary Report*; Intermountain Forest and Range Experiment Station, U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 1980; Volume 95.
38. Novak, M.D.; Chen, W.J.; Orchansky, A.L.; Ketler, R. Turbulent exchange processes within and above a straw mulch. Part II: Thermal and moisture regimes. *Agric. For. Meteorol.* **2000**, *102*, 155–171. [CrossRef]
39. Adekalu, K.; Olorunfemi, I.; Osunbitan, J. Grass mulching effect on infiltration, surfacerunoff and soil loss of three agricultural soils in Nigeria. *Bioresour. Technol.* **2007**, *98*, 912–917. [CrossRef]
40. Edwards, L.; Burney, J.R.; Richter, G.; MacRae, A.H. Evaluation of compost and straw mulching on soil-loss characteristics in erosion plots of potatoes in Prince Edward Island, Canada. *Agric. Ecosyst. Environ.* **2000**, *81*, 217–222. [CrossRef]
41. Balwinder-Singh; Humphreys, E.; Eberbach, P.L.; Katupitiya, A.; Yadvinder-Singh; Kukal, S.S. Growth, yield, and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule. *Field Crops Res.* **2011**, *121*, 209–225. [CrossRef]
42. Rahma, A.E.; Warrington, D.N.; Lei, T. Efficacy of wheat straw mulching in reducing soil and water losses from three typical soils of the Loess Plateau, China. *Int. Soil Water Conserv. Res.* **2019**, *7*, 335–345. [CrossRef]
43. Liu, Y.; Wang, J.; Liu, D.; Li, Z.; Zhang, G.; Tao, Y.; Pan, J.; Chen, F. Straw Mulching Reduces the Harmful Effects of Extreme Hydrological and Temperature Conditions in Citrus Orchards. *PLoS ONE* **2014**, *9*, e87094. [CrossRef]
44. Pyper, M.; Vinge, T. *A Visual Guide to Handling Woody Materials for Forested Land Reclamation*; Oil Sands Research and Information Network; University of Alberta, School of Energy and the Environment: Edmonton, AB, Canada, 2012; 10p. [CrossRef]
45. Jumpponen, A.; Väre, H.; Mattson, K.G.; Ohtonen, R.; Trappe, J.M. Characterization of 'safe sites' for pioneers in primary succession on recently deglaciated terrain. *J. Ecol.* **1999**, *87*, 98–105. [CrossRef]
46. Wells, J.M.; Boddy, L. Wood decay, and phosphorus and fungal biomass allocation, in mycelial cord systems. *New Phytol.* **1990**, *116*, 285–295. [CrossRef]
47. McKeague, J.A. *Manual of Soil Sampling and Methods of Analysis*, 2nd ed.; Canadian Society of Soil Science: Pinawa, MB, Canada, 1978.
48. Hicks, C.R. *Fundamental Concepts of Design of Experiments*, 2nd ed.; Holt, Reinhart and Winston: New York, NY, USA, 1982; pp. 55–57.
49. Orman, O.; Adamus, M.; Szewczyk, J. Regeneration processes on coarse woody debris in mixed forests: Do tree germinants and seedlings have species-specific responses when grown on coarse woody debris? *J. Ecol.* **2016**, *104*, 1809–1818. [CrossRef]
50. Ekblad, A.; Huss-Danell, K. Nitrogen Fixation by *Alnus incana* and Nitrogen Transfer from *A. incana* to *Pinus sylvestris* Influenced by Macronutrients and Ectomycorrhiza. *New Phytol.* **1995**, *131*, 453–459. [CrossRef]
51. Fessenden, R.J. *Use of Actinorrhizal Plants for Land Reclamation and Amenity Planting in the USA and Canada*; Syncrude Canada: Fort McMurray, AB, Canada, 1979.
52. Brisebois, A.; Major, J.E. Effects of CO_2 Treatments on Functional Carbon Efficiencies and Growth of Forest Tree Seedlings: A Study of Four Early-Successional Deciduous Species. *Forests* **2024**, *15*, 193. [CrossRef]
53. Tao, Z.; Li, C.; Li, J.; Ding, Z.; Xu, J.; Sun, X.; Zhou, P.; Zhao, M. Tillage and straw mulching impacts on grain yield and water use efficiency of spring maize in Northern Huang–Huai–Hai Valley. *Crop J.* **2015**, *3*, 445–450. [CrossRef]
54. Goulet, F. Frost heaving in forest tree seedings: A review. *New For.* **1995**, *9*, 67–94. [CrossRef]
55. Chalker-Scott, L. Impact of Mulches on Landscape Plants and the Environment—A Review. *J. Environ. Hortic.* **2007**, *25*, 239–249. [CrossRef]
56. Wu, J.-B.; Guan, D.-X.; Han, S.-J.; Zhang, M.; Jin, C.-J. Ecological functions of coarse woody debris in forest ecosystem. *J. For. Res.* **2005**, *16*, 247–252. [CrossRef]
57. Hutnik, R.J.; Cunningham, F.E. Paper birch (*Betula papyrifera* Marsh.). In *Silvics of forest trees of the United States*; U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Upper Darby, PA, USA, 1965; pp. 93–98.
58. Farrar, J.L. Canadian Forest Service. In *Trees in Canada*; Fitzhenry & Whiteside Ltd.: Markham, ON, Canada, 1995.
59. Brisebois, A.; Major, J.E. *Morphological and Allometric Variation of Four Coppiced Early-Successional Species, Used in Land Restoration, under CO_2 and Soil Moisture Treatments, Natural Resources Canada*; Canadian Forest Service: Fredericton, NB, Canada, 2024; to be submitted.
60. Rokich, D.P.; Dixon, K.W.; Sivasithamparam, K.; Meney, K.A. Smoke, mulch, and seed broadcasting effects on woodland restoration in Western Australia. *Restor. Ecol.* **2002**, *10*, 185–194. [CrossRef]
61. Schwencke, J. Recent advances in *Frankia* physiology and biochemistry with notes on practical implications. *Microb. Interact. Agric. For.* **1988**, *1*, 121–148.

62. Ingestad, T.; Lund, A.-B. Nitrogen Stress in Birch Seedlings. I. Growth Technique and Growth. *Physiol. Plant.* **1979**, *45*, 137–148. [CrossRef]
63. Leak, W.B. *Relationship of Species and Site Index to Habitat in the White Mountains of New Hampshire*; USDA Forest Service, Northeastern Forest Experiment Station: Broomall, PA, USA, 1978; Volume 397, 9p.