FOREST GROWTH ORGANIZATION OF WESTERN CANADA

Quantification of Herbicide Impacts on the Timber Resource

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Prepared By:

THEXLWIZ CONSULTING LTD.

FOREST GROWTH
ORGANIZATION OF WESTERN CANADA

FOREST RESOURCE IMPROVEMENT ASSOCIATION OF ALBERTA (FRIAA)

Executive Summary

This project was initiated to evaluate the long-term impacts of herbicide use on the timber resource including composition and structure and to project stand development from current stand conditions using Alberta herbicide data and growth models and determine yield and rotation implications.

Our study used forest herbicide monitoring plots that were established in the mid-1990's. These plots had a relatively large (1 ha) untreated area that was assessed using the same parameters as the herbicide treated area in the Fall of 2019, over 20 years after the first herbicide applications. While the original installations were placed in uniform cutblocks with regards to ecosite/phase, stand history and silviculture regime; subsequent non-uniform/uncontrolled treatments in some blocks make it difficult to draw treatment specific inferences. Nevertheless, these large research plots provide the best available information in Alberta.

It was found that herbicide treatment significantly reduced aspen cover, height and density in openings located in the Lower Foothills natural subregion of Alberta. Aspen density was reduced by 96% and basal area by as much as 98%. Our study agrees with the findings of several other studies that multiple herbicide treatments will result in an almost complete removal of aspen in treated areas resulting in a pure conifer stand. Treatment application timing, frequency and application method will determine the amount of deciduous that may be present in smaller patches in spray swaths or in areas between highlight treatments or other deciduous that are seeded in or resprout following mechanical tending treatment.

Overall growth response and survival of the planted white spruce 20 years from treatment was high in the treated areas. The herbicide treatment increased the average DBH of spruce by almost 50% and promoted the relative dominance of conifer from 31% of basal area in untreated areas to 97% in treated areas. We also observed an almost 3-fold increase in white spruce total volume in treated areas over 20 years after the first application of herbicide (74 m^3/ha vs 27 m^3/ha for treated and untreated areas, respectively). At the time of assessment there was a 7-fold increase in spruce gross merchantable volume (15/10/30 utilization) in treated areas (41 m^3/ha vs 6 m^3/ha in control plots). Given the average age and height of these stands, the magnitude of merchantable volume metrics needs to be interpreted with caution, as many trees are just on the 'cusp' of jumping the merchantable threshold in the next few years.

Untended spruce is certainly growing significantly slower as can be seen in DBH and basal area growth, but survival and ingress appear to be on par with the treated spruce. This may be related to the significant improvements in silviculture in the early 1990's, specifically the introduction of styroblock containers that drastically increased the survival rates of planted seedlings due to a well-developed, healthy root system. Many companies also increased planting densities and used better site preparation methods and equipment.

This long-term study shows that herbicide use clearly benefited conifer at the expense of deciduous over 20-years after the first treatment. There are substantial observed gains in conifer growth that will result in increased conifer peak MAI and reduced rotation length in these stands. However, the overall silviculture regime likely determined the scale of impact on the deciduous cover and the survival and growth response of the conifer. While herbicide treatments shifted the species composition to conifer and resulted in significant growth response from the planted spruce, it is likely that density management treatments such as commercial thinning would further increase piece size and reduce rotation length.

MGM projections of future stands growth in untreated areas average as conifer-dominated mixedwood over a 140-year horizon. Tended areas have virtually no deciduous component due to multiple herbicide treatments and MGM projects them as pure conifer stands, as a result.

MGM model simulations of treated stands produced slightly higher total merchantable volumes (494 m^3/ha) as compared to untreated (455 m^3/ha) at 100 years. Conifer MAI in treated areas is significantly larger (5.6 vs. 3.2 m^3/ha/year) and peaks earlier than in untreated areas (70 vs 90 years). Conifer piece size is also significantly larger in treated areas.

GYPSY projections of future stands growth in untreated areas average as deciduous-dominated mixedwood over a 140-year horizon. Treated stands are projected as pure conifer stands.

Total basal area and volume are similar at 100 years of age, although treated stands show slightly higher numbers for these stand attributes. The culmination MAI for conifer is much higher (5.8 vs. 2.5 m^3/ha/year) and peaks earlier (80 vs 90 years in treated and untreated, respectively). Conifer piece size is also substantially larger in treated stands as projected by GYPSY.

Projections by both models indicate substantial gains in conifer growth and reduced length of rotation in stands subjected to multiple herbicide treatments. Differences exist however in the magnitude of response and also in the development trajectories of untreated stands.

GYPSY was found to be significantly under-predicting the white spruce basal area in herbicide treated plots. Therefore, all GYPSY projections were based on localized basal area whereas the observed basal area was used to adjust model projections.

Differences between the two models is expected as there are significant differences in modeling architecture and approach: GYPSY is a stand level model where stand attributes are projected while MGM is “growing” tree lists.

Based on our review, it is apparent that our growth models still need work when it comes to projecting managed stand growth and yield. While the general trend is similar regarding increased growth of planted white spruce, higher conifer peak MAI and shorter rotation; there are significant projection differences in magnitude between the available models in herbicide treated stands. Untreated stands are projected very differently by MGM and GYPSY. Understanding these differences with regards to model architecture, data initialization (averaging input versus output), site index application methods and the handling of ingress/ingrowth are areas that will require more research. Significant improvements and advances in our knowledge and understanding are still needed in the modeling of the effects of forest vegetation management in order to bring these models into forest-level decision making.

However, models require local, representative data that come from long-term, controlled experiments with replication where the effect of treatments can be separated. Given current uncertainties regarding the acceptance of herbicide use in forest management, adding alternative, non-chemical vegetation management treatments (e.g., bend-and-break, mechanical brushing, grazing etc.) could also be useful in order to model the long-term responsiveness of these treatments. Operational style monitoring of large permanent sample plots can also play a role if long-term time series measurements are available. This is an expensive endeavor that can only be achieved through cooperative research programs with long-term financial backing.

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1. Overview

The Forest Growth Organization of Western Canada (FGrOW), an association of fRI Research submitted a proposal to the Forest Resource Improvement Association of Alberta (FRIAA) for a project to evaluate the long-term effects of herbicide use on coniferous and deciduous tree abundance and growth and to assess changes in plant community composition, diversity and structure.

This document describes the analysis that was undertaken to quantify the long-term impacts of herbicide use on the timber resource using Alberta Herbicide Monitoring installations.

The analysis of the long-term impact of herbicide use on non-timber values, including plant communities and wildlife habitat is discussed under separate cover.

1.1 Introduction

Forest vegetation management is a part of silviculture directed at manipulating the rate and course of secondary forest succession to achieve a forest of specific composition, structure and rate of growth (Wagner 1993). Herbicides are widely used as a forest vegetation management tool in Alberta to achieve successful regeneration of white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*). Glyphosate is the most commonly used herbicide in Alberta to control highly competitive species such as bluejoint reedgrass (*Calamagrostis canadensis*) and trembling aspen (*Populus tremuloides*) with the premise that the release of young conifers from competing vegetation will result in significant increases in survival and growth.

Recent articles regarding the potential carcinogenicity of glyphosate (Benbrook 2019, Cox 2019), and the purported impacts of herbicide use on forest resilience (Stolte 2019) and wildlife (Gosch 2019) have caused considerable public concern. In particular, concerns arise from the potential for herbicide exposure (presumed or real) jeopardizing the health and safety of public users of the forest whilst the forest industry reaps any benefit accruing to said herbicide treatment.

At present, the only truly long-term assessment of herbicide use for reforestation is the Austin Pond study established in 1977 in Maine (Daggett 2003). The study examined the effect of a variety of herbicides used in concert with later pre-commercial thinning assessing growth of desired conifer species and growth of hardwood species 29 years after herbicide application.

Fortier and Messier (2006), make a strong case for herbicide use in forest management being an enabling mechanism for cost-effective ecosystem-based management. Also, Wagner *et al.* (2006), demonstrate the utility of herbicides in assuring successful reforestation at a global scale.

This project will provide silviculturists in Alberta with local, quantitative data on the long-term effects of herbicide use on forest ecosystems and the ability to quantify the impacts of discontinuing the use of herbicides for reforestation success. The project will assess the impact on tree growth, and forest composition and structure of safe use of herbicides for forest renewal. This information would be of considerable value in informing discussion with stakeholders as to why herbicides are used for forest renewal and their longer-term impact on an array of forest ecosystem services.

1.2 Objectives

The main objectives of this project are to:

1. Quantify the impact of herbicide use on the timber resource including composition and structure more than 20 years after application.
2. Project long-term stand development from current stand conditions using Alberta growth models and determine yield and rotation implications.

The project will result in improvements in managing the forest resource through developing an improved understanding of the long-term outcomes of herbicide use for forest management.

2. Materials and Methods

Unfortunately, most of the currently available Alberta data sources do not enable quantitative comparison of reforestation using the same silviculture regime with and without herbicide use – thus they are not able to specifically assess the impact of operational herbicide use on forest renewal. In most cases (for example, the Provincial Growth and Yield Initiative (PGYI) plot data and the Empirical Post Harvest Assessment Project) the data sources obliquely assess herbicide effects as part of the reforestation regime. Plots might have been established before or after herbicide treatment and oftentimes there is no spatial records of the plot area being affected by the treatment or not. The Judy Creek Mixedwood Trial and the Regenerated Lodgepole Pine Trial include areas not treated with herbicides but do not include an operational herbicide treatment for reference and therefore are unable to address specific questions arising from operational use. Different companies, silviculture regimes, herbicide application methods, ecosites together play a role as confounding factors in assessing and separating treatment response[1].

An exception to this general rule is the forest herbicide monitoring plots established in 1995, 1996 and 1997. These plots included a relatively large (1 ha) untreated area that was assessed using the same parameters as the herbicide treated area. While the original installations were placed in uniform cutblocks with regards to ecosite/phase, stand history and silviculture regime; subsequent non-uniform/uncontrolled treatments in these blocks make it difficult to draw treatment specific inferences. Treatment response can only be separated in well-controlled experiments (trials) preferably with replications. No such data set was available therefore the decision was made to re-measure the herbicide monitoring plots in the fall of 2019 for use in our analysis.

The difficulty in quantifying the herbicide response signal, is that these are operational monitoring plots with no controls on silviculture following herbicide application. While treatment response can be evaluated and quantified in these plots, the overall silviculture regime (including the subsequent uncontrolled treatments) will determine the scale of the response rather than the original herbicide application alone. Hence the value of controlled experiments - despite their cost.

2.1 Study Area

In the fall of 2002, twelve cutblocks with an Alberta Herbicide Monitoring installation (Figure 2-1), situated on representative white spruce-trembling aspen boreal mixedwood sites, planted to white spruce, and operationally released with an aerial application of glyphosate, were surveyed using a system of paired monitoring plots (Figure 2-2). Fiber production implications of herbicide treatments, and several silviculture scenarios were modeled using the Mixedwood Growth Model (Pitt *et al.* 2004).

In the fall of 2019, we re-assessed these twelve cutblocks for re-measurement. The main criterion for inclusion was to ensure that there was no significant disturbance of the treated or untreated areas in the openings. Unfortunately, four openings had to be dropped from the 2019 remeasurement schedule due

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[1] A detailed assessment and screening of these data sets were beyond scope for this project due to time and budget.

to significant industrial disturbance or spraying in the untreated reference area (Table 2-1). As a result, only eight of the twelve openings were remeasured in 2019.

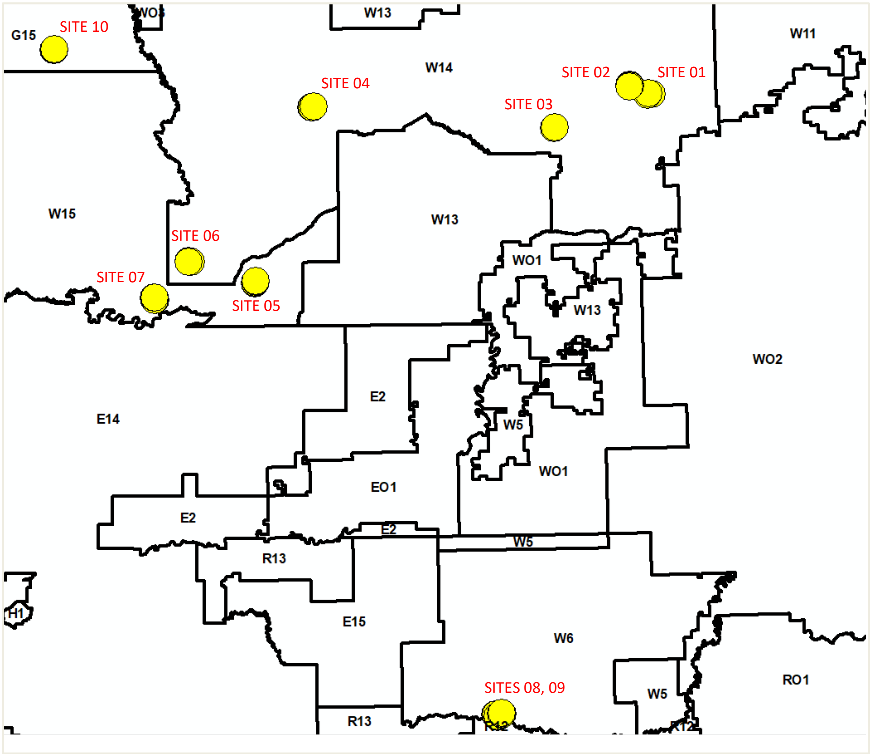

Figure 2-1. Overview map of the study sites (Source: John Nash, Greenlink)

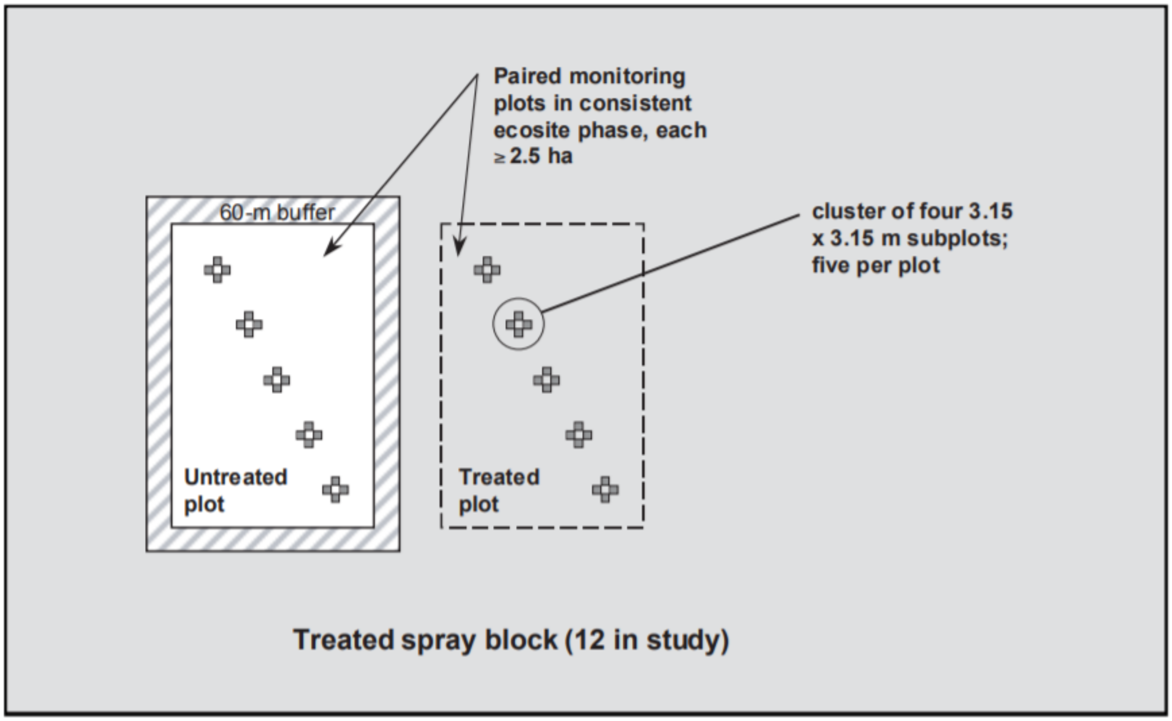

Figure 2-2. Schematic diagram of a herbicide monitoring installation in 2002 (Source: Pitt *et al.* 2004)

Table 2-1. List of cutblocks with herbicide monitoring installations by measurement year

Site No.	Company	Block Number	Harvest Year	Measurement Year		Reason for Exclusion
				2002	2019	
1	Blue Ridge Lumber	130-75	1995	✓	✓	
2	Blue Ridge Lumber	120-37	1979	✓	✓	
3	Alberta Newsprint	W06-1002	1995	✓		Industrial disturbance
4	Blue Ridge Lumber*	270-58	1993	✓	✓	Sprayed untreated area
5	Alberta Newsprint	WP-1012	1990	✓	✓	
6	Blue Ridge Lumber	690-38	1998	✓	✓	
7	Alberta Newsprint	HC-1096	1992	✓	✓	
8	Alberta Newsprint	W06-1048A	1995	✓	✓	
9	Alberta Newsprint	W06-1042	1996	✓	✓	
10	Canfor Grande Prairie	S14036	1993	✓	✓	
11	Manning Diversified	179	1994	✓		Sprayed untreated area
12	Manning Diversified	152	1995	✓		Sprayed untreated area

** Site was visited in 2019 but was abandoned as the non-treated area had been sprayed in 2005.*

All openings are in the Lower Foothills natural subregion, mostly on mesic/subhygric sites and clay loam/silty clay loam soils (Pitt *et al.* 2004).

2.2 Treatments

Seven of the eight remeasured openings received an initial aerial glyphosate herbicide treatment between 1994 and 1999 using 6 L/ha (2.1 kg active ingredient per ha) except for site 5 which received only 1.4 kg/ha (Table 2-2). Site 2 was treated with hexazinone via a ground application in 1990. All initial broadcast glyphosate herbicide treatments were at least 20 years ago, providing a unique opportunity to examine the long-term impact of herbicide on plant community survival and growth.

Table 2-2. Tending history of remeasured openings

Site No.	Initial Tending				Second Tending			
	Herbicide	Rate (g/ha)	Year	Method	Herbicide	Rate (g/ha)	Year	Method
1	Glyphosate	2136	1997	Aerial	Glyphosate	2136	2000	Aerial
2	Hexazinone	Unknown	1990	Ground			2003	Manual
5	Glyphosate	1424	1994	Aerial				
6	Glyphosate	2136	1999	Aerial	Glyphosate	2136	2006	Aerial
7	Glyphosate	2136	1996	Aerial				
8	Glyphosate	2136	1999	Aerial	Triclopyr	3230	2006	Basal bark*
9	Glyphosate	2136	1998	Aerial	Glyphosate	1424	2007	Backpack*
10	Glyphosate	2136	1999	Aerial			2003	Manual

** Second treatment was of untreated buffers left on block edges during initial treatment*

Six of the eight openings received a follow-up tending treatment that varied from aerial broadcast application (sites 1 and 6) to highlight application of glyphosate and triclopyr (sites 8 and 9); while sites 2 and 10 received manual tending using brush-saw. The high number of openings that received secondary tending are most likely due to the companies trying to meet Alberta's mandatory free-to-grow regeneration standard that was in effect when these openings were harvested. These standards not only included strata stocking requirements for conifer, mixedwoods, and deciduous but also required minimum height standards be met by year 8 (Establishment) and free-to-grow (FTG) standards for coniferous trees be met by year 14 (Performance). The FTG requirement was a competition free cylinder around each conifer crop tree. FTG required a coniferous crop tree to be free of deciduous trees and shrubs greater than two-thirds its height within 1 m radius of its stem (AAF 2020).

By design, the initial silviculture regime in these openings were similar including prompt reforestation after harvest, mechanical site preparation and planting followed by the herbicide tending treatment. There were some differences with regards to the extent of site preparation, planting densities and stock size. In addition to the second herbicide treatment (Table 2-2), some of these blocks also received additional site preparation (site 1) and planting (sites 1 and 10). These additional uncontrolled silviculture events pose a challenge in the evaluation of herbicide treatment response, especially due to the relatively small sample size.

Detailed silviculture history of these sites is provided in Appendix I.

2.3 Measurements

In the fall of 2019, we returned to eight openings that were measured in 2002 to carry out an assessment of composition, abundance and size of the overstory tree layer and the layer of non-tree vegetation including shrubs, herbs and grasses, mosses and lichens.

The sampling design was changed to better capture vegetation differences and tree response across the openings. Due to budgetary constraints, temporary sample plots (TSPs) were established at the centre of only 3 of the 5 original plot clusters in the treated and untreated areas of each opening (Figure 2-2).

At each TSP location, we established a 200 m^2 circular plot (r=7.98m) where all trees with a DBH greater than 5 cm were measured. A concentric subplot of 50 m^2 (r=3.99m) was used to measure all saplings greater than 130 cm height to a DBH of 5 cm. Live regeneration (≤130cm height) and non-tree vegetation cover (ocular estimates over a 2-dimensional plane) were recorded in four circular 10 m^2 (r=1.78m) subplots along the four cardinal directions located 3.99 m from the plot centre (Figure 2-3).

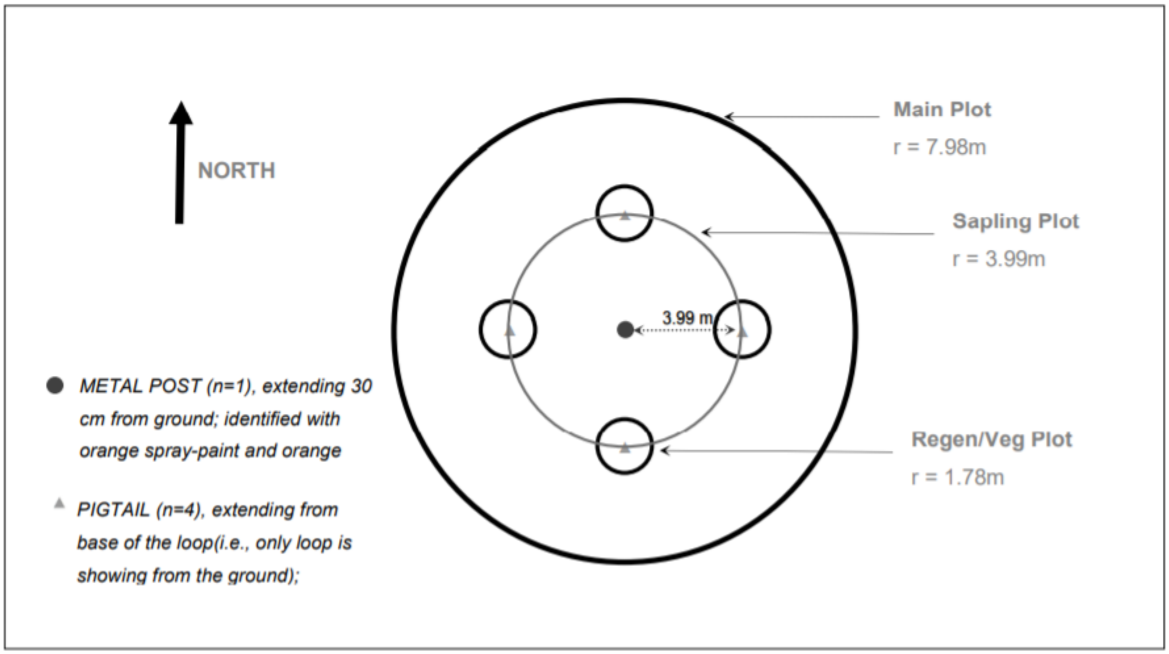

Figure 2-3. Temporary sample plot layout in 2019 (Source: Greenlink 2020)

Plot #3 from the untreated portion of site 6 was determined to be sprayed in 2006 and therefore was replaced in the summer of 2020 with a new TSP at a random location in the remaining portion of the untreated area of this block.

In addition to the field sampling, photo-interpreted percent stocking was estimated by Greenlink (2020) from high-resolution imagery for the treated and untreated portions of the openings using provincial Regeneration Standard of Alberta (RSA) protocols (AAF 2020). Percent stocking was obtained for total conifer and deciduous, as well as by RSA species groups.

2.4 Data Analysis

The TSP data was compiled to create species level summaries for each plot; these summaries were then combined to create summaries by species type (coniferous vs. deciduous) for statistical analysis and yield modelling. Average density, basal area, and gross merchantable volume[2] were calculated on a unit-area (per hectare) basis by species group. TSP data were averaged by site and treatment. Maximum DBH, maximum height and top height[3] were also calculated from the TSP data. In addition, conventional averages for tree level data (DBH, height, HDR[4] and tree volume) were computed by site and treatment by averaging across all live trees sampled in each plot.

We carried out statistical comparisons of current stand conditions in treated and untreated areas more than 20 years after the initial broadcast herbicide treatment. Treated and untreated plot means of each response variable were compared using analysis of variance (ANOVA) assuming a randomized complete block design (2 treatments, 8 blocks)[5]. Separate analyses were conducted for white spruce and trembling aspen, as well as combined responses for all conifer [white spruce + lodgepole pine + balsam fir (*Abies balsamea*)] and all deciduous [trembling aspen + balsam poplar (*Populus balsamifera*) + paper birch (*Betula papyrifera*)]. Normality of the response variables and residuals were evaluated graphically and natural log transformation was done, where necessary. All statistical analyses were completed in SAS V9.4 (SAS Institute, Cary, NC, USA).

Due to the small sample size and the lack of proper replication, concerns about the assumption of normality and statistical power necessitated the use of non-parametric approaches such as the Permutation Test[6]. The null hypothesis under this test is that the two groups (treated/untreated) do not differ on the outcome (i.e., that the outcome is observed independently of treatment assignment). Given the small sample size (n=8), all 256 permutations were run to get the exact p-value using R Statistical Software (version 4.1.0; package: broman; function: paired.perm.test).

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[2] Utilization limits were defined as 15 cm minimum stump diameter over bark at 30 cm stump height, 10 cm top diameter inside bark and 3.66 m minimum merchantable length.

[3] Top height was defined as the average height of the 100 eligible largest DBH trees per hectare. Eligibility was defined as all live trees with no significant impediment to height growth (e.g., forks, dead or broken tops).

[4] Height to DBH ratio (cm/m).

[5] This is equivalent to a paired t-test ($F=t^2$) when block is treated as a random factor and treatment as a fixed factor. Least squares means and their standard errors can also be easily obtained.

[6] The use of the Paired Permutation t-test was suggested to the project team by Douglas G. Pitt, biometrician. Note that there are several permutation tests such as the Monte-Carlo Permutation Test for Paired individual Scores (package: surveillance) and others are available in the R statistical software for these non-parametric tests.

2.5 Growth Model Projections

After assessing the current stand conditions and the impact of herbicide treatment, we evaluated the longer-term outcomes by projecting the observed plot data using the Mixedwood Growth Model (MGM, MGM21 Beta VS8.2.21.39/Rev6378) and the Growth and Yield Projection System (GYPSY v. May 2009), the two most commonly used growth models in Alberta. Model projections for various stand attributes (density, basal area, and gross volumes) were summarized by site and treatment. Projected values at 80 years stand age were also used in various statistical comparisons.

2.5.1 MGM Simulations

MGM is a deterministic, distance-independent individual tree growth model developed by researchers at the University of Alberta (Bokalo *et al*. 2013). The model can be initiated either with a tree list, or by using MGM's tree list simulator to generate a tree list. Required model inputs include stand age, natural sub-region, mean climate moisture index (CMI), species-specific site index and a tree list including species, DBH, height, age and tree factor (trees per hectare) for each tree in the list.

Recently, MGM has gone through significant modifications including new climate and composition sensitive maximum size-density functions, new revised survival functions, new height increment and diameter increment functions and the full implementation of the GYPSY site index curves for Alberta.

The crop planning interface was streamlined and simplified by removing several flags that were required in previous versions[7]. The system now includes an internal age solver for all species thus eliminating the need for pre-processing data.

Among the forest growth models for western Canada, MGM has the unique ability to model tree-level growth in multi-cohort/multi-strata (e.g. mixed species or vertically structured) stands.

The raw TSP data was converted into an MGM tree list, where each plot was projected separately as per the suggested best practices by the MGM development team (Johnson *et al*. 2020). Individual TSP projections (i.e. outputs) were then averaged by site and treatment.

Top height by species was carefully evaluated in each TSP. Site index was calculated using total age of the planted stock for spruce and pine assuming 1+0 stock, the block age for aspen[8]. Average site index values were then calculated at the opening-level using spruce and pine site index from the treated portion of the opening and the aspen site index from the untreated portion of the opening (Phil Comeau pers. comm. 2020). Black spruce was not present in the TSP data, so we set the MGM site index to 10 m as a default.

Individual tree ages were calculated by the Internal Age Solver of MGM. Stand age was calculated as a difference between the measurement year and skid clearance year.

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[7] One notable example is the MA Flag that was previously used as a mortality adjustment option to simulate stand breakup at older ages. This is no longer required due to the new climate and composition sensitive maximum size-density functions of MGM.

[8] No age was collected in the TSPs, therefore we needed to assume that the top height (site) trees are selected from the planted stock for spruce and pine and skid clearance represents that oldest/largest aspen. The calculated site indices were within the ecological range for the Lower Foothills natural subregion and can be considered conservative given that the oldest possible age was selected.

We calculated the mean CMI from monthly ClimateNA (v6.11) data collected from 1981-2010 based on the latitude, longitude, and elevation of each individual plot.

Utilization limits for merchantable volume projections were set at 13.4 cm minimum DBH, 30 cm stump height and 10 cm top diameter inside bark to closely mimic the 15/10/30 provincial baseline utilization[9].

The general setup for the MGM runs is presented in Table 2-3. Natural subregion was Lower Foothills for all plot locations.

Table 2-3. MGM runs input settings

Site No.	Treat	Lat	Lon	Elev	CMI	Stand Age	Site Index (m)			
							SW	AW	PL	SB
1	N	54.445	-115.299	892	14.0	24	23.1	21.6	21.1	10.0
	T	54.444	-115.296	882	13.7					
2	N	54.461	-115.366	927	15.7	40	20.3	22.1	15.5	10.0
	T	54.464	-115.365	933	15.9					
5	N	54.070	-116.694	1080	18.4	29	20.3	19.0	21.4	10.0
	T	54.067	-116.696	1081	18.7					
6	N	54.110	-116.930	1062	20.5	21	16.7	20.1	19.5	10.0
	T	54.111	-116.925	1062	20.5					
7	N	54.037	-117.049	1052	20.6	27	20.1	20.2	18.9	10.0
	T	54.033	-117.048	1023	20.0					
8	N	53.169	-115.869	1006	17.7	24	22.9	19.1	23.1	10.0
	T	53.173	-115.876	1035	18.1					
9	N	53.175	-115.855	1032	18.0	23	22.2	20.9	20.8	10.0
	T	53.174	-115.852	1010	17.7					
10	N	54.547	-117.406	826	15.7	26	19.4	16.9	19.3	10.0
	T	54.547	-117.406	823	15.6					

Note that individual TSP CMI values were used during the MGM simulations.

Only basic MGM projections of treated and untreated plots were carried out without any additional follow up treatment scenarios.

Most of these stands have been subjected to multiple herbicide treatments and are at the age where pre-commercial thinning (PCT) is no longer an option. Commercial thinning (CT) opportunities might exist (thinning from below) to increase piece size and satisfy short-term fibre objectives. However, MGM simulations of CT treatments were not explored due to budget constraints and also due to the potential re-calibration of MGM for PCT/CT and other enhanced forest management (EFM) opportunities in the near future[10].

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[9] In MGM, we currently cannot set minimum diameter based on stump diameter over bark, which is the widely used method to define tree utilization in Alberta.

[10] Brian Roth, Director of FGrOW pers. communication, 2021.

2.5.2 GYPSY Simulations

The GYPSY model is a stand-level growth model developed by the Province of Alberta (Huang *et al.* 2009a, 2009b). Model inputs include stand age plus species group[11]-specific inputs: top height or site index, age, density, stocking (optional), and basal area (optional). Spatial patterning is modelled via an (optional) stocking input, which modifies both the density and basal area increment functions within the GYPSY model. If stocking is not provided to the model, a non-spatial version of GYPSY is used. Huang *et al*. (2009a) recommend using the non-spatial version of GYSPY for fire origin stands, and wherever possible, the spatial version for post-harvest managed stands.

Basal area inputs are used to localize predicted basal area increment curves to observed plot data. Where basal area inputs are not available, basal area increment is predicted by the model. Competition between species is built into the model's structure in two manners: via a species composition function, as well as through interactions within several of the model functions. Aspen and black spruce species groups are unaffected by the presence of other species except via species composition equations embedded in the model. White spruce and pine species groups are affected by the presence of other species groups via modifiers to the density, basal area increment, and percent stocking models.

The raw TSP data was re-compiled by GYPSY species group using all live trees greater than 130 cm. Top height and site index calculation methodology closely followed those used in the MGM run setup to ensure compatibility in stand initialization. GYPSY is a stand-level model; therefore, we averaged the TSP data by site and treatment. Percent stocking by site, treatment and species group was provided by Greenlink (2020). Stand age was calculated as a difference between measurement year and skid clearance year.

Observed basal area was used to localize predicted basal area increment curves[12]. We also ran GYPSY without the basal area adjustment to assess the model's ability to predict basal area, especially in the untreated portion of the stand.

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[11] Species groups: AW (aspen, poplar and birch), PL (pines + larch), SB (black spruce), SW (white spruce + fir).

[12] Observed basal area is only used to scale model predictions, it does not affect projection of density, stocking or top height in the GYPSY sub-models.

3. Results

The relatively small sample size limits the power for statistical hypothesis testing, and it may be sensitive to individual block results; therefore, these results must be interpreted with caution. The uncontrolled follow-up treatments in some of the blocks could inflate or deflate treatment response, as well. In addition to standard parametric testing, non-parametric permutation t-tests were used to address the concerns about the assumption of normality and small sample size.

Least squares treatment means were calculated for various tree and stand attributes using analysis of variance. Statistical significance was determined at three significance levels to provide a range for interpretation given the small sample: Not significant (NS), weakly significant (“*”, $p<0.10$), moderately significant (“**”, $p<0.05$) and highly significant (“***”, $p<0.01$). Results from the Paired Permutation t-tests are given in the tables only if they differ from the results of parametric testing.

3.1 Current Stand Conditions

The eight blocks in this study represent an average stand age of 27 years (ranging 21 to 40 years) and an average time since the original glyphosate treatment of 23 years (ranging from 20 to 29 years). As discussed earlier, treatment effect is potentially influenced by the various uncontrolled follow-up treatments in some of these blocks.

3.1.1 Trembling Aspen

Aspen consistently dominated the untreated plots and as expected, differed significantly in nearly all responses measured (Table 3-4). Average aspen height was almost 40% lower in treated areas. Site occupancy measures such as density, percent stocking, basal area are all significantly lower in treated areas. Many of the openings received a follow-up tending treatment, essentially creating a conifer monoculture in the treated portion of the stands.

Table 3-4. Treatment response – Trembling aspen

Species	Response Variable	Untreated (N)	Treated (T)	Standard Error	Parametric test		Permutation t-test
					p > F	Significance	
Trembling Aspen	Maximum tree height (m)	14.3	10.2	0.6	0.0023	***	
	Average tree height (m)	9.6	5.9	0.9	0.0208	**	
	Top height (m)	13.1	9.1	0.8	0.0162	**	*
	Maximum tree DBH (cm)	16.1	11.4	1.3	0.0402	**	*
	Average tree DBH (cm)	7.9	5.4	0.8	0.0540	*	NS
	Quadratic mean DBH (cm)	8.6	6.7	0.6	0.0527	*	
	Height-DBH ratio (m/cm)	1.21	1.12	0.08	0.4064	NS	
	Density (stems/ha)	3,927	154	674	0.0055	***	
	Stocking (%)	84.1	9.5	2.6	0.0000	***	
	Basal area (m^2/ha)	21.3	0.4	3.2	0.0025	***	
	Volume (0/0) (m^3/ha)	115.0	2.2	22.9	0.0102	**	***
	Volume (15/10) (m^3/ha)*	31.3	1.4	17.1	0.0025	***	**

* *p value applies to natural log transformed values*

The permutation t-tests indicated similar results with slightly less significance than the parametric tests, except for total (0/0) volume which was found to be highly significant. Detailed output of the permutation tests is given in Appendix I.

The DBH and height distributions of the trembling aspen are presented in Figure 3-4 and Figure 3-5, respectively.

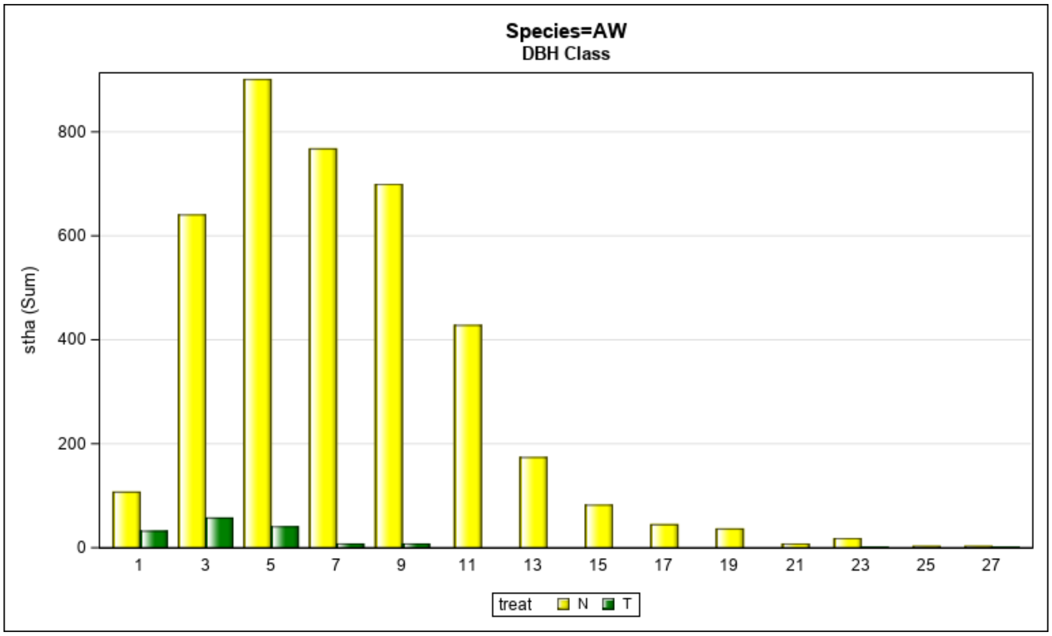

Figure 3-4. Stem distribution by 2-cm DBH class – Trembling aspen

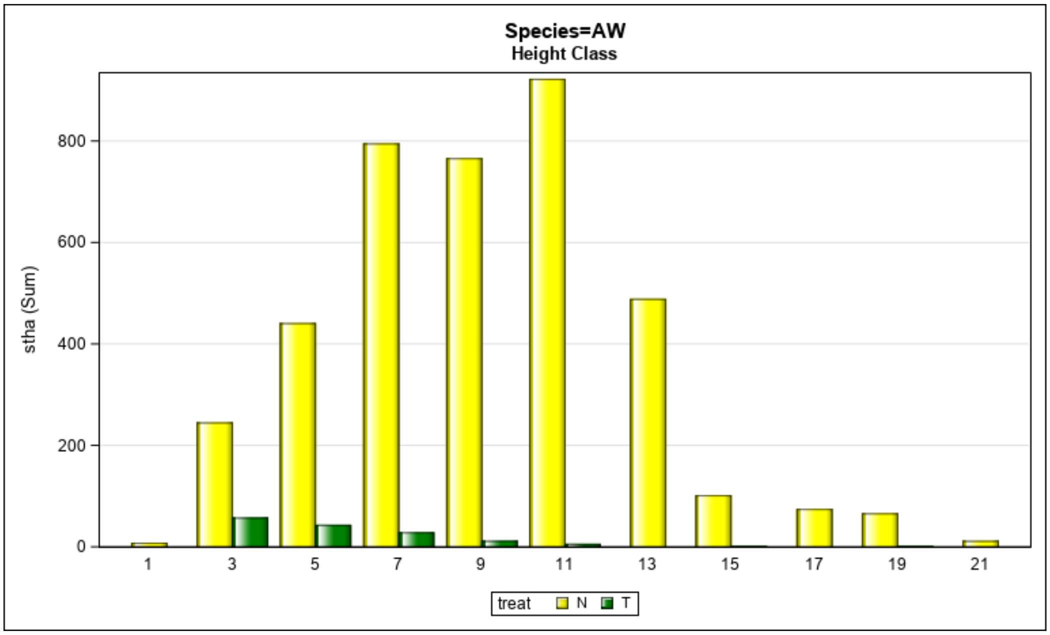

Figure 3-5. Stem distribution by 2-m height class – Trembling aspen

Based on the data on tree size, distribution, and cover, we can state that most of the aspen present in the treated areas regenerated subsequent to treatments.

3.1.2 White Spruce

Planted white spruce responded positively to the conifer release treatment as indicated by the very significant increase in basal area and gross volume metrics (Table 3-5). Average DBH is almost 50% greater and basal area is almost 140% greater in treated areas.

Average density and percent stocking are not significantly different between treated and untreated areas, indicating that site occupancy is similar for white spruce regardless of treatment. The average densities are slightly higher than the nominal planting densities (including the follow-up treatments) over 20 years after initial planting which indicates good survival rates for the planted spruce in both treated and untreated areas and the presence of significant ingress[13].

While spruce height was around 10% taller in treated plots, this difference was not statistically significant regardless of height metrics used. The limited height growth response combined with the significant growth in diameter resulted in significantly lower white spruce height to DBH ratio (tree slenderness) in treated areas.

The non-parametric permutation t-tests indicated that average tree DBH and quadratic mean DBH may be not significant and basal area (a related plot-level attribute) may be only moderately significant.

Table 3-5. Treatment response – White spruce

Species	Response Variable	Untreated (N)	Treated (T)	Standard Error	Parametric test		Permutation t-test
					p > F	Significance	
White Spruce	Maximum tree height (m)	10.4	11.3	0.7	0.3693	NS	
	Average tree height (m)	6.0	7.1	0.6	0.2570	NS	
	Top height (m)	9.4	10.4	0.6	0.2872	NS	
	Maximum tree DBH (cm)	14.4	18.1	1.2	0.0778	*	
	Average tree DBH (cm)	6.7	9.9	1.2	0.0922	*	NS
	Quadratic mean DBH (cm)	7.7	11.2	1.2	0.0784	*	NS
	Height-DBH ratio (m/cm)	0.88	0.75	0.03	0.0106	**	
	Density (stems/ha)	1,688	1,852	348	0.7480	NS	
	Stocking (%)[*]	67.5	72.5	4.3	0.6306	NS	
	Basal area (m^2/ha)	7.5	17.7	1.7	0.0037	***	**
	Volume (0/0) (m^3/ha)	26.9	73.9	9.6	0.0107	**	
	Volume (15/10) (m^3/ha)[*]	5.6	40.8	10.3	0.0009	***	

[*] *p value applies to natural log transformed values*

The DBH and height distributions of the white spruce are presented in Figure 3-6 and Figure 3-7.

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[13] The sampling design for measurements in permanent sample plots did not allow for time-series remeasurements, therefore tree mortality and ingress cannot be reliably separated. Only the net change in stems can be assessed. Observed average spruce densities in the 2002 analysis (Pitt *et al.* 2004) suggest that 63% of the spruce are present in the treated areas and 76% in the untreated areas which may also indicate intra-specific competition of the spruce due to the significant growth observed in the treated areas.

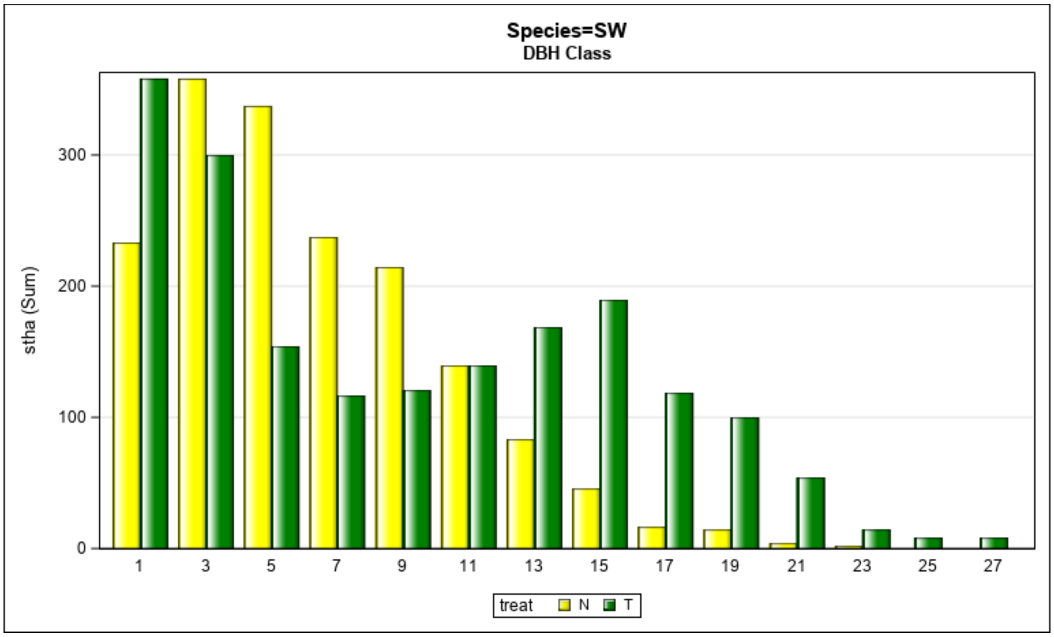

Figure 3-6. Stem distribution by 2-cm DBH class – White spruce

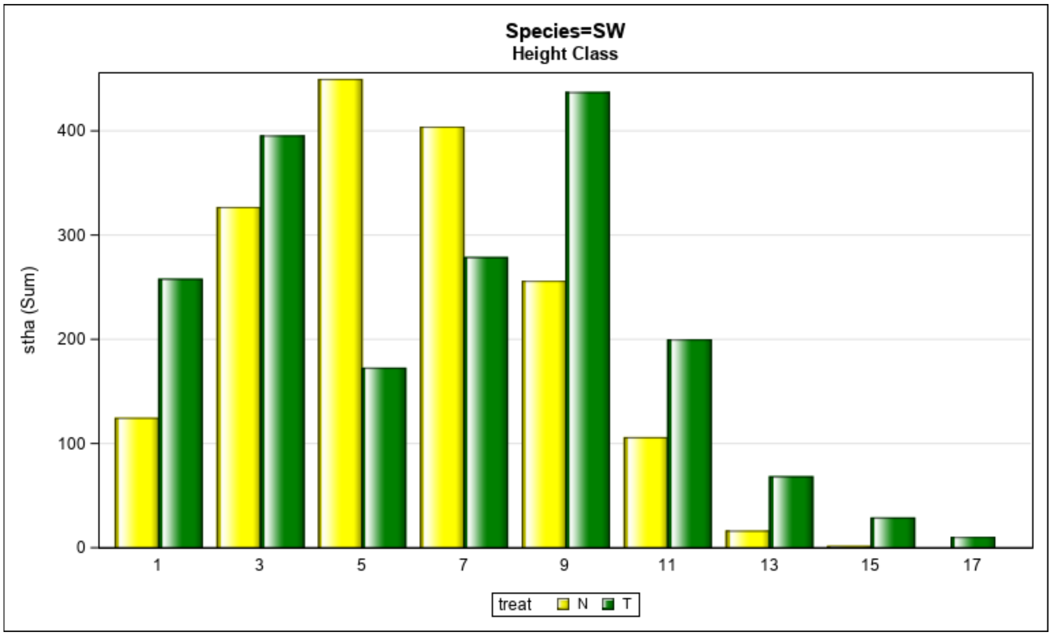

Figure 3-7. Stem distribution by 2-m height class – White spruce

The bimodal nature of the diameter and height distributions also show the amount of ingress that is present in these stands. The significantly higher growth rate of the planted spruce is also well-reflected in the DBH distributions of the treated areas vs the untreated areas.

3.1.3 All Deciduous

Untreated areas have balsam poplar and birch that represent about 20% (~1,050 stems/ha) of all deciduous stems. Birch and poplar represent over 80% (~700 stems/ha) of the deciduous component in treated areas as most of the aspen have been killed off as a result of multiple tending treatments (Table 3-6).

Most stand metrics for the deciduous are statistically significant and different between treated and untreated areas; however, this is largely driven by the aspen component (Table 3-7).

Table 3-6. Deciduous density and basal area by species and treatment

Treatment	Deciduous Density (stems/ha)				Deciduous Basal Area (m^2/ha)			
	Aw	Pb	Bw	Total	Aw	Pb	Bw	Total
Untreated (N)	3,927	419	644	*4,990*	21.3	1.5	1.8	*24.6*
Treated (T)	154	315	381	*850*	0.4	0.2	0.4	*1.0*

The birch and poplar stems in these stands represent volunteers that do not generally pose a significant competitive threat to the spruce.

Table 3-7. Treatment response – All Deciduous

Species	Response Variable	Untreated (N)	Treated (T)	Standard Error	Parametric test		Permutation t-test
					p > F	Significance	
All Deciduous	Maximum tree height (m)	14.3	9.0	0.7	0.0009	***	
	Average tree height (m)	9.0	5.3	0.8	0.0150	**	***
	Top height (m)	13.0	7.6	0.8	0.0017	**	***
	Maximum tree DBH (cm)	16.3	8.9	0.7	0.0002	***	
	Average tree DBH (cm)	7.4	4.0	0.8	0.0269	**	
	Quadratic mean DBH (cm)	8.1	4.6	0.8	0.0154	**	***
	Height-DBH ratio (m/cm)	1.22	1.13	0.05	0.2374	NS	
	Density (stems/ha)*	4,990	850	872	0.0028	**	***
	Stocking (%)	84.1	9.5	2.6	0.0000	***	
	Basal area (m^2/ha)	24.6	1.0	3.2	0.0012	**	***
	Volume (0/0) (m^3/ha)	128.1	4.0	23.1	0.0067	**	***
	Volume (15/10) (m^3/ha)*	31.8	1.7	16.9	0.0009	***	**

* *p value applies to natural log transformed values*

Non-parametric permutation tests indicated slightly higher significance for average tree height, top height, quadratic mean DBH, density, basal area and total (0/0) volume. Gross merchantable volume was found to be slightly less significant when permutation tests were used.

As shown in Figure 3-8 and Figure 3-9, most of the poplar and birch in treated areas are volunteers that are coming in, while a larger proportion of poplar in the untreated areas is of similar height as the aspen.

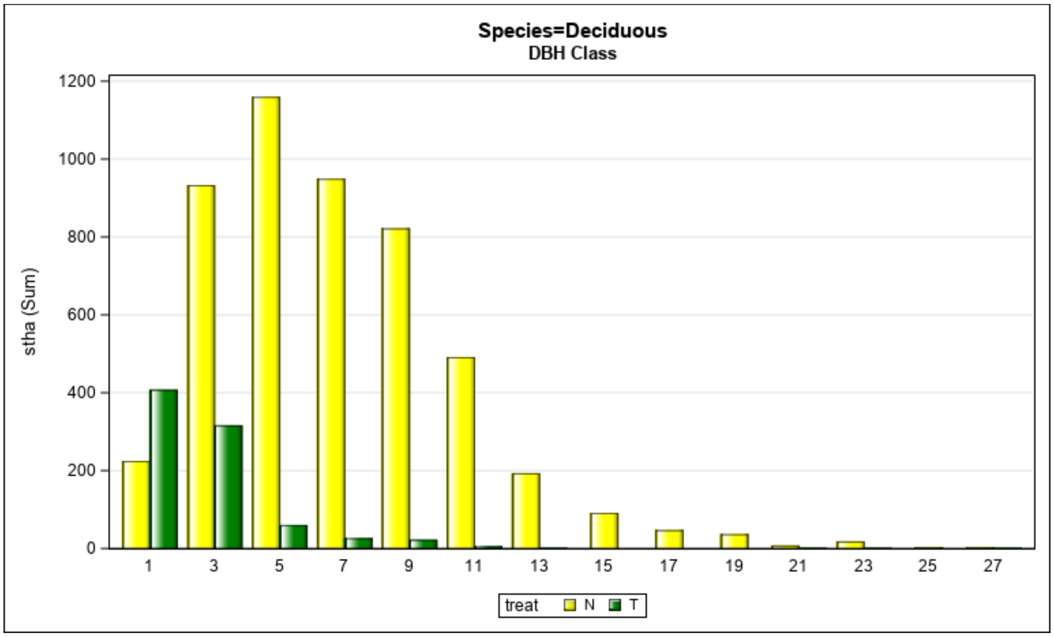

Figure 3-8. Stem distribution by 2-cm DBH class – All deciduous

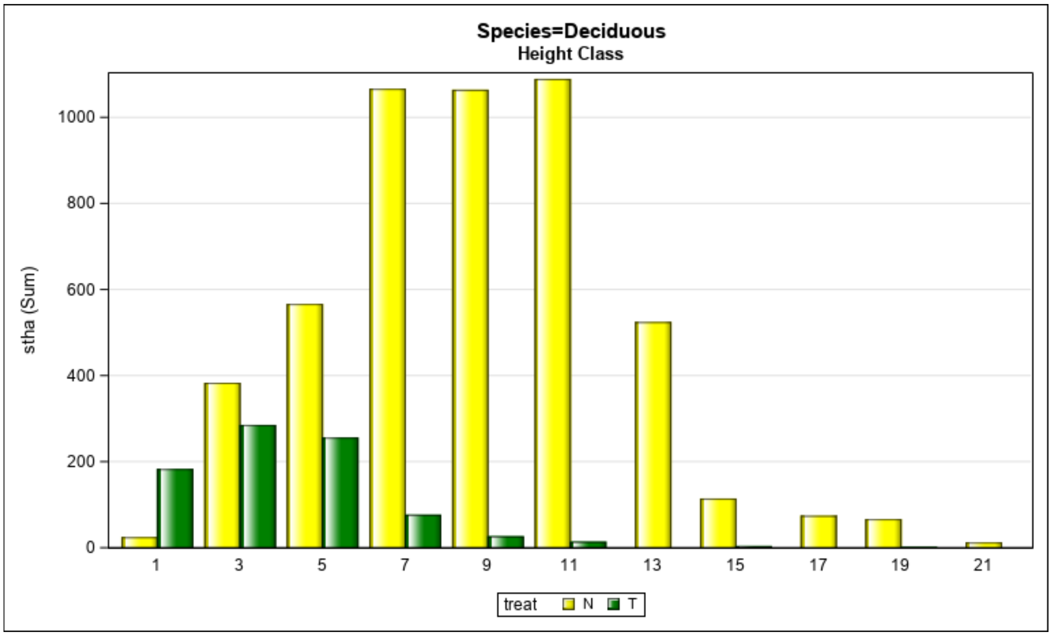

Figure 3-9. Stem distribution by 2-m height class – All deciduous

3.1.4 All Coniferous

Treated areas have a significant component of lodgepole pine (36% of conifers) and a minor component of balsam fir (6%) in addition to white spruce. Untreated areas have very little pine and balsam fir, and the conifer component is mostly dominated by white spruce (Table 3-8).

Table 3-8. Coniferous density and basal area by species and treatment

Treatment	Coniferous Density (stems/ha)				Coniferous Basal Area (m^2/ha)			
	Sw	Pl	Fb	Total	Sw	Pl	Fb	Total
Untreated (N)	1,688	221	300	*2,208*	7.5	2.3	1.2	*11.1*
Treated (T)	1,852	1,163	196	*3,210*	17.7	9.3	0.8	*27.8*

Conifer height and density were not found to be significantly different (Table 3-9) between treated and untreated areas, similar to the findings for white spruce (Table 3-5). Non-parametric permutation tests indicated that all conifer average tree DBH and the HDR may not be significant and merchantable volume may be highly significant.

However, the ingress pine and balsam fir appear to occupy the site in gaps where the spruce was not present. This is reflected in the significantly higher conifer stocking (94%) in treated areas. Note that stocking was <u>not</u> significantly different for white spruce alone in treated vs untreated areas (Table 3-5).

Table 3-9. Treatment response – All Coniferous

Species	Response Variable	Untreated (N)	Treated (T)	Standard Error	Parametric test		Permutation t-test
					p > F	Significance	
All Coniferous	Maximum tree height (m)	11.7	12.2	0.7	0.5871	NS	
	Average tree height (m)	6.4	7.6	0.5	0.1298	NS	
	Top height (m)	10.3	11.1	0.5	0.3417	NS	
	Maximum tree DBH (cm)	16.0	19.7	1.1	0.0471	**	
	Average tree DBH (cm)	7.2	9.7	0.9	0.0983	*	NS
	Quadratic mean DBH (cm)	8.3	11.1	1.0	0.0793	*	
	Height-DBH ratio (m/cm)	0.86	0.79	0.03	0.0820	*	NS
	Density (stems/ha)	2,208	3,210	549	0.2374	NS	
	Stocking (%)	69.4	94.3	2.2	0.0001	***	
	Basal area (m^2/ha)	11.1	27.8	1.5	0.0001	***	
	Volume (0/0) (m^3/ha)	44.6	122.4	9.7	0.0008	***	
	Volume (15/10) (m^3/ha)	12.6	56.1	10.9	0.0260	**	***

* *p value applies to natural log transformed values*

Based on the DBH (Figure 3-10) and height (Figure 3-11) distributions of all conifers, we can see that while balsam fir represents mostly volunteers, pine stems in treated areas are of similar stature to the planted spruce, indicating planted origin or natural regeneration after harvest. Silviculture history records reveal (Appendix II) that indeed, some of the sites received planted pine in addition to spruce (sites 1, 6, 9 and 10) or a portion of the block was left for natural regeneration (site 8).

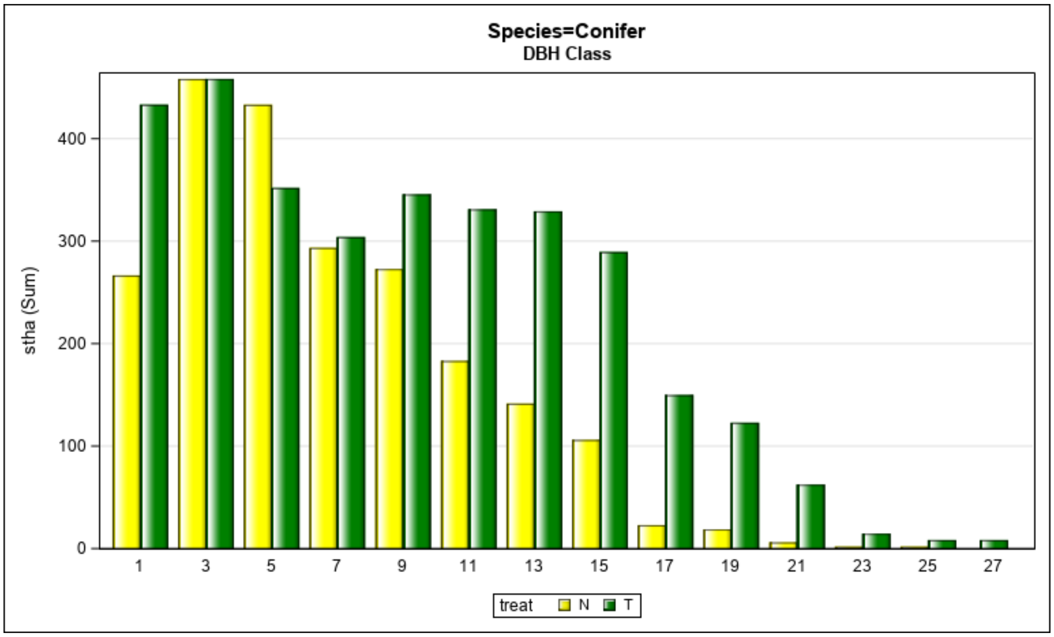

Figure 3-10. Stem distribution by 2-cm DBH class – All coniferous

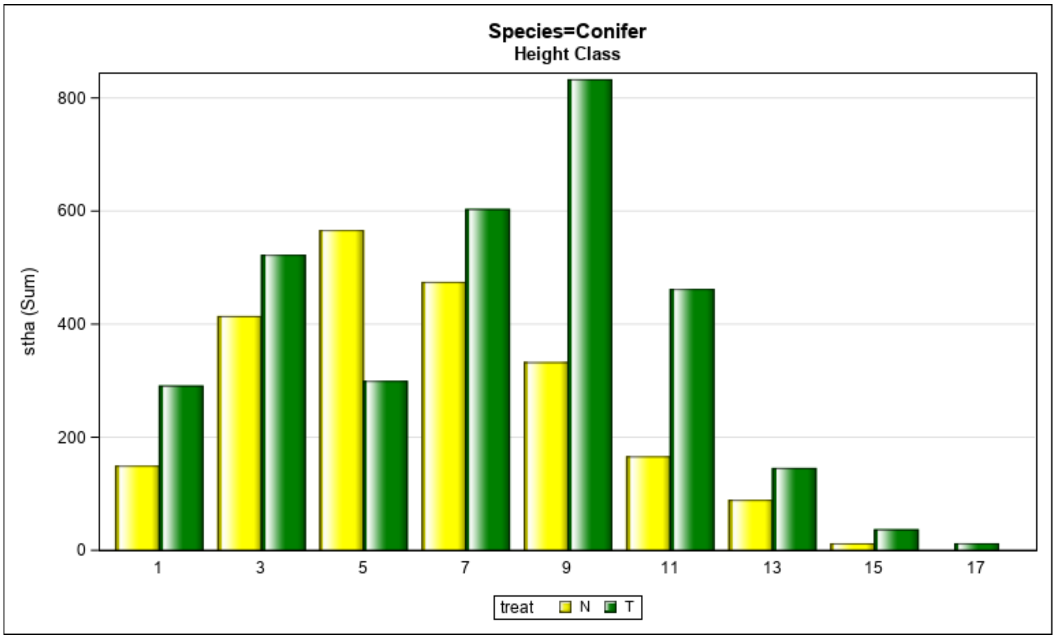

Figure 3-11. Stem distribution by 2-m height class – All coniferous

3.1.5 Overall

Total stem densities in treated plots were 45% less than the densities observed in untreated areas (Table 3-10). However, total basal area and total gross volumes were not found to be significantly different for the blocks in our study.

Non-parametric permutation tests yielded similar results with the exception of total (0/0) volume indicating a weak ($p<0.10$) significance.

Table 3-10. Treatment response – Overall

Species	Response Variable	Untreated (N)	Treated (T)	Standard Error	Parametric test		Permutation t-test
					p > F	Significance	
Overall	Density (stems/ha)	7,198	4,060	930	0.0485	**	
	Basal area (m^2/ha)	35.7	28.8	2.9	0.1321	NS	
	Stocking (%)	98.3	96.4	0.6	0.0541	*	
	Volume (0/0) (m^3/ha)	172.7	126.4	18.0	0.1113	NS	*
	Volume (15/10) (m^3/ha)	44.4	57.9	9.4	0.3459	NS	

With the average of 69% deciduous basal area (also 69% by stem density) at the time of assessment, most of the untreated areas could be classified as deciduous-leading mixedwood (DC) stands. With only 3% of deciduous basal area, treated areas should be classified as pure coniferous stands. However, depending on the definition used (Corns 1988), with 21% deciduous density, the treated stands could also be classified as coniferous-leading mixedwood stands, but that would be overly generous for the deciduous component that is mostly represented by small birch and poplar.

3.2 MGM Projections

The TSP data were submitted to MGM as input tree lists as described in Section 2.5.1 for forecasting the growth of each plot. Outputs from the model (density, basal area and merchantable volume by conifer and deciduous) were averaged by site (block) and treatment.

MGM projections of future stands growth in untreated areas average as conifer-dominated mixedwood over a 140-year horizon (Figure 3-12). This is somewhat surprising but could be attributed to the model being updated with new survival functions and new climate and composition sensitive maximum size-density functions that appears to have changed white spruce and aspen survival in a significant way from the previous versions of the model[14].

Tended areas have virtually no deciduous component due to multiple herbicide treatments and MGM projects them as pure conifer stands, as a result (Figure 3-12).

Model simulations of treated stands produced slightly higher total merchantable volumes (494 m^3/ha) as compared to untreated (455 m^3/ha) at 100 years. These projected volumes however are likely within prediction and modeling errors and thus conifer release using herbicide seems to amount to “trading” deciduous for conifer merchantable volume in these stands. When comparing volume projections, MGM appears to follow the principle that the amount of dry matter produced on a given site remains relatively constant, regardless how it is apportioned among stems and between species (Smith 1962).

Conifer MAI in treated areas is significantly larger (5.6 vs. 3.2 m^3/ha/year) and peaks earlier (70 vs 90 years) than in untreated areas (Figure 3-16). Conifer piece size is also significantly larger in treated areas (i.e. larger average merchantable volume per tree) as shown in Figure 3-17. These MGM projections indicate substantial gains in conifer growth and reduced length of rotation in stands subjected to multiple herbicide treatments. The planted white spruce in untreated areas do not appear to be suppressed in any significant way and will provide reasonable solid wood opportunities for medium and small log markets.

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[14] Models may go through several calibration processes over time when new data becomes available. For example, the original projections of untreated herbicide plots (Pitt *et al*. 2004) forecasted deciduous-dominated stands using MGM 2002A which was constructed from data collected in fully-stocked natural stands. Long term managed stand time series data collected in controlled experiments are needed for the proper calibration of our growth models.

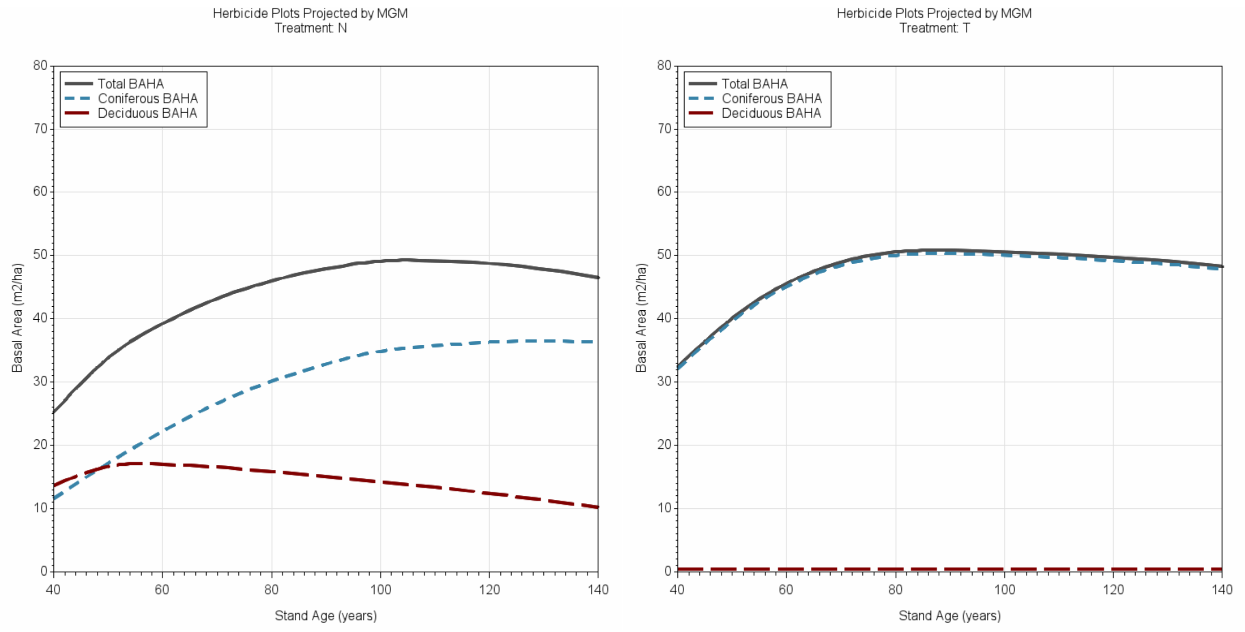


Figure 3-12. MGM basal area projection by treatment (untreated-N is shown on the left side)

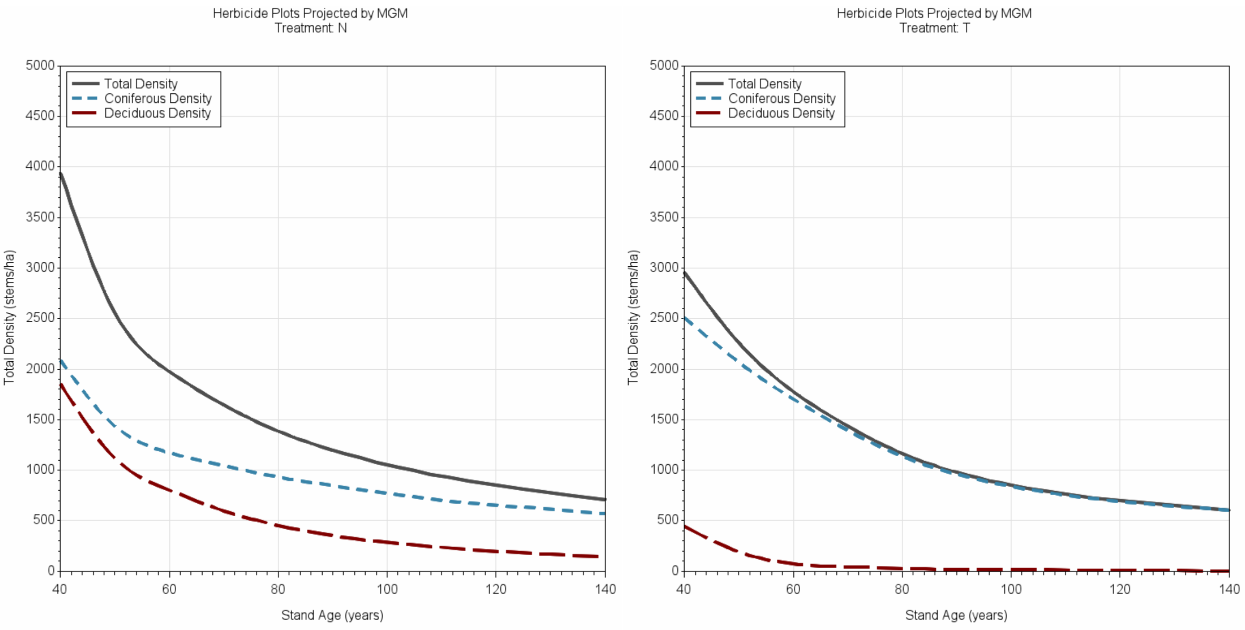


Figure 3-13. MGM all stem density projection by treatment

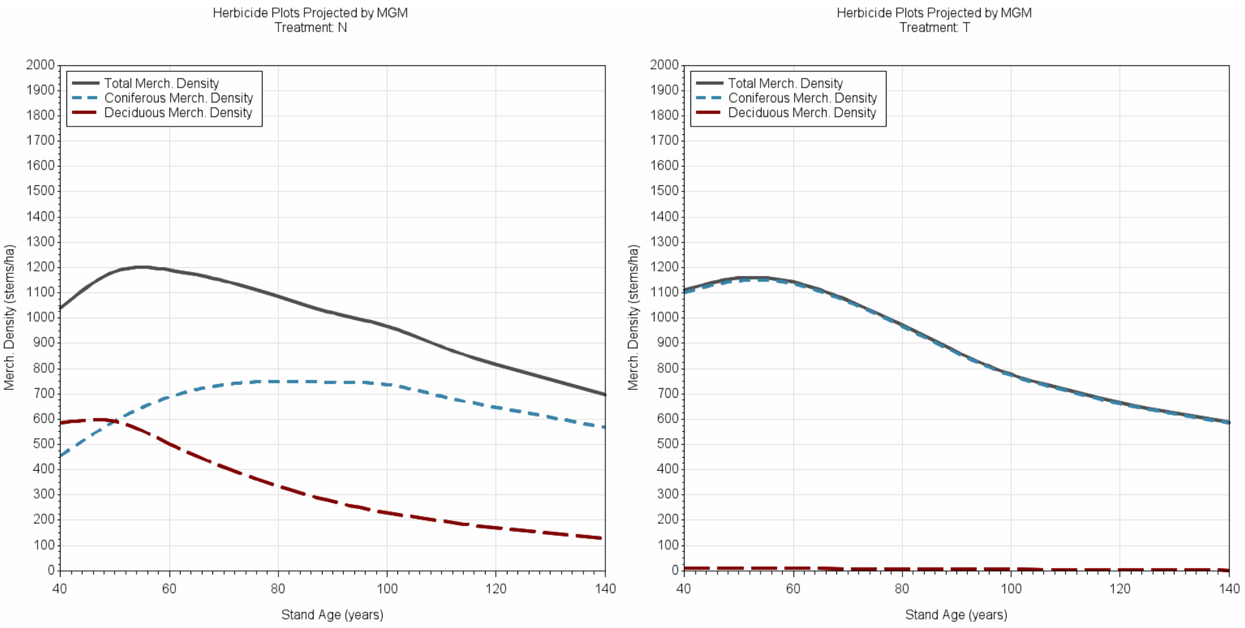


Figure 3-14. MGM merchantable stem density projection by treatment

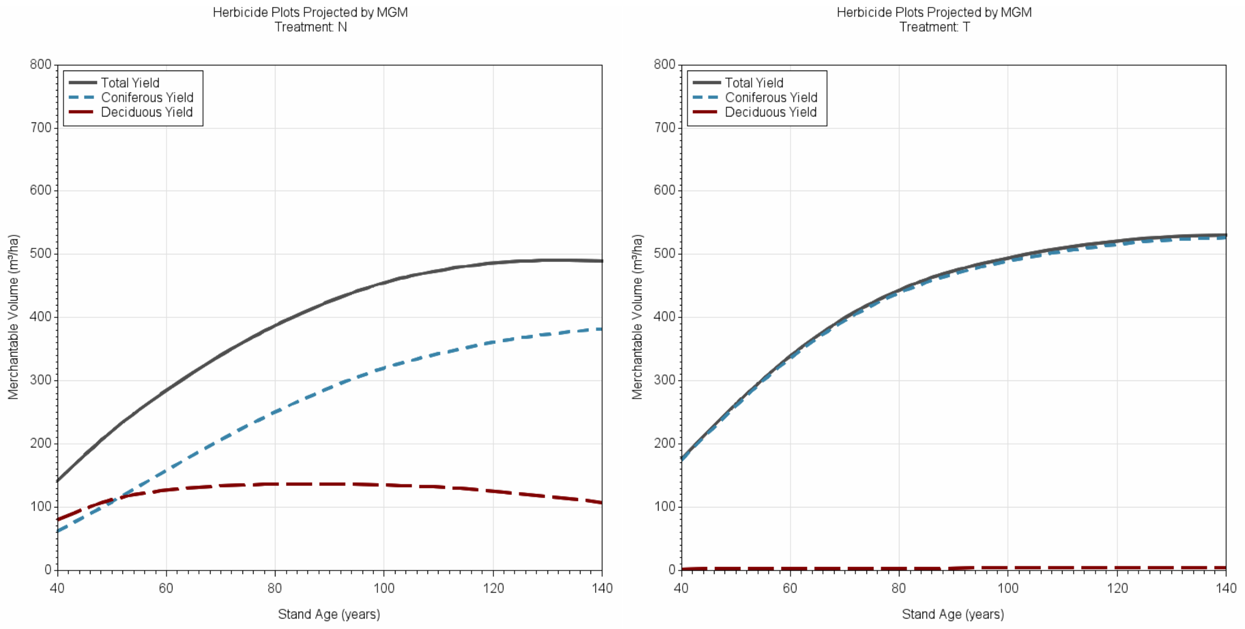


Figure 3-15. MGM gross merchantable volume projection by treatment

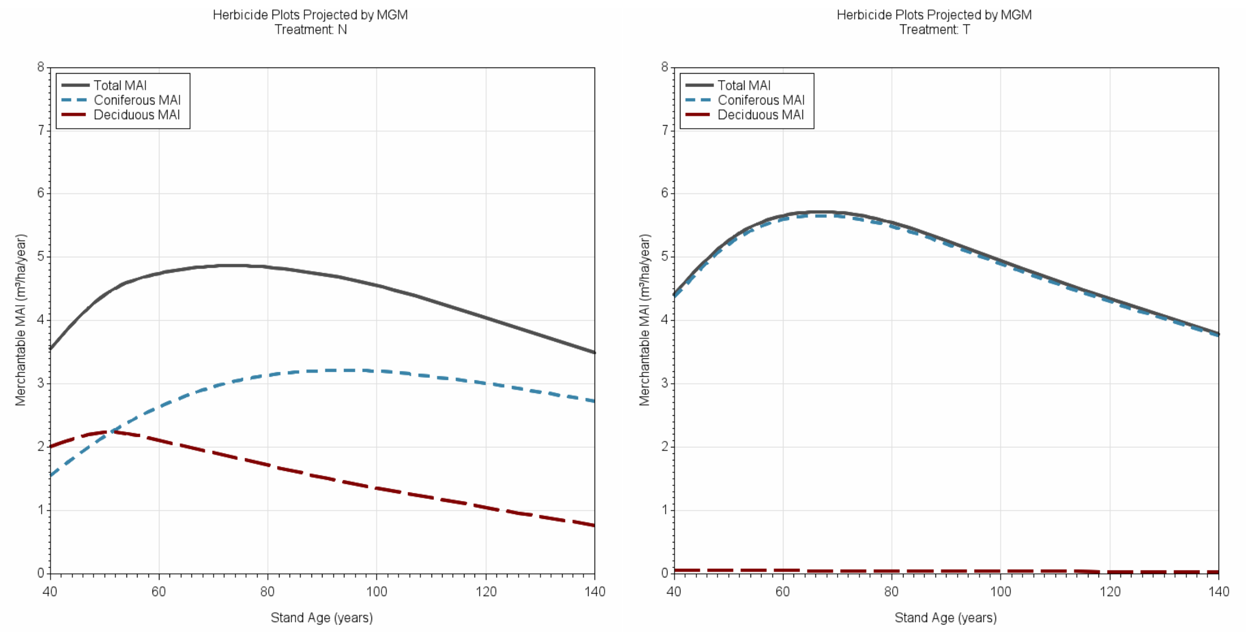


Figure 3-16. MGM gross merchantable MAI projection by treatment

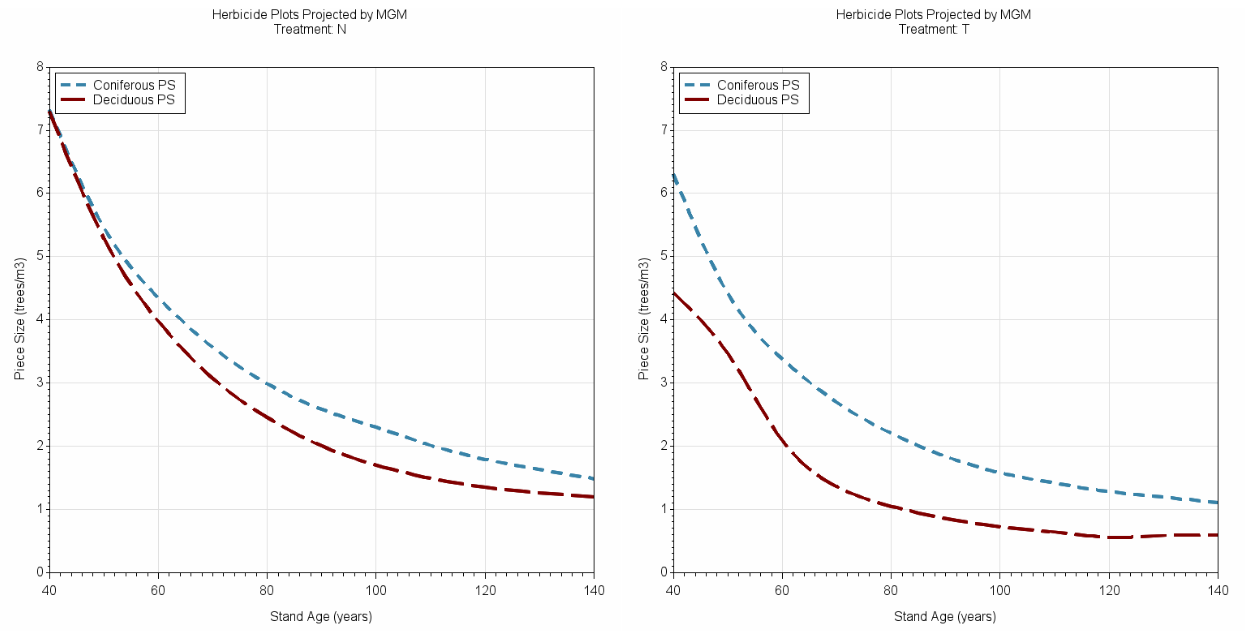


Figure 3-17. MGM gross merchantable piece size projection by treatment

3.3 GYPSY Projections

GYPSY is a stand-level model where projections are based on stand attributes by species groups rather than “growing” a tree list. All projections were based on localized basal area whereas the observed basal area was used to adjust model projections.

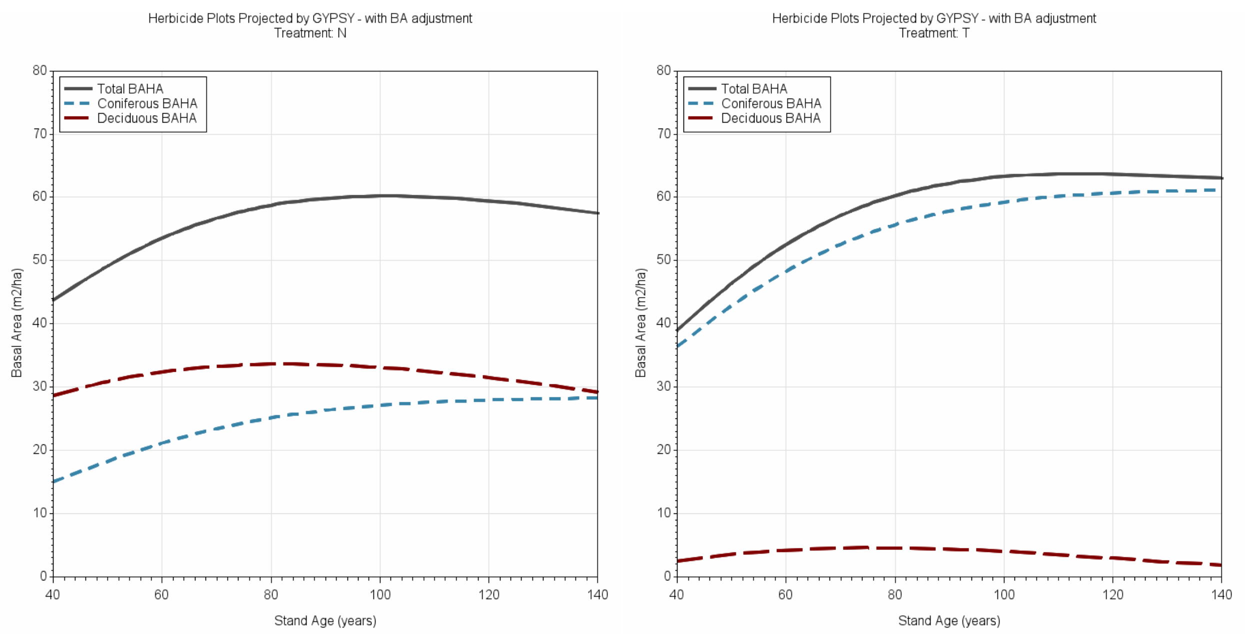


Figure 3-18. GYPSY basal area projection by treatment (untreated-N is shown on the left side)

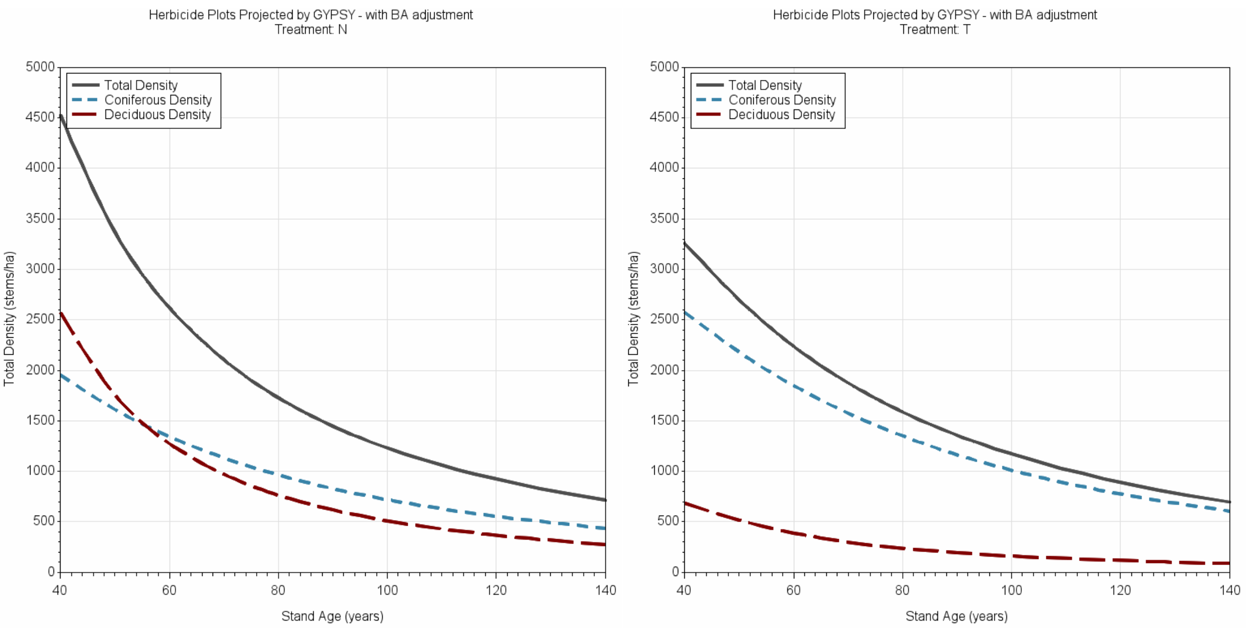


Figure 3-19. GYPSY all stem density projection by treatment

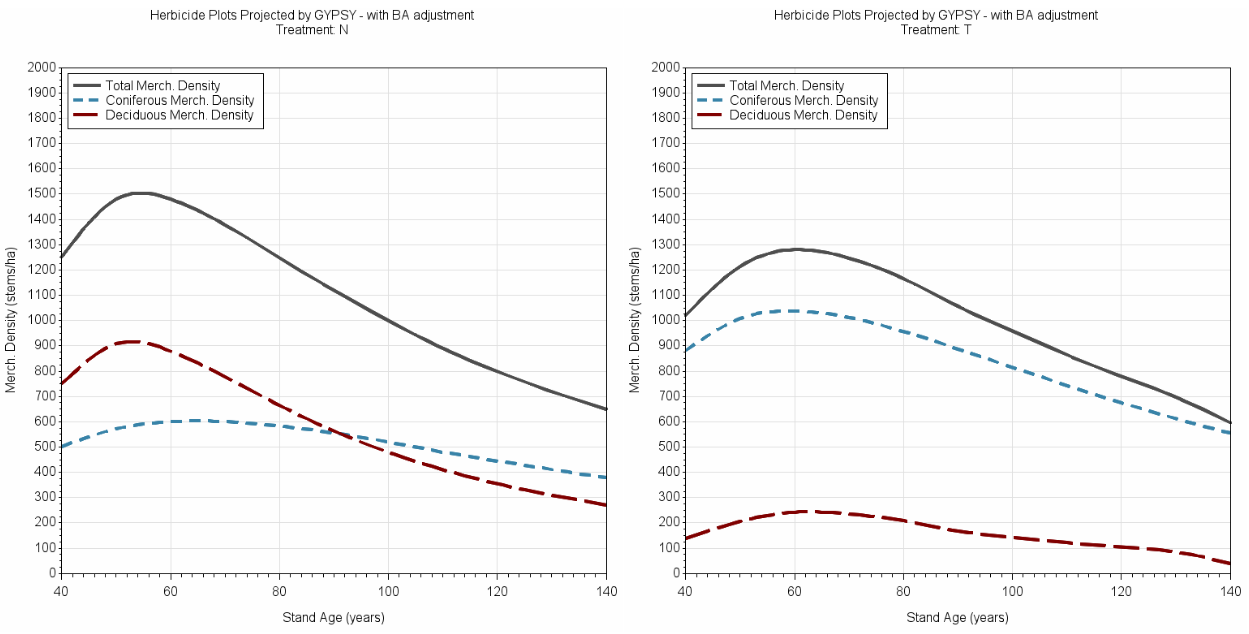


Figure 3-20. GYPSY merchantable stem density projection by treatment

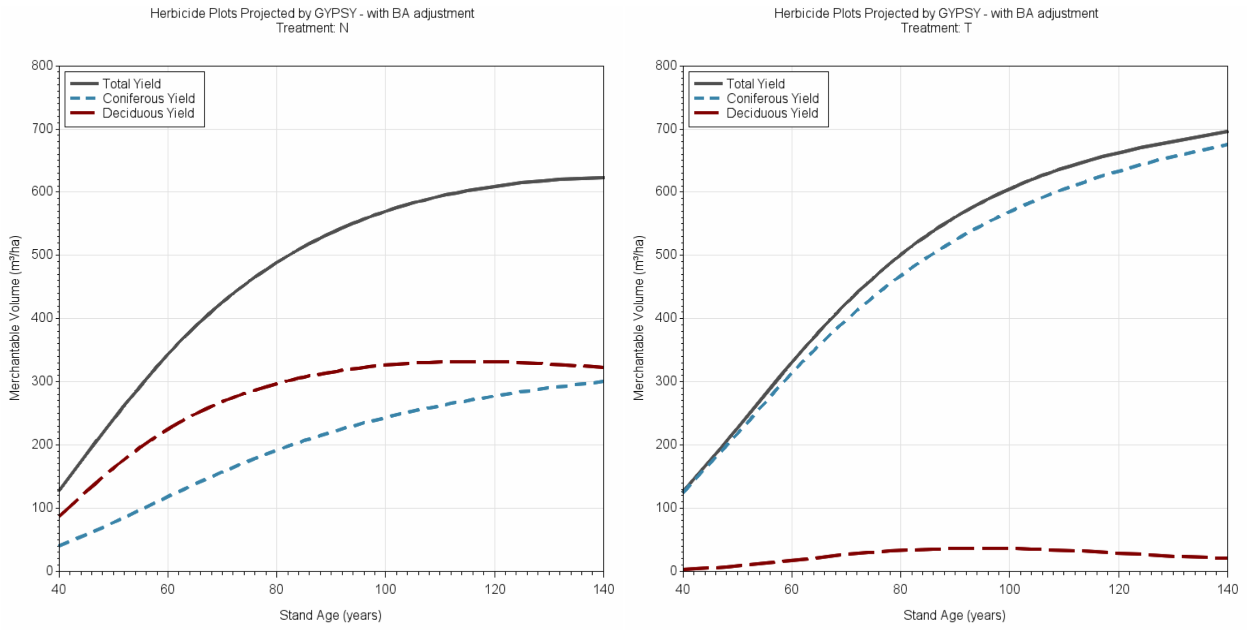


Figure 3-21. GYPSY gross merchantable volume projection by treatment

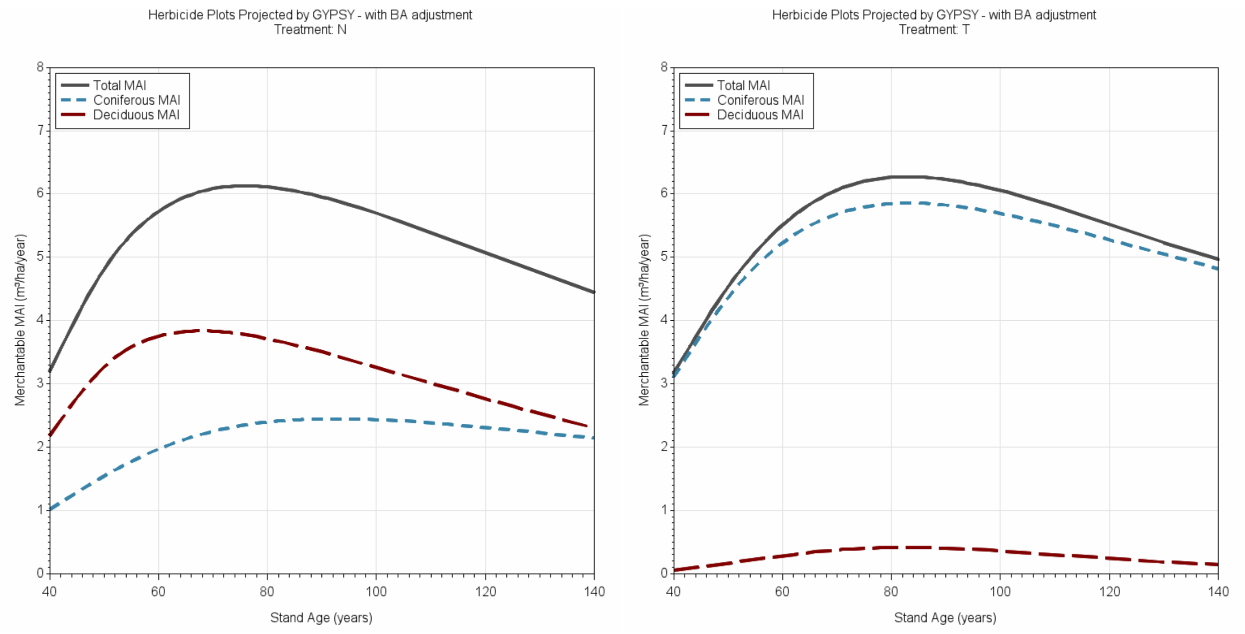


Figure 3-22. GYPSY gross merchantable MAI projection by treatment

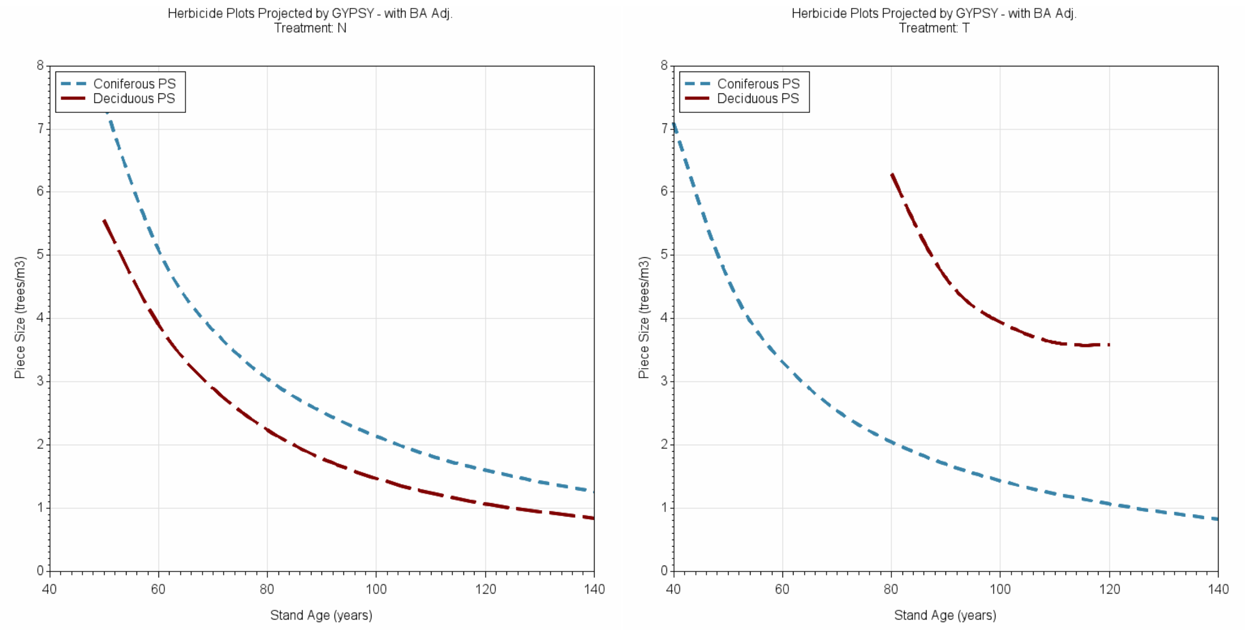


Figure 3-23. GYPSY gross merchantable piece size projection by treatment

GYPSY projections of future stands growth in untreated areas average as deciduous-dominated mixedwood over a 140-year horizon (Figure 3-18, Figure 3-21). Treated stands are projected as pure conifer stands as there was no significant aspen component left in these stands due to multiple herbicide treatments.

Total basal area and volume are similar at 100 years of age, although treated stands show slightly higher numbers for these stand attributes. The culmination MAI for conifer is much higher (5.8 vs. 2.5 m^3/ha/year) and peaks earlier (80 vs 90 years in treated and untreated, respectively). Conifer piece size is also substantially larger in treated stands as projected by GYPSY.

GYPSY was also run without the basal area adjustment to assess the model's ability to predict basal area, especially in the untreated portion of the stand. The basal area predictions by the model were then compared to the observed basal area for the aspen and white spruce component. It was found that model predictions for basal area were substantially lower than those observed in these young stands (Table 3-11).

Table 3-11. Observed average basal area vs. GYPSY predictions by species & treatment

Treatment	Basal Area (m^2/ha)			
	Trembling Aspen		White Spruce	
	Obs	Pred	Obs	Pred
Untreated (N)	24.6	14.0	8.8	1.9
Treated (T)	1.0	1.5	18.5	3.6

These findings appear to support a recent study of the Empirical Post-Harvest Database that found significant GYPSY prediction issues of white spruce basal area. It was found that stands with a small aspen component GYPSY dramatically over-predicted basal area and the over-prediction appears to get worse with time. For stands with relatively larger aspen components the model under-predicted basal area and the under-prediction was progressively worse with increasing observed basal area. This suggests a substantial and non-linear bias (Froese 2020).

3.4 Comparing Yield Projections

MGM and GYPSY both exhibit similar trends regarding much higher conifer yields and earlier conifer MAI culmination in treated versus untreated areas, but the magnitude of those differences vary significantly (Figure 3-24 and Figure 3-25). Peak conifer MAI in treated stands is very high for both models (above 5.5 m^3/ha/year), but MGM appears to culminate a decade or so earlier at 70 years.

The major difference in model projections is in stands that received no herbicide treatment, especially regarding the deciduous yield. MGM projects significant conifer growth at the expense of deciduous in the next couple of decades thus projecting a conifer-dominated mixedwood stand. GYPSY on the other hand projects slower conifer growth and much higher deciduous growth resulting in a deciduous-dominated mixedwood stand at rotation.

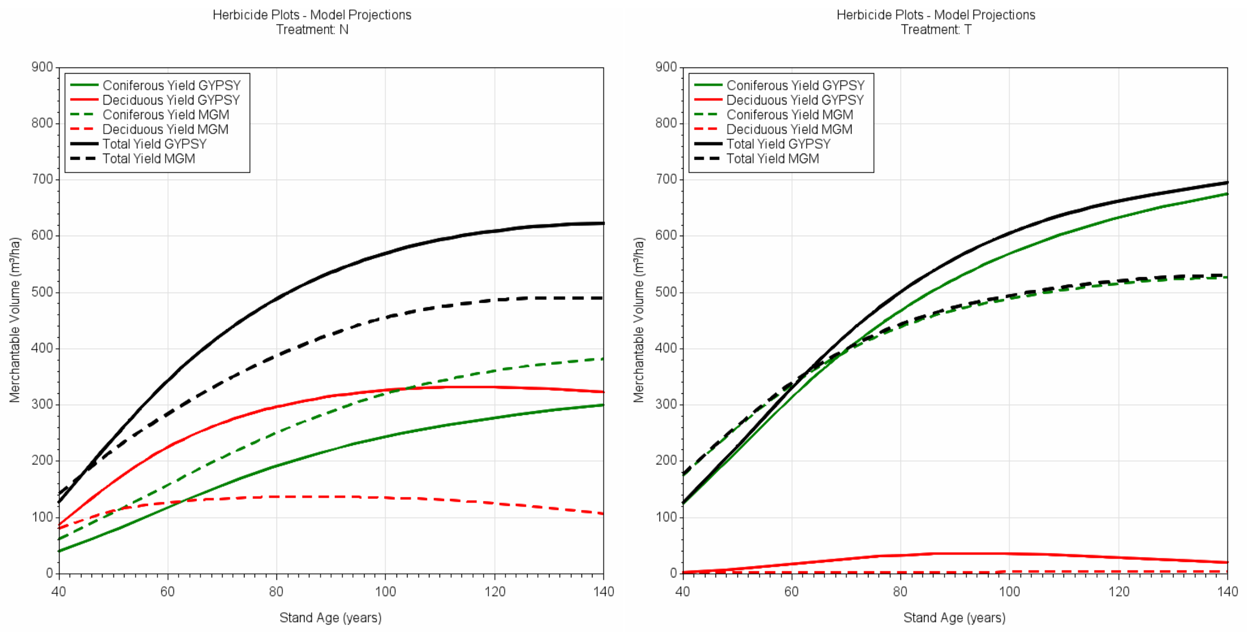


Figure 3-24. GYPSY and MGM gross merchantable volume projection by treatment

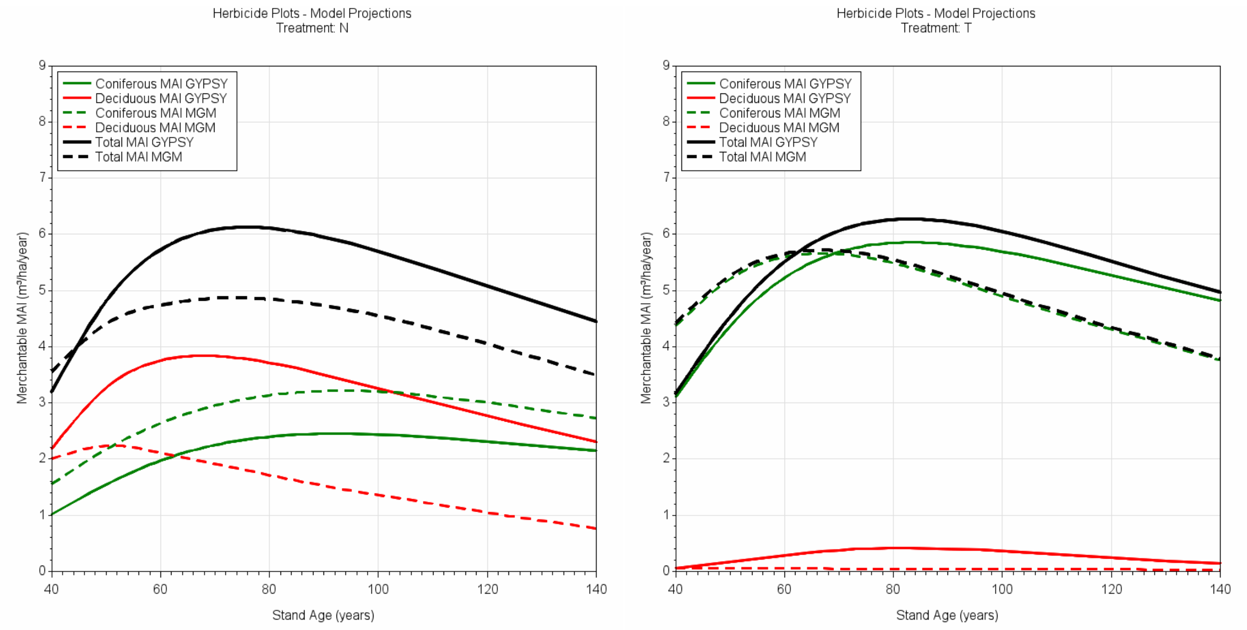
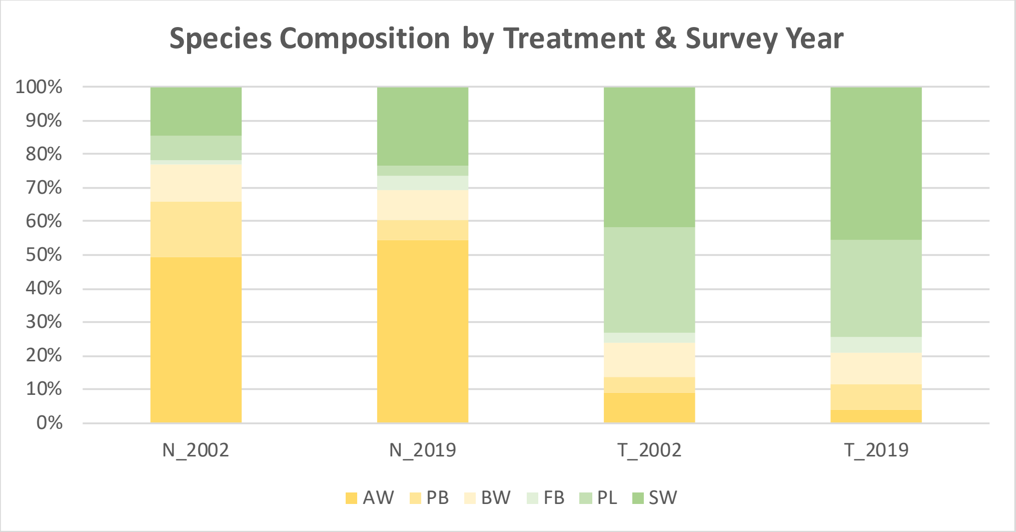


Figure 3-25. GYPSY and MGM gross merchantable MAI projection by treatment

4. Discussion

This long-term study shows that herbicide use clearly benefited conifer at the expense of deciduous over 20-years after the first treatment. However, the overall silviculture regime likely determined the scale of impact on the deciduous cover and the survival and growth response of the conifer.

Herbicide treatment is an effective vegetation management tool for shifting long-term species composition to softwood dominance and maintaining it 20-25 years after application (Figure 4-26).



Treat/Species	Species Composition (% density)					
	AW	PB	BW	SW	PL	FB
N_2002	49%	16%	11%	14%	8%	1%
N_2019	55%	6%	9%	23%	3%	4%
T_2002	9%	5%	10%	42%	31%	3%
T_2019	4%	8%	9%	46%	29%	5%

Figure 4-26. Species composition based on density by treatment and survey year

Herbicide treatment significantly reduced aspen cover, height and density in openings located in the Lower Foothills natural subregion of Alberta. Aspen density was reduced by 96% and basal area by as much as 98%. Our study agrees with the findings of several other studies (Pitt *et al*. 2004, Fu *et al*. 2008, Comeau and Fraser 2018) that multiple herbicide treatments will result in an almost complete removal of aspen in treated areas resulting in a pure conifer stand. Treatment application timing, frequency and application method will determine the amount of deciduous that may be present in smaller patches in spray swaths or in areas between highlight treatments or other deciduous that are seeded in or resprout following mechanical tending treatment.

Overall growth response and survival of the planted white spruce was high in the treated areas. The herbicide treatment increased the average DBH of spruce by almost 50% and promoted the relative dominance of conifer from 31% of basal area in untreated areas to 97% in treated areas. We also observed an almost 3-fold increase in gross total volume in treated areas over 20 years after the first application of herbicide. At the time of assessment there was a 7-fold increase in spruce gross merchantable volume (15/10/30 utilization) in treated areas. Given the average age and height of these stands, merchantable volume metrics need to be interpreted with caution, as many trees are just on the 'cusp' of jumping the merchantable threshold in the next few years.

The lack of significant response in height growth of the planted spruce is consistent with other studies. Comeau and Fraser (2018) found that there was no significant effect of herbicide treatment on spruce height, indicating that a reduction in height of this moderately shade tolerant species only occurs with extremely high levels of overtopping aspen competition. This is also supported by the earlier study of these same openings (Pitt et al. 2004) that found no significant difference in spruce average height five years after the herbicide treatment despite high levels (over 13,000 stems/ha) of deciduous competition in the untreated areas.

While the spruce was about 30% shorter than the aspen in 2002 in the treated areas, it is now roughly 30% taller than the aspen, but this effect is difficult to attribute solely to the initial herbicide treatment since it is confounded with site-preparation and follow-up herbicide treatments.

Untended spruce is certainly growing significantly slower as can be seen in DBH and basal area growth, but survival and ingress appear to be on par with the treated spruce and mortality does not appear to be anywhere close to those predicted by the earlier version of MGM (Pitt *et al.* 2004). This may be related to the significant improvements in silviculture in the early 1990's, specifically the introduction of styroblock containers that drastically increased the survival rates of planted seedlings due to a well-developed, healthy root system. Better understanding of plant physiology, fertilized, well-balanced substrate, great insulation and better stock handling contributed to better and more uniform stock quality. Many companies also increased planting densities and used better site preparation methods and equipment (e.g., line mounders, disk trenchers) helped to improve soil moisture and temperature regimes without stimulating competition of grasses and broadleaf vegetation (Mihajlovich pers. comm. 2020).

While the number of conifer stems (density) was not significantly different between treated and untreated areas, conifer percent stocking was different. Spruce stocking was similar between treated and untreated sites indicating an implied uniform spatial pattern representing planted spruce. However, ingress pine and balsam fir in treated areas appear to fill the gaps thus almost fully occupying the site at 94% vs only 69% in the untreated areas when overall conifer stocking is assessed.

With regards to model projections, MGM and GYPSY both showed similar trends regarding treated versus untreated stands with significantly higher conifer yields and earlier conifer MAI culmination. Total predicted volumes of all species were comparable. However, there were major differences in magnitude and proportion of yield forecasts in untreated stands for the conifer and deciduous components.

MGM predicted that untreated areas would develop into a conifer-dominated mixedwood stand while GYPSY forecasted a deciduous-dominated mixedwood at rotation.

Will the planted spruce overtake aspen in the main canopy in the next couple of decades in these untreated areas as forecasted by MGM? Pitt *et al*. (2004) suggested that planted spruce may not be well-positioned relative to canopy gaps except by chance and may not exhibit as significant growth and may suffer greater losses than suggested by the model. At the same time, deciduous may exhibit survival rates that are better than suggested by the model, additional aspen may also come in through seeding in, ingrowth and re-sprouting even in herbicide treated areas in small patches between spray swaths.

Recent findings in the Regenerated Lodgepole Pine trial suggests that lower levels of treatment effectiveness may be achieved operationally, when compared to well-controlled research trials[15]. This may also be an important factor to consider when calibrating models from controlled experiments because of the potential over-estimation of treatment effects in the final model.

Differences between model projections are expected due to different model architecture and the data used for calibration. GYPSY is a stand-level model that was mainly calibrated from PSP data located in natural, fire-origin stands. There was no differentiation regarding various silviculture treatments, only current stand conditions are projected based on key stand level attributes. On the other hand, MGM is a deterministic, distance-independent individual tree growth model that enables the modeling of forest vegetation management scenarios by growing and manipulating individual trees. Calibration data was originally also based on mostly natural stands, with more and more managed stand plot data and experimental research trial information incorporated into the model calibration process over time.

Some of the impacts of the ingrowth and ingress of spruce is likely not captured in either model due to limitations in either the submodels (e.g., GYPSY density functions) or internal setting of flags (e.g., MGM AllowIngrowth = False). More research is needed regarding the impact of model initialization when it comes to averaging the input (i.e., plot data in an opening) or projecting individual plots and averaging the projections. Site index is a major driver of growth models, therefore understanding the impact of its application (block versus plot level) on growth projection is also paramount.

Models will always “lag” behind silviculture hence the need for long-term time-series data to properly calibrate growth models. For example, any data that was used in the calibration of MGM in the early 2000’s would not have captured the significant shift away from bareroot stock and the introduction of new site preparation equipment and methods that resulted in drastic improvements in planted conifer survival rates.

Although best practices have been developed for these models for model setup, data needs and use, these will need to be continually updated to reflect changes in modeling approach/functionality and changes in requirements for forest management planning in Alberta.

It is quite possible that our herbicide plot data exceeds the models’ scope and the range of calibration data, potentially resulting in prediction errors that are “amplified” further over time, suggesting that model forecasts may not represent what would actually occur. Therefore, long term monitoring of these experiments may be needed to improve our understanding of how changes in site conditions produced by management practices can influence future growth.

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[15] Dick Dempster, pers. comm. 2021.

5. Conclusions

It is evident from this project and many other studies that herbicide treatment is a highly effective silviculture tool for shifting long-term species composition and structure to softwood dominance that persists 20-25 years after application. There are substantial observed gains in conifer growth that will result in increased conifer peak MAI and reduced rotation length in these stands.

There is strong value proposition in herbicide use which makes conifer reforestation efforts more consistent and reliable in the boreal forests of Alberta, but the overall silviculture regime including prompt reforestation and proactive treatments will determine the rate of success.

Based on our review, it is also apparent that our growth models still need work when it comes to projecting managed stand growth and yield. While the general trend is similar regarding increased growth of planted white spruce, higher conifer peak MAI and shorter rotation; there are significant projection differences in magnitude between the available models in herbicide treated stands. Untreated stands are projected very differently by MGM and GYPSY. Understanding these differences with regards to model architecture, data initialization (averaging input versus output), site index application methods and the handling of ingress/ingrowth are areas that will require more research.

Significant improvements and advances in our knowledge and understanding are still needed in the modeling of the effects of forest vegetation management in order to bring these models into forest-level decision making.

However, models require local, representative data that come from long-term, controlled experiments with replication of large enough plots where the effect of treatments can be separated. Given the current uncertainty regarding the acceptance of herbicide use in forestry, these controlled experiments may need to include alternative, non-chemical vegetation management options such as mechanical brushing, bend-and-break and grazing; if evaluations of such options using models are desired in the future.

This is an expensive endeavor that can only be achieved through cooperative research programs with long-term financial backing. These applied research programs need to be initiated early. Research that begins after a “crisis” has started is of limited value (Wagner 1993).

In addition, a large province-wide network of PSP installations in managed stands will provide high quality time-series data in the growth phase for further model development and calibration. The current PGYI PSP network provides a great example of the value of cooperative effort.

6. References

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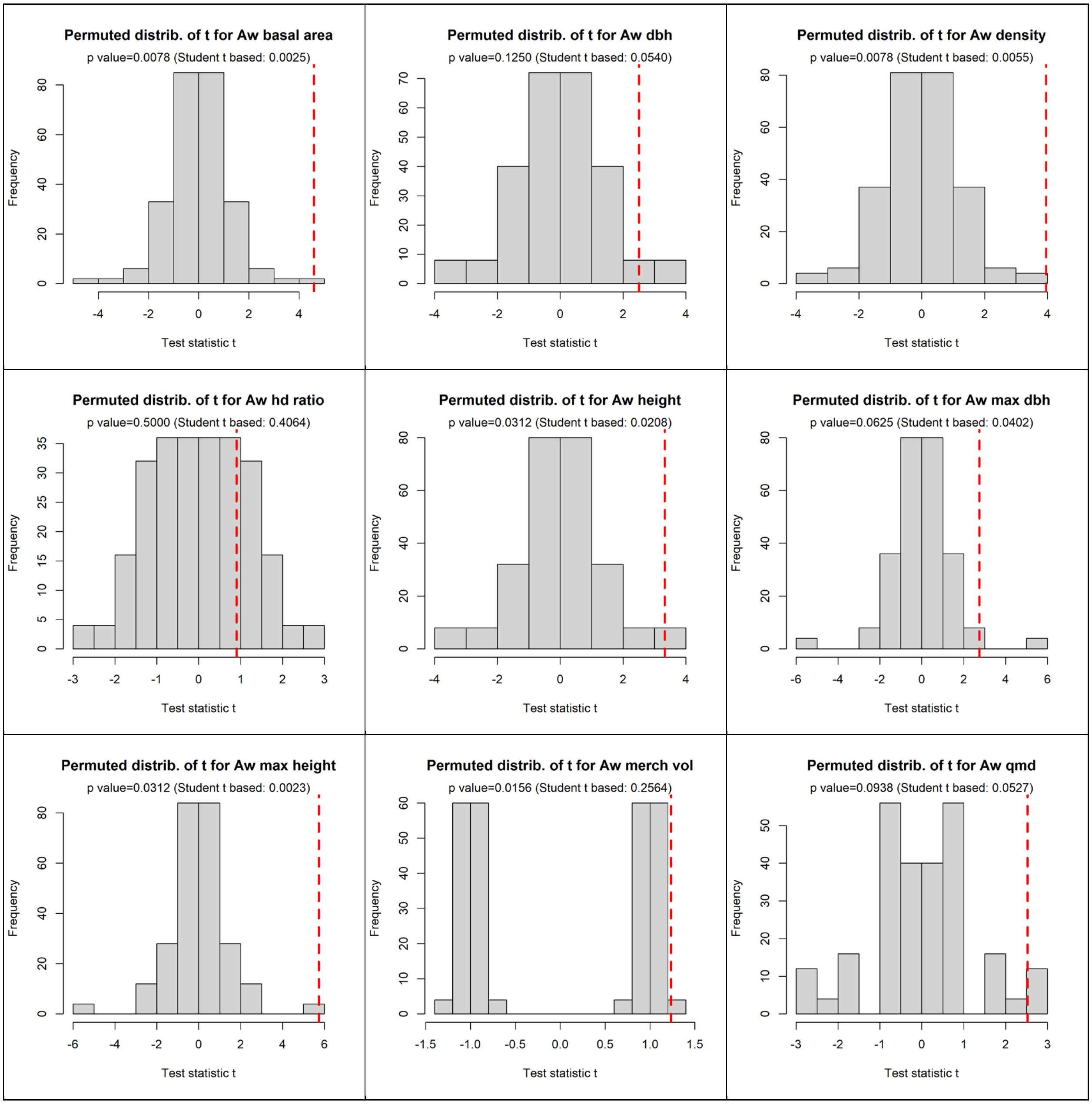
Appendix I – Permutation t-tests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Test statistic t
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p value=0.1250 (Student t based: 0.0540)
Frequency
0 10 20 30 40 50 60 70
-4 -2 0 2 4
Test statistic t
Permuted distrib. of t for Aw density
p value=0.0078 (Student t based: 0.0055)
Frequency
0 20 40 60 80
-4 -2 0 2 4
Test statistic t
Permuted distrib. of t for Aw hd ratio
p value=0.5000 (Student t based: 0.4064)
Frequency
0 5 10 15 20 25 30 35
-3 -2 -1 0 1 2 3
Test statistic t
Permuted distrib. of t for Aw height
p value=0.0312 (Student t based: 0.0208)
Frequency
0 20 40 60 80
-4 -2 0 2 4
Test statistic t
Permuted distrib. of t for Aw max dbh
p value=0.0625 (Student t based: 0.0402)
Frequency
0 20 40 60 80
-6 -4 -2 0 2 4 6
Test statistic t
Permuted distrib. of t for Aw max height
p value=0.0312 (Student t based: 0.0023)
Frequency
0 20 40 60 80
-6 -4 -2 0 2 4 6
Test statistic t
Permuted distrib. of t for Aw merch vol
p value=0.0156 (Student t based: 0.2564)
Frequency
0 10 20 30 40 50 60
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
Test statistic t
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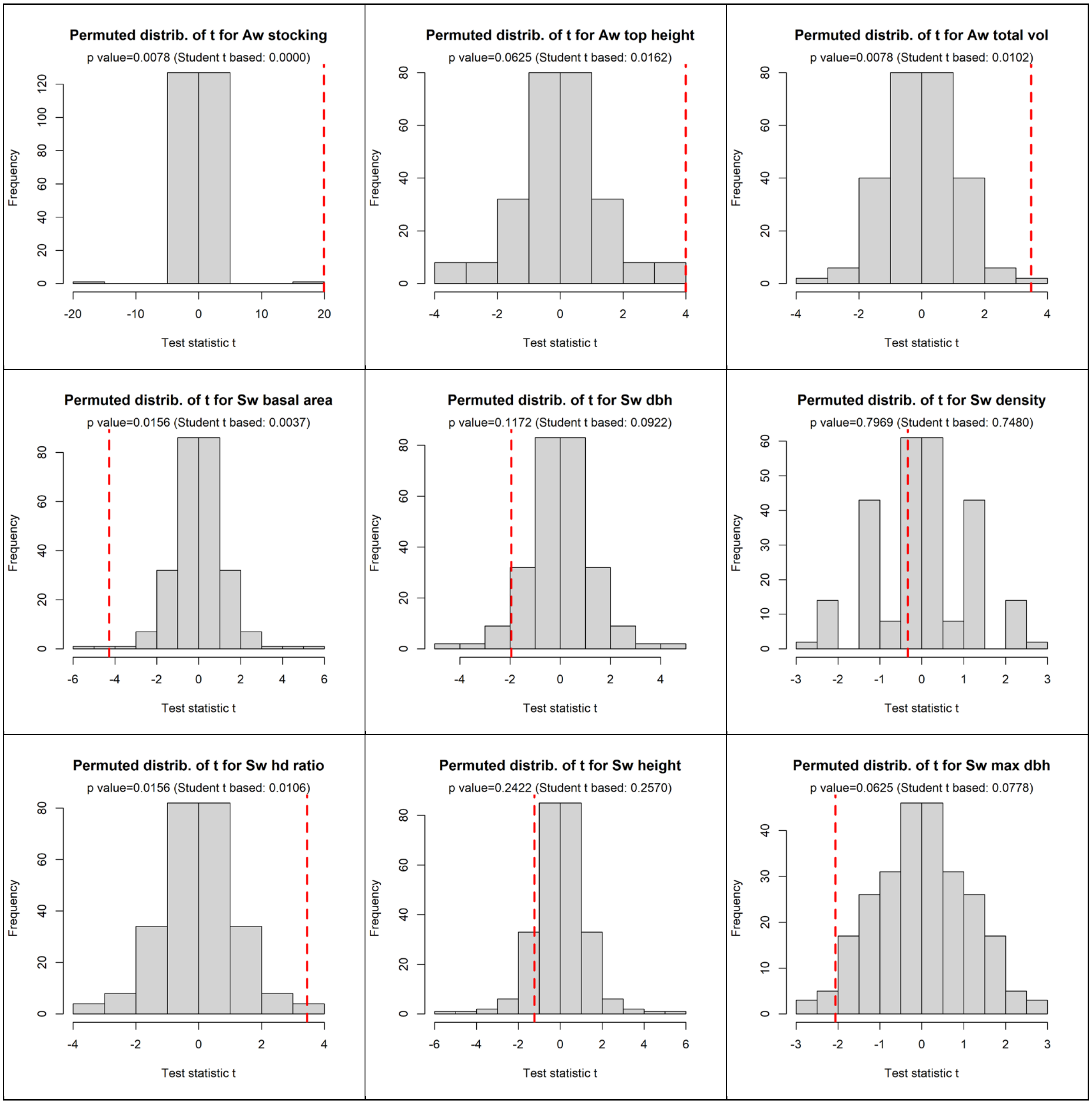
Test statistic t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Permuted distrib. of t for Aw total vol
p value=0.0078 (Student t based: 0.0102)
Permuted distrib. of t for Sw basal area
p value=0.0156 (Student t based: 0.0037)
Permuted distrib. of t for Sw dbh
p value=0.1172 (Student t based: 0.0922)
Permuted distrib. of t for Sw density
p value=0.7969 (Student t based: 0.7480)
Permuted distrib. of t for Sw hd ratio
p value=0.0156 (Student t based: 0.0106)
Permuted distrib. of t for Sw height
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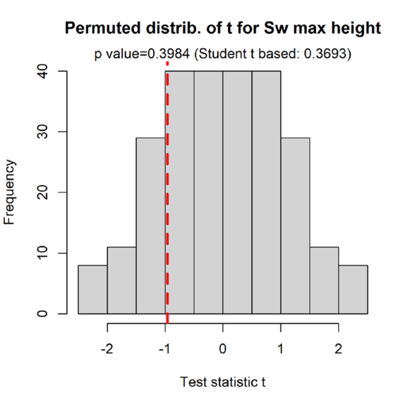
Frequency
Test statistic t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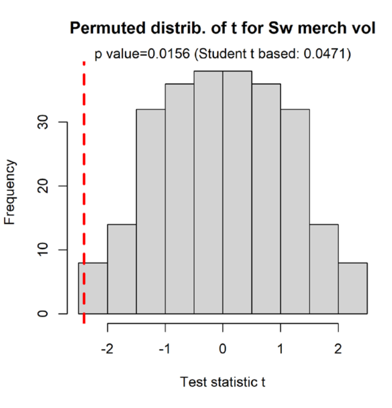
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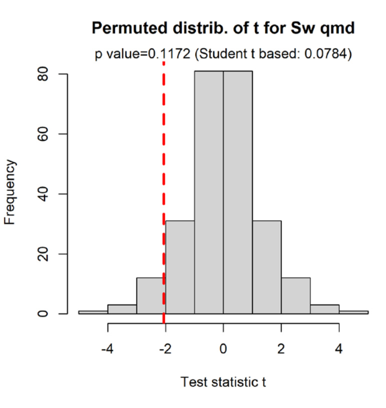
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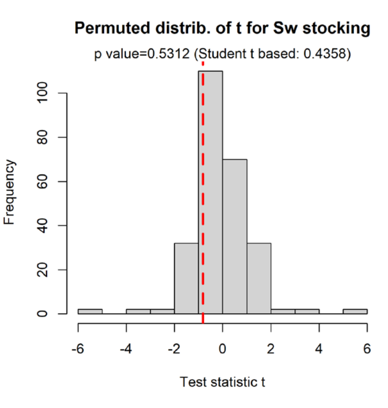
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4
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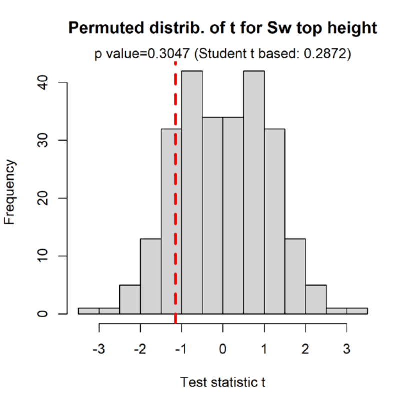
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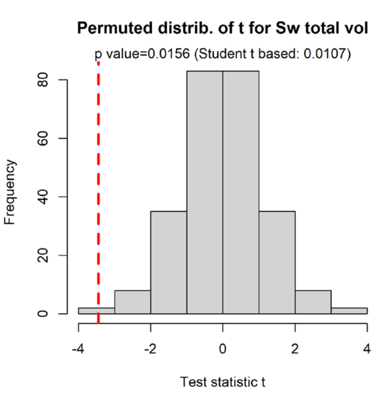
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2
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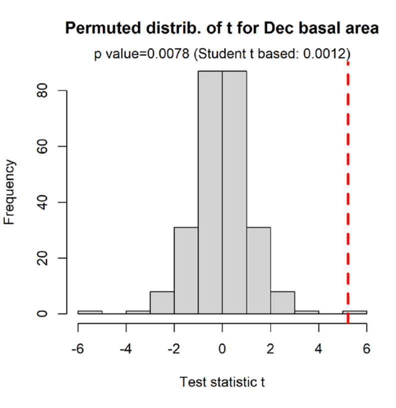
Test statistic t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0
2
4
6
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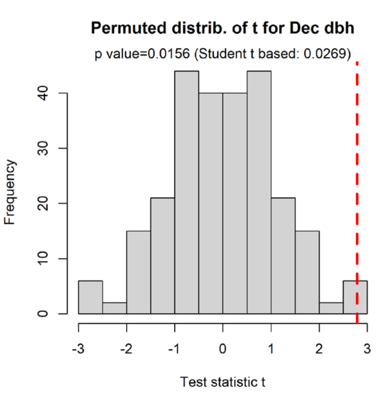
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2
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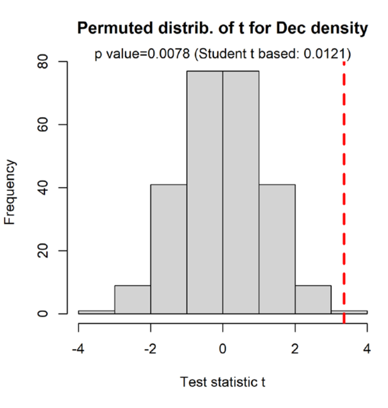
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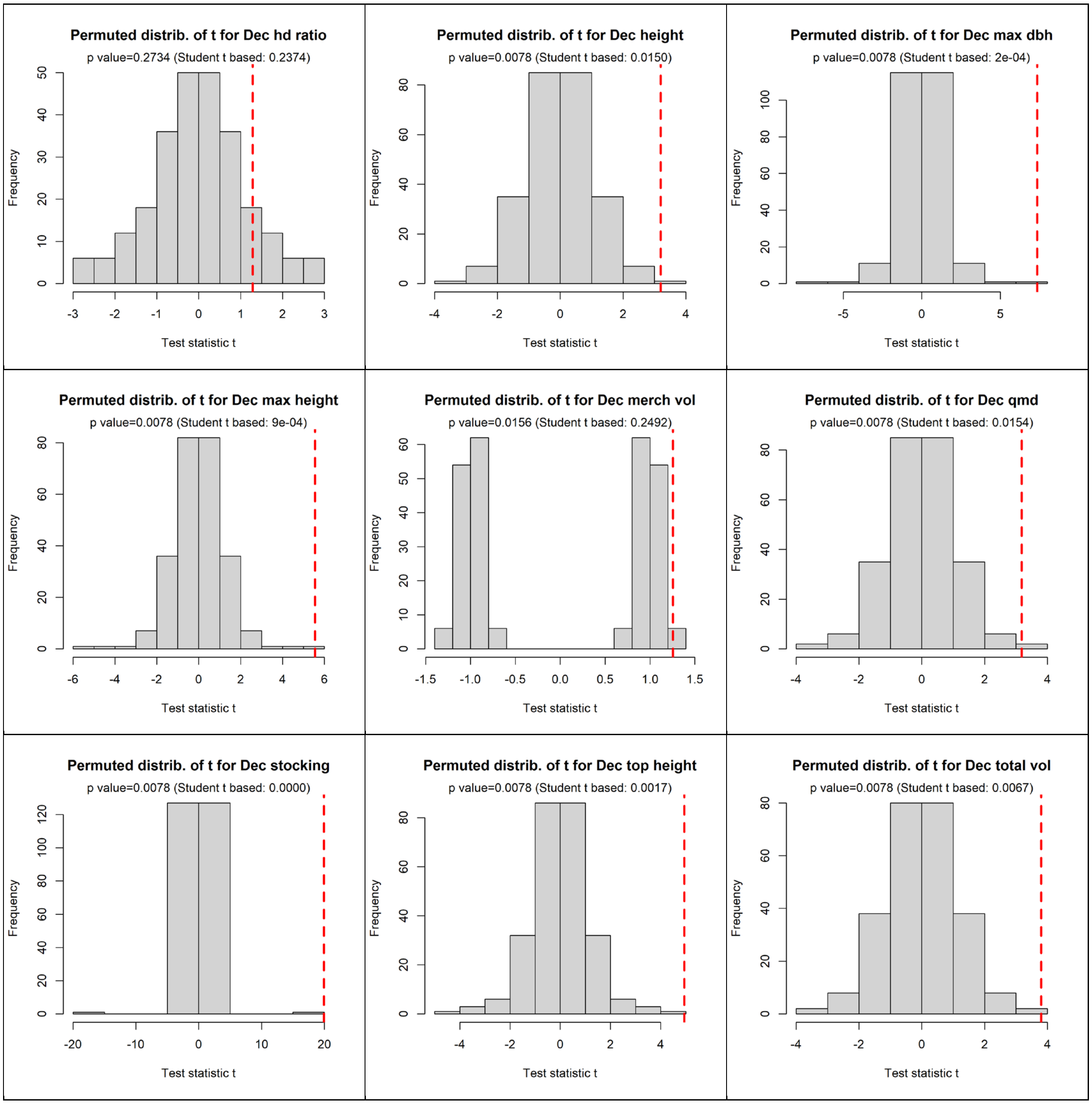
60
80
-4
-2
0
2
4
Test statistic t


Permuted distrib. of t for Dec hd ratio
p value=0.2734 (Student t based: 0.2374)
Frequency
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Permuted distrib. of t for Dec height
p value=0.0078 (Student t based: 0.0150)
Frequency
Test statistic t
Permuted distrib. of t for Dec max dbh
p value=0.0078 (Student t based: 2e-04)
Frequency
Test statistic t
Permuted distrib. of t for Dec max height
p value=0.0078 (Student t based: 9e-04)
Frequency
Test statistic t
Permuted distrib. of t for Dec merch vol
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Frequency
Test statistic t
Permuted distrib. of t for Dec qmd
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Frequency
Test statistic t
Permuted distrib. of t for Dec stocking
p value=0.0078 (Student t based: 0.0000)
Frequency
Test statistic t
Permuted distrib. of t for Dec top height
p value=0.0078 (Student t based: 0.0017)
Frequency
Test statistic t
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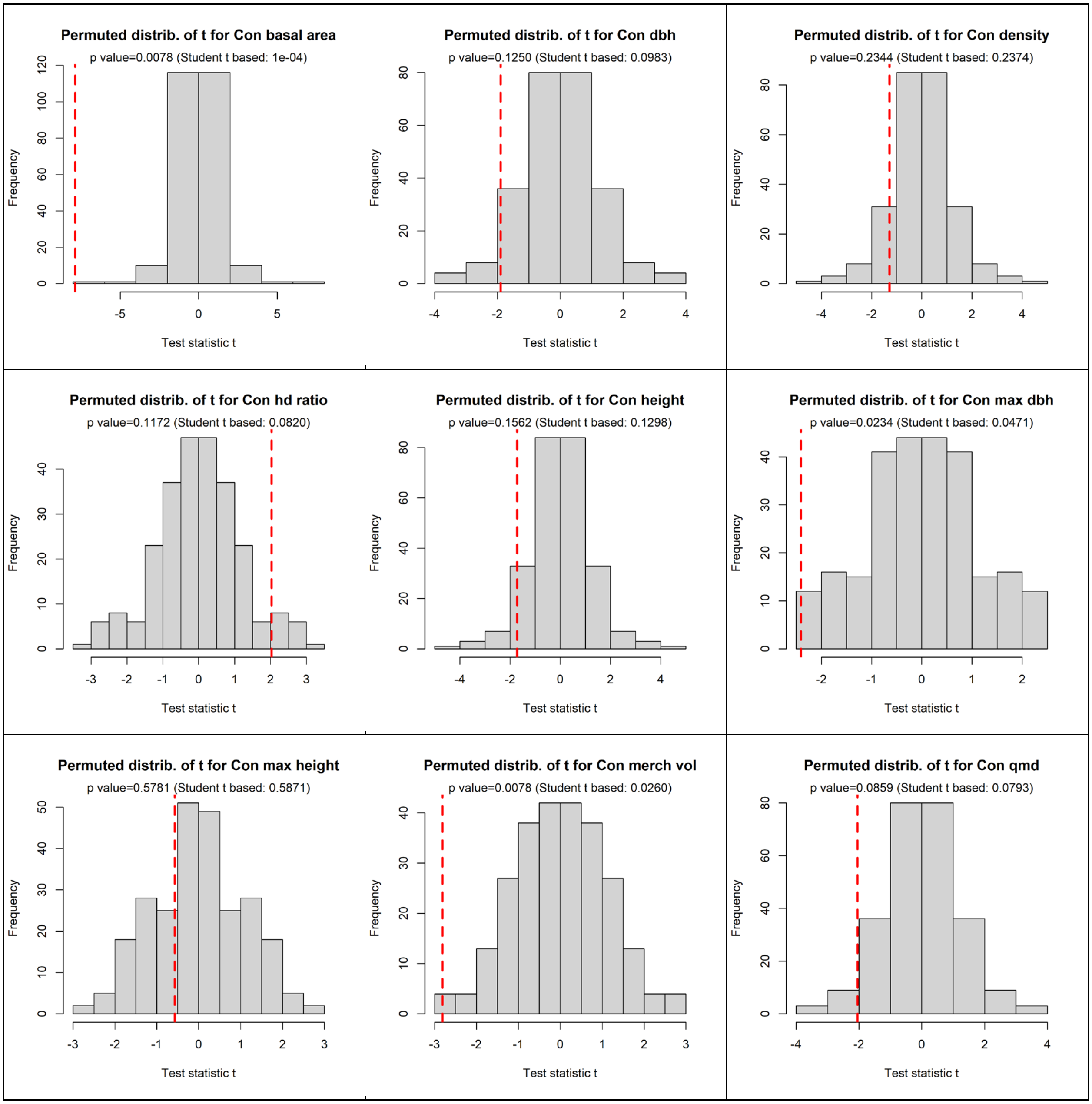
Frequency
Test statistic t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Frequency
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20
40
60
80
100
120
-5
0
5
Test statistic t
Permuted distrib. of t for Con dbh
p value=0.1250 (Student t based: 0.0983)
Frequency
0
20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Con density
p value=0.2344 (Student t based: 0.2374)
Frequency
0
20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Con hd ratio
p value=0.1172 (Student t based: 0.0820)
Frequency
0
10
20
30
40
-3
-2
-1
0
1
2
3
Test statistic t
Permuted distrib. of t for Con height
p value=0.1562 (Student t based: 0.1298)
Frequency
0
20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Con max dbh
p value=0.0234 (Student t based: 0.0471)
Frequency
0
10
20
30
40
-2
-1
0
1
2
Test statistic t
Permuted distrib. of t for Con max height
p value=0.5781 (Student t based: 0.5871)
Frequency
0
10
20
30
40
50
-3
-2
-1
0
1
2
3
Test statistic t
Permuted distrib. of t for Con merch vol
p value=0.0078 (Student t based: 0.0260)
Frequency
0
10
20
30
40
-3
-2
-1
0
1
2
3
Test statistic t
Permuted distrib. of t for Con qmd
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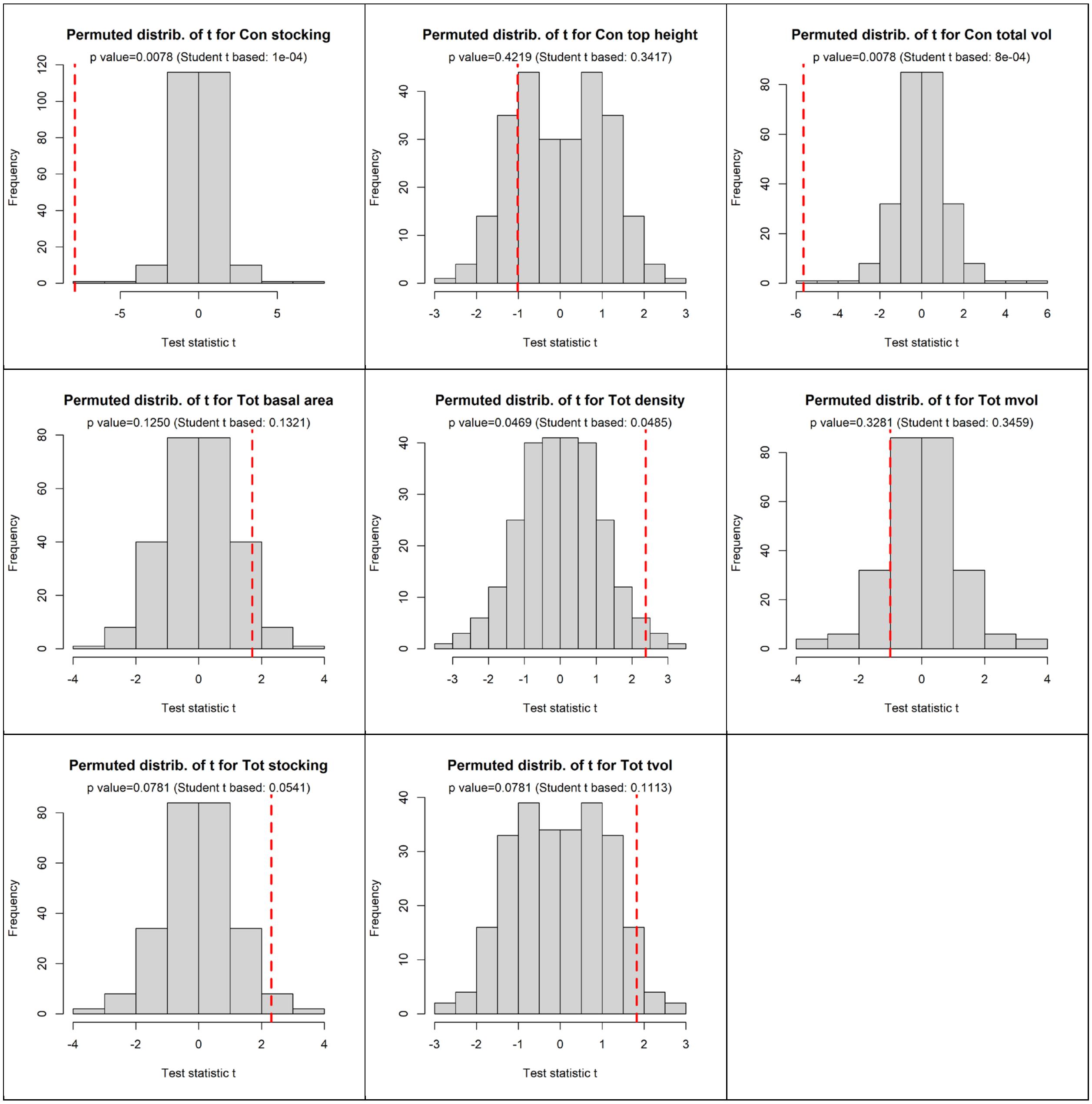
Test statistic t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80
100
120
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0
5
Test statistic t
Permuted distrib. of t for Con top height
p value=0.4219 (Student t based: 0.3417)
Frequency
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10
20
30
40
-3
-2
-1
0
1
2
3
Test statistic t
Permuted distrib. of t for Con total vol
p value=0.0078 (Student t based: 8e-04)
Frequency
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20
40
60
80
-6
-4
-2
0
2
4
6
Test statistic t
Permuted distrib. of t for Tot basal area
p value=0.1250 (Student t based: 0.1321)
Frequency
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20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Tot density
p value=0.0469 (Student t based: 0.0485)
Frequency
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10
20
30
40
-3
-2
-1
0
1
2
3
Test statistic t
Permuted distrib. of t for Tot mvol
p value=0.3281 (Student t based: 0.3459)
Frequency
0
20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Tot stocking
p value=0.0781 (Student t based: 0.0541)
Frequency
0
20
40
60
80
-4
-2
0
2
4
Test statistic t
Permuted distrib. of t for Tot tvol
p value=0.0781 (Student t based: 0.1113)
Frequency
0
10
20
30
40
-3
-2
-1
0
1
2
3
Test statistic t

Appendix II – Silviculture History

Site = 1		Treated		Untreated
Company		Blue Ridge Lumber		
Block Number		130-75		
Harvest Year		1995		
Area (ha)		48.0		5.4
Site		Mesic	Medium	
Site Preparation #1	Method	DIPO		None
	Year	1996		
	Area (ha)	6.5		
Establishment #1	Species	Sw/Pl		Sw/Pl
	Type	Plant		Plant
	Year	1996		1996
	Stock size	Bareroot		Bareroot
	Area (ha)	48.0		5.4
	Density	1461		1461
Tending #1	Herbicide	Glyphosate		None
	Rate (g/ha)	2136		
	Year	1997		
	Method	Aerial		
	Area (ha)	48.0		
Site Preparation #2	Method	Mound	Plough	None
	Year	2003	2004	
	Area (ha)	9.0	1.5	
Establishment #2	Species	Pl		Pl
	Type	Plant		Plant
	Year	2004		2004
	Stock size	410-Cu		410-Cu
	Area (ha)	48.0		5.4
	Density			
Tending #2	Herbicide	Glyphosate	Glyphosate	None
	Rate (g/ha)	2136	2136	
	Year	2000	2005	
	Method	Aerial	Aerial	
	Area (ha)	48.0	8.0	
Survey	Conifer	3.57 m^3/ha/yr		
	Deciduous	0.34 m^3/ha/yr		
	Total	3.91 m^3/ha/yr		

Site = 2		Treated	Untreated
Company		Blue Ridge Lumber	
Block Number		120-37	
Harvest Year		1979	
Area (ha)		18.0	9.0
Site		Mesic/Subhygric	Rich
Site Preparation #1	Method	PLOUGH	PLOUGH
	Year	1980	1980
	Area (ha)	18.0	9.0
Establishment #1	Species	Sw	Sw
	Type	Plant	Plant
	Year	1980	1980
	Stock size	Unknown	Unknown
	Area (ha)	18.0	9.0
	Density	1555	1555
Tending #1	Herbicide	Hexazinone	None
	Rate (g/ha)	Unknown	
	Year	1990	
	Method	Ground	
	Area (ha)	18.0	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species		
	Type		
	Year		
	Stock size		
	Area (ha)		
	Density		
Tending #2	Herbicide	None	None
	Rate (g/ha)		
	Year	2003	
	Method	Motor-manual	
	Area (ha)	18.0	
Survey	Conifer	86.0%	
	Deciduous	2.5%	
	Total	91.0%	

Site = 5		Treated	Untreated
Company		Alberta Newsprint	
Block Number		WP-1012	
Harvest Year		1990	
Area (ha)		57.9	2.0
Site		Mesic	Medium
Site Preparation #1	Method	DISK	DISK
	Year	1990	1990
	Area (ha)	57.9	2.0
Establishment #1	Species	Sw	Sw
	Type	Plant	Plant
	Year	1991	1991
	Stock size	313C	313C
	Area (ha)	57.9	2.0
	Density	1421	1421
Tending #1	Herbicide	Glyphosate	None
	Rate (g/ha)	1424	
	Year	1994	
	Method	Aerial	
	Area (ha)	57.9	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species		
	Type		
	Year		
	Stock size		
	Area (ha)		
	Density		
Tending #2	Herbicide	None	None
	Rate (g/ha)		
	Year		
	Method		
	Area (ha)		
Survey	Conifer	92.4%	
	Deciduous	5.7%	
	Total	98.1%	

Site = 6		Treated	Untreated
Company		Blue Ridge Lumber	
Block Number		690-38	
Harvest Year		1998	
Area (ha)		30.9	1.6
Site		Mesic	Medium
Site Preparation #1	Method	MOUND	None
	Year	1998	
	Area (ha)	1.2	
Establishment #1	Species	Pl/Sw/Sb	Pl/Sw/Sb
	Type	Plant	Plant
	Year	1998	1998
	Stock size	S410	S410
	Area (ha)	30.9	1.6
	Density	1650	1650
Tending #1	Herbicide	Glyphosate	None
	Rate (g/ha)	2136	
	Year	1999	
	Method	Aerial	
	Area (ha)	30.9	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species		
	Type		
	Year		
	Stock size		
	Area (ha)		
	Density		
Tending #2	Herbicide	Glyphosate	None
	Rate (g/ha)	2136	
	Year	2005	
	Method	Aerial	
	Area (ha)	18.0	
Survey	Conifer	91.5%	
	Deciduous	31.4%	
	Total	94.2%	

Site = 7		Treated	Untreated
Company		Alberta Newsprint	
Block Number		HC-1096	
Harvest Year		1992	
Area (ha)		45.0	5.5
Site		Mesic/Subhygric	Rich
Site Preparation #1	Method	DISK	DISK
	Year	1992	1992
	Area (ha)	45.0	5.5
Establishment #1	Species	Sw	Sw
	Type	Plant	Plant
	Year	1993	1993
	Stock size	415B	415B
	Area (ha)	45.0	5.5
	Density	1761	1761
Tending #1	Herbicide	Glyphosate	None
	Rate (g/ha)	2136	
	Year	1996	
	Method	Aerial	
	Area (ha)	45.0	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species		
	Type		
	Year		
	Stock size		
	Area (ha)		
	Density		
Tending #2	Herbicide	None	None
	Rate (g/ha)		
	Year		
	Method		
	Area (ha)		
Survey	Conifer	79.7%	
	Deciduous	14.4%	
	Total	84.7%	

Site = 8		Treated		Untreated
Company		Alberta Newsprint		
Block Number		**W06-1048A**		
Harvest Year		1995		
Area (ha)		16.8		11.8
Site		Subhygric	Medium/Rich	
Site Preparation #1	**Method**	MOUND		
	Year	1997		
	Area (ha)	12.1		
Establishment #1	**Species**	Sw	Pl	Pl
	Type	Plant	LFN	LFN
	Year	1998		
	Stock size	415B		
	Area (ha)	12.1	5.0	11.8
	Density	1276		
Tending #1	**Herbicide**	Glyphosate	Glyphosate	None
	Rate (g/ha)	2136	1568	
	Year	1999	1999	
	Method	Aerial	Aerial	
	Area (ha)	6.8	10.3	
Site Preparation #2	**Method**			
	Year			
	Area (ha)			
Establishment #2	**Species**			
	Type			
	Year			
	Stock size			
	Area (ha)			
	Density			
Tending #2	**Herbicide**	Triclopyr	None	None
	Rate (g/ha)	3230		
	Year	2006		
	Method	Basal bark		
	Area (ha)	5.8		
Survey	**Conifer**	90.6%		
	Deciduous	4.7%		
	Total	95.3%		

Site = 9		Treated	Untreated
Company		Alberta Newsprint	
Block Number		W06-1042	
Harvest Year		1996	
Area (ha)		20.4	3.0
Site		Mesic	Medium
Site Preparation #1	Method	None	None
	Year		
	Area (ha)		
Establishment #1	Species	Sw	Sw
	Type	Plant	Plant
	Year	1996	1996
	Stock size	415B	415B
	Area (ha)	20.4	3.0
	Density	1775	1775
Tending #1	Herbicide	Glyphosate	None
	Rate (g/ha)	2136	
	Year	1998	
	Method	Aerial	
	Area (ha)	20.4	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species		
	Type		
	Year		
	Stock size		
	Area (ha)		
	Density		
Tending #2	Herbicide	Glyphosate	None
	Rate (g/ha)	1424	
	Year	2007	
	Method	Backpack	
	Area (ha)	16.5	
Survey	Conifer	90.6%	
	Deciduous	51.6%	
	Total	96.6%	

Site = 10		Treated	Untreated
Company		Canfor Grande Prairie	
Block Number		S14036	
Harvest Year		1993	
Area (ha)		22.1	1.9
Site		Mesic/Subhygric	Medium
Site Preparation #1	Method	DIPO	DIPO
	Year	1993	1993
	Area (ha)	21.4	1.9
Establishment #1	Species	Sw	Sw/Pl
	Type	Plant	Seed
	Year	1993	1994
	Stock size	313B	
	Area (ha)	14.3	9.6
	Density	1523	
Tending #1	Herbicide	Glyphosate	None
	Rate (g/ha)	2136	
	Year	1999	
	Method	Aerial	
	Area (ha)	21.4	
Site Preparation #2	Method		
	Year		
	Area (ha)		
Establishment #2	Species	Sw	
	Type	Re-Plant	
	Year	1999	
	Stock size	415B	
	Area (ha)	22.1	
	Density	1640	
Tending #2	Herbicide	None	None
	Rate (g/ha)		
	Year	2003	
	Method	Manual Brush	
	Area (ha)	22.1	
Survey	Conifer	51.6%	
	Deciduous	10.9%	
	Total	62.5%	

For additional information, please contact:
Brian Roth, *PhD*
Director
Forest Growth Organization of Western Canada
1176 Switzer Drive
Hinton, Alberta
T7V 1V3
Telephone : (780) 709-1393
Email : brian.roth@friresearch.ca

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